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Comparative Evaluation of the Physicochemical Properties of Animal Tallow-Based Hybrid Biofuels Compared with Diesel Fuel

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A B S T R A C T

In recent years, renewable energy especially biofuels have attracted growing interest due to its ability to help reduce the environmental problems caused by traditional fossil fuels. Tallow, a type of fat obtained from animals, is a widely accessible source of lipids and is showing great potential for use in making biofuels. However, the choice of tallow source plays a pivotal role in determining the physicochemical properties of such biofuels. This study presents the experimental evaluation of the physicochemical properties of animal tallow-based hybrid biofuels, its blends (B10(10% animal tallow biodiesel + 90% diesel) and B20 (20% animal tallow biodiesel + 80% diesel)) with petroleum diesel. The key properties analyzed include, density, calorific value, kinematic viscosity, flash point, cloud point, pour point, fire point, and carbon residue. The study reveals that animal tallow–based hybrid biofuels, MHBF, B10 and B20, provide a favorable balance between fuel properties and usability when compared to diesel. Increment in flash point and fire point of MHBF, B10, and B20 indicating safer storage and handling. Cold flow properties show the mixed behavior. On the basis of physicochemical chemical properties these fuels can serve as viable alternatives, contributing to sustainable energy development.

1. INTRODUCTION

Global energy demand is steadily increasing due to population growth, urbanization, and economic development. Uneven fossil fuel distribution causes dependence on specific regions, leading to price instability and supply disruptions for importing countries [1]. The growing need for energy, along with rising environmental concerns, has led to extensive research focused on developing eco-friendly alternative fuels from renewable sources [2]. The global shift toward biodiesel from renewable lipids highlights animal fats like tallow as economical, abundant feedstocks, though bovine spongiform encephalopathy (BSE) concerns limit traditional uses, making biodiesel a safer alternative and sustainable [2]. Animal fats consist of triglycerides, where three fatty acids are linked to one glycerol molecule. These fatty acids differ in chain length and in the number and arrangement of double bonds [3]. Biodiesel from animal fats and vegetable oils is similar, but animal-based fuel contains more saturated fatty esters. This results in higher viscosity and melting point, especially in beef tallow biodiesel [4]. Raw materials strongly influence biodiesel properties: animal fat fuels have higher cloud points and can solidify in cold weather, while soybean-based biodiesel flows better due to more unsaturated fatty acids [3]. Other important properties include viscosity and density, which are typically higher than those of conventional diesel [2]. Second generation biofuels come from non-edible sources like crop residues and wood, using advanced conversion technologies, reducing food competition and offering a more sustainable and environmentally friendly energy alternative clean [5]. Tallow is rendered animal fat widely used in cooking, soap making, and biofuel production. It contains triglycerides like oleic, palmitic, stearic, and linoleic acids, making it valuable for industrial applications [6]. Animal fat is processed through rendering to make it usable and safe for applications like cooking, healthcare products, and machinery, converting raw fat into a refined, practical form more efficient [7]. Biodiesel from goat tallow is produced by transesterification using sulfuric acid catalyst at 59.33% concentration, reacting for 2.5 hours with an alcohol to oil ratio of 31.88:1 under controlled conditions [8].

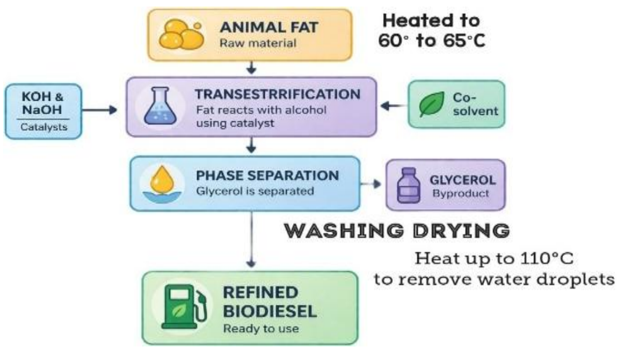

Fig. 1. A stepwise approach to biodiesel production.

Figure 1 shows the process starts with using waste animal fat as the raw material [9]. The fat is heated to 60–65°C to liquefy it for processing. Then transesterification occurs using KOH or NaOH with a co-solvent, converting the melted fat into biodiesel efficiently and completely [9]. Adewale and colleague explored recent advancements in biodiesel production techniques that make use of animal fat waste. As interest increases in finding alternatives to edible oils, animal fat waste (AFW) has emerged as a promising non-edible option for producing biodiesel [10]. The study examined chicken fat behavior at varying temperatures using USY, HZSM-5, Al_2O_3, and SiO_2 catalysts in a fixed bed reactor, finding acid catalysts greatly enhanced conversion efficiency [11]. The study enhanced biodiesel production using ultrasonic assistance with chicken fat feedstock, achieving 94.8% yield by optimizing 1% catalyst, 7:1 alcohol-oil ratio, and reducing reaction time to only 9 minutes [12]. Meza-Gordillo developed a lubricant using chicken fat and biodiesel, adding additives to meet ISO standards. Chicken fat was extracted by autoclaving and direct heating, with direct heating yielding a higher 52.06% output [13]. Biodiesel is a renewable fuel that serves as an eco-friendly substitute for traditional diesel made from petroleum [14]. It is produced from natural sources such as vegetable oils and animal fats, making it a more sustainable and cleaner option for energy use [15]. Recently, attention has increased on using animal waste fats rich in triglycerides for biodiesel. These materials, collected from slaughterhouses, restaurants, veterinary sources, and food industries, provide an abundant, sustainable resource [16]. Unlike edible oils, they are not fit for human consumption, typically deemed unsuitable due to their origin or quality. Instead, they are commonly used as inexpensive animal feed or discarded as waste [17]. Biodiesel derived from vegetable oils, plant-based sources, and animal fats can be seamlessly integrated into conventional diesel engines with minimal modifications [18]. This biodiesel mainly consists of fatty acid methyl esters obtained through the process of trans-esterification of the triglycerides present in the feedstock [19]. Scientists are exploring animal fats as biodiesel sources because they are widely available. Materials like chicken waste, mutton fat, beef tallow, and lard provide a sustainable and promising fuel alternative [20]. Biodiesel was produced using beef tallow and soybean oil. Its quality was tested according to national diesel standards. Sulfonated polystyrene acted as a catalyst to enhance the chemical conversion process [21]. The study explored beef tallow as a biodiesel feedstock, comparing it with vegetable oil biodiesel, focusing on raw material availability, conversion efficiency, and the overall economic feasibility of production [21, 22]. Various investigations have explored the feasibility of utilizing fish oil for biodiesel synthesis, often juxtaposing its properties with those of biodiesel derived from cooking oils [23]. Additionally, biodiesel production has been explored using beef tallow, chicken skin, and pork lard, with researchers experimenting with different purification techniques [24]. Thus, finding alternative biodiesel feedstocks is essential. Animal-based materials are promising due to low cost and wide availability. Scientists study different animal sources, though supply varies across regions globally significantly [25]. Animal fats are converted into bio-oil and bio-char through oxygen-free pyrolysis. Fast pyrolysis enhances conversion efficiency. Using ZSM-5 catalyst at 443°C produces diesel-like fuel, though cost feasibility remains uncertain. Kraiemet al. found that when waste fish undergo pyrolysis at 5000 C it generates bio-oil with a calorific value of 9391 kca/kg [26]. Ben Hassen-Trabelsi and colleagues produced pyrolyzate from poultry, lamb, and swine with yields ranging from 45.8% to 61.6%. Their team concluded that the bio-oil obtained needs additional improvements in its fuel properties before it can be effectively utilized in diesel engines [27]. Diglycerides and free fatty acids act as natural surfactants, helping hybrid biofuels mimic diesel properties. Aghbashlo developed a water–diesel–biodiesel nano-emulsion that improved efficiency and significantly reduced harmful emissions compared to diesel [28]. Waste animal fats are too thick for direct engine use. Mixing diesel with methyl esters reduces viscosity. Studies show tallow methyl ester–diesel blends perform effectively in four-stroke engines [29]. Reductions in carbon oxide and hydrocarbon exhaust emissions were observed, with the exception of a minor increase in nitrogen oxides [29]. Shahir and colleagues achieved a comparable outcome when studying a beef tallow-diesel blend for CRDI engines. Their findings suggested that widespread adoption of waste fat methyl esters could offer a solution to environmental pollution [30]. Freire and his team tested a blend of chicken methyl ester, bioethanol, and diesel, observing reduced fuel consumption at varying loads, while emissions increased steadily with higher engine speeds overall [31]. The blended fuel performed well in diesel engines. Mixing chicken fat biodiesel and fish methyl ester with diesel lowered viscosity, improved atomization. [32]. Transesterification, also known as alcoholysis, converts beef tallow into biodiesel by reacting triglycerides with alcohol and a catalyst, producing esters and glycerol; however, high fatty acid content can cause soap formation [33]. Animal fats can be converted into biodiesel using alkaline, acidic, or enzymatic catalysts. A thermochemical, noncatalytic method using carbon dioxide and alumina achieved 93.5% conversion efficiently at room temperature [34]. Microemulsification is a simple, low-cost method for producing renewable biofuels that is environmentally friendly, requires no heating or complex equipment, avoids chemical reactions, eliminates by-products, and reduces overall production costs [35, 36]. Microemulsions are clear, stable liquids containing very tiny droplets uniformly dispersed. Surfactants keep them mixed by reducing separation. Such fuels form when polar liquids blend with oils, creating efficient biofuels [37]. Earlier studies used water in microemulsion fuels, but ethanol is now preferred because it has higher energy content, improves fuel output, and forms stable water-in-oil like systems suitable for engines [38]. Choosing the right surfactant for microemulsion hybrid biofuel is challenging. Surfactants and co-surfactants affect stability, structure, and key properties like viscosity, density, and energy content, helping match biodiesel characteristics [39]. Nonionic surfactants suit microemulsion biofuels because they mix well with alcohols, tolerate electrolytes and metals, and maintain fuel stability during production and storage, minimizing unwanted chemical reactions [40]. Microemulsions have distinct physical, chemical, and dynamic properties. Understanding their formation and behavior requires careful study of these characteristics to explain how they work and how they can be effectively used [41]. Microemulsification is a method that reduces viscosity by blending normally immiscible liquids, where biodiesel or its mixtures with petrodiesel are combined with alcohols to improve flow and fuel performance overall [38]. A surfactant along with a co-surfactant is added to lower the interfacial tension between the liquids, helping to create a stable and uniform emulsion [35]. Microemulsions are transparent, stable mixtures where oil and water combine as oil-in-water or water-in-oil systems, maintained by surfactants and co-surfactants that ensure long-term thermodynamic stability [42]. Winsor categorized microemulsions into four types: Type I oil-in-water, Type II water-in-oil reverse micelles, Type III bicontinuous middle phase, and Type IV a single homogeneous isotropic phase forming stable system [35]. Despite its lower calorific value, MHBF absorbs more heat during vaporization [38]. Microemulsions alter fuel combustion by improving volatility and mixing. They promote micro-explosions, where tiny water droplets rapidly vaporize in heat, breaking fuel into finer particles for better and more efficient burning [36].

2. PHYSICOCHEMICAL PROPERTIES

Density is a key fuel property affecting engine performance, controlling combustion behavior, relating to cetane number, and influencing the heat energy released during burning process [43]. EN14214 specifies biodiesel density between 860 and 900 kg/m^3. Viscosity mainly depends on reaction conditions and the extent to which transesterification proceeds to completion during fuel production and quality control [44]. Based on the obtained results with ASTM D1217-15 standard test method, the value of density obtained for MHBF, B10 and B20 were 872, 840 and 854 kg/m^3 respectively. Viscosity plays a key role in how well fuel is atomized and injected into the engine [45]. If the fuel has high viscosity, it doesn't spray properly, leading to incomplete combustion and more smoke and harmful emissions [46]. If fuel viscosity is too low, lubrication decreases, causing wear and leakage; if too high, injection requires more energy, leading to poor atomization, lower power, and increased exhaust particulate emissions [47]. According to the results obtained on redwood viscometer, the value of kinematic viscosity obtained for MHBF, B10 and B20 were 3.45, 2.9 and 3.1 cst respectively. Alptekin and Canakci show in their study that flash point is the lowest temperature at which fuel produces enough vapour to ignite with a spark. Biodiesel's higher flash point improves safety during storage, handling, and transportation [45]. Biodiesel with a higher flash point as it lowers the chances of accidental fire is safer to handle, store, and transport. Flash point of waste animal fat biodiesel is often much higher than the recommended standard as found in studies. However, if the flash point is too high as seen in chicken fat and tallow biodiesel it can lead to ignition issues in the engine, which is not desirable [48]. According to the results obtained on ASTM D93 standard the value of flash point obtained for MHBF, B10 and B20 were 62^0, 69^0 and 75^0 respectively. The lowest temperature at which fuel can flow is called pour point [49]. Temperature affects this property and determines biodiesel performance in varying climates. Increasing biodiesel proportion raises the pour point, causing greater cold-weather problems compared to conventional diesel fuel for vehicles overall [50]. Pour point is the lowest temperature at which a liquid remains flowable. Biodiesel with high saturated fatty acids has higher CFPP, so beef tallow biodiesel often exceeds recommended cold flow limits [51]. Based on the ASTM D5853-05 standard, the pour point values obtained for MHBF, B10 and B20 were recorded as -14^0, -15^0 and -17^0 respectively. Khalifeh and Esmaeili show in their study that the cloud point, however, depends on temperature and varies with conditions. As per the ASTM D6751 standard, there is no fixed limit for cloud point; instead, it should be evaluated separately for different climatic conditions [42]. Cold Filter Plugging Point (CFPP) indicates biodiesel performance in cold weather. Cloud and pour points assess low-temperature usability. Higher saturated esters worsen flow. Cloud point marks wax crystal formation, causing a cloudy appearance [44]. Based on the obtained results with ASTM D2500 standard test method, the value of cloud point obtained for MHBF, B10 and B20 were -5^0, -4^0 and -2^0 respectively. Ravikumar and colleague show that the fire point of different biodiesel blends was measured and found to be higher compared to conventional diesel. Pure biodiesel showed the maximum fire point temperature. The results indicated that increasing the proportion of biodiesel in a blend raises the fire point, making the fuel less flammable as the biodiesel content increases [15]. According to the results obtained using the ASTM D93 standard test method, the cloud point value obtained for MHBF, B10 and B20 were -5^0, -4^0, and -2^0 respectively. Oner and Altun show that, tallow methyl ester is denser and more viscous than diesel, with better cetane quality. However, it has lower flash point and energy content due to residual methanol, removable by distillation [52, 53]. The calorific value of MHBF, B10 and B20 were measured using a bomb calorimeter following the ASTM D240 standard. The obtained values were 41.5, 40 and 39.5 MJ/kg, which is very similar to that of diesel. This means only a small drop in energy output per kg, ensuring nearly similar performance. Ravikumar and colleague show in their study that, biodiesel produced from chicken skin has a higher energy value than that from pig tallow. However, blending both reduces the calorific value because increased oxygen content lowers overall fuel energy efficiency [15, 54]. Carbon residue indicates a fuel's tendency to form carbon deposits inside the engine during combustion. In biodiesel, it helps estimate how much carbon buildup may occur with prolonged usage [15]. In the case of MHBF, B10 and B20, its carbon residue were measured using the ASTM D189 standard test method. The result showed a low value of 0.052, 0.05 and 0.06 % respectively. Table 1 shows the physicochemical properties of animal tallow based microemulsion hybrid biofuel, (MHBF), B10 and B20.

Table 1. Physicochemical properties of animal tallow based MHBF, B10 and B20.

Properties	**Standard test methods**	**MHBF**	**B10**	**B20**
Density (kg/m^3)	ASTM D1217-15	872	840	854
Calorific Value (MJ/kg)	Bomb Calorimeter ASTM D 240	41.5	40	39.5
Kinematic Viscosity (cst)	Redwood viscometer	3.45	2.9	3.1
Flash Point (^{0}C)	ASTM D93	62^0	69^0	75^0
Cloud Point (^{0}C)	ASTM D2500	-5^0	-4^0	-2^0
Pour Point (^{0}C)	ASTM D5853-05	-14^0	-15^0	-17^0
Fire Point (^{0}C)	ASTM D93	65^0	73^0	78^0
Carbon residue (%)	Carbon Residue Apparatus ASTM D189	0.052	0.05	0.06

2.1 Density

The density of animal tallow depends on several factors, including its chemical makeup, the type of animal it comes from, and the surrounding temperature. On average, at room temperature (approximately 20°C), its density usually falls between 0.91 and 0.95 grams per cubic centimeter (g/cm^3). This value can shift slightly depending on how the tallow is processed and its exact fat composition [55]. Equation (1) shows the formula of density [56].

$$\text{Density } (\rho) = \frac{m}{v} \text{ kg/m}^3 \ \frac{\text{Mass of Liquid}}{\text{Mass of equal volume of water}} \quad (1)$$

A pycnometer is used to determine density based on the mass of a known volume of liquid [57]. A clean and dry density bottle was first filled with distilled water up to the 50 cm^3 mark. It was then placed in a water bath until the water temperature stabilized at 20°C. After carefully drying the outside of the bottle, it was weighed and recorded as mass m_1. Next, the bottle was emptied, thoroughly dried, and refilled with the test sample to the same 50 cm^3 mark. It was returned to the water bath until the sample reached a consistent temperature of 40°C. Once stabilized, the outside was wiped dry, and the bottle was weighed again, noted as mass m_2. This process was repeated three times for each test sample of animal tallow-based biofuel to ensure accuracy. Figure 2 show the pycnometer to measure the density of fuels using a standard test method of ASTM D1217-15.

Fig. 2. Pycnometer for density measurement.

Equation (2) shows the relative density of each sample was calculated using a specific formula [58].

$$RD = \frac{m2}{m1}[1 + x(t-20)^0C] \quad (2)$$

Where RD is the Relative density, m_1 is mass of water, m_2 is mass of fat or oil, t is equal to 40 ^{0}C and x is Coefficient of cubical expansion for borosilicate glass (0.00001) K-1.

Figure 3 show the comparison of densities of different fuels i.e. diesel, MHBF, B10 and B20.

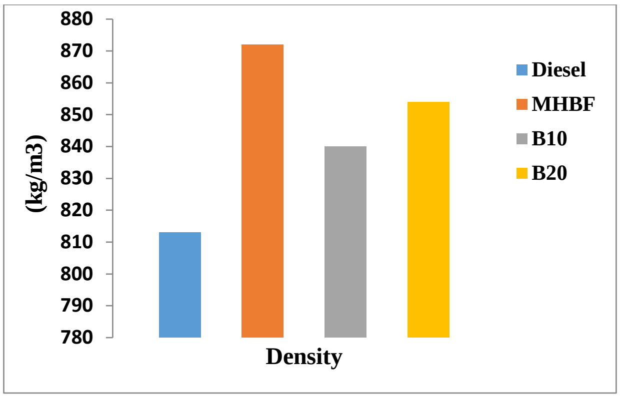

Fig. 3. Variation in fuel density for diesel, MHBF, B10 and B20.

Density is also effective in fuel atomisation [59]. Fuel density is an important property that influences the atomization and combustion behavior of fuels. It is primarily affected by the concentration of alkyl esters and any residual alcohol remaining in biodiesel after production. According to the EN 14214 specification, the acceptable density range for biodiesel lies between 860 and 900 kg/m^3 [44].

The experimental results shows that the value of density for MHBF is 7.26% increasing, For B10 it is 3.32 % increasing and for B20 it is 5.04 % increasing compare to diesel. Higher density of fuel shows larger droplet size, leads to poor atomization, slower evaporation and slightly incomplete combustion. Higher density shows more mass of fuel injected per stroke results in increased fuel consumption and slight increase in power output. It is also results in better lubrication. Higher density biofuels i.e. MHBF, B10 and B20, using in CI engine can improve combustion efficiency due to oxygen content led to reduction in CO and UHC, but slight increment in Nox due to higher temperature.

2.2 Kinematic Viscosity

The kinematic viscosity of animal tallow can vary based on several factors such as temperature, specific composition, and processing method. Typically, animal tallow is a semi-solid fat obtained from rendering animal fat, mainly from cattle, sheep, or pigs. Kinematic viscosity serves as a gauge of the fuel's flow resistance and can additionally aid in determining the fatty acid composition in the primary source material utilized for biofuel production [51, 60]. The methyl esters derived from bovine fat exhibit a notably elevated concentration of high molecular weight saturated fatty acids. Consequently, the pure biodiesel demonstrated a higher viscosity (5.3 mm^2/s) compared to the accepted viscosity threshold for petroleum diesel [61, 62]. However, at a B2 level, the viscosity change is negligible, maintaining it within the typical range for petrodiesel. In essence, the addition of 2% biodiesel to diesel had no discernible impact on its viscosity [51, 63]. Figure 4 show the Redwood viscometer to measure the kinematic viscosity of biofuels.

Fig. 4. Redwood viscometer for the viscosity measurement.

Figure 5 shows the variation of kinematic viscosity of fuels. The experimental results show that the value of kinematic viscosity for diesel is much lower compare to MHBF, B10 and B20. On comparison with MHBF it is 15.94 % decreasing for B10 and for B20 it is 10.14 % decreasing. Lower viscosity shows very finer atomization and better air fuel mixing. MHBF, B10 and B20 showing balanced spray characteristics.

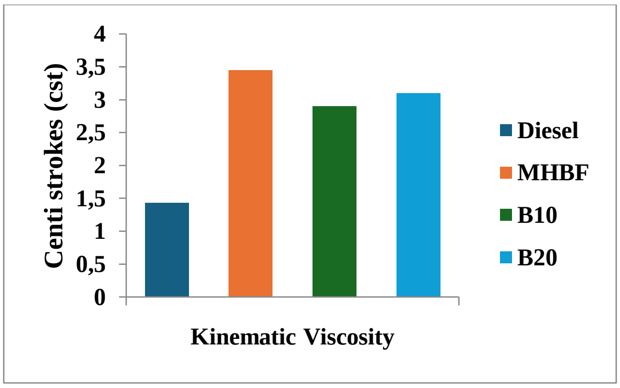

Fig. 5. Variation in fuel kinematic viscosity for diesel, MHBF, B10 and B20.

Higher value of kinematic viscosity fuel while using in a CI engine may increase CO and UHC emissions. B10 and B20 show moderate value lower than MHBF sometime comparable to diesel. High-viscosity fuels show high resistance to flowing, and are more effective in providing lubrication qualities. These fuels may use in marine diesels engine, industrial boilers, and other stationary power stations where fuel warming or preheating systems help overcome their poor flowing properties. Although, greater viscosity unfavorably affects fuel injection and spray atomization will result in larger droplet sizes, slower evaporation rates, incomplete combustion, carbon deposition, and increased smoke emissions. With low fuel viscosities, there will be an easy flow through the fuel lines and injectors, thus resulting in smaller fuel droplets and better air-fuel mixture. Therefore, such fuels are used extensively in modern diesel engines, gas turbines, aviation applications, home furnaces, and small diesel generators. Controlled viscosities ensure effective atomization and controlled combustion efficiency, as well as minimizing particulates. Very low viscosities might lead to a poor lubricating process, hence causing additional wear of the injection equipment and fuel pumps.

2.3 Flash Point

Recognition of fuel volatility is characterized by using parameters such as distillation behaviors, vapour pressure and flash point. The flash point is a minimum temperature at which under specified test conditions, a fuel releases sufficient vapors to form an ignitable mixture with air. However, the flash point does not directly affect engine operation but it is an important safety parameter. Flash point provides valuable information regarding the fuel's flammability. It helps to determine necessary precautions for its safe handling, transportation and storage [64]. Typically, the flash point of conventional diesel ranges in between 540 and 71 °C whereas biodiesel generally exhibits a flash point higher than 93 °C. Due to higher flash point, biodiesel is safer to handle, store, and transport so it has lower risk of accidental ignition and fire hazards [65]. This characteristic serves as a clear indication of the necessary precautions essential for handling, transporting, and storing the fuel. Concerning biodiesel, specifying the flash point aims to restrict the alcohol content within this biofuel, ensuring safer handling, transportation, and storage protocols [40, 51]. Biodiesel made from bovine fat has a much higher flash point than regular diesel fuel, making it safer in terms of fire risk. According to ANP regulations, fuels must have a flash point of at least 38°C. While standard diesel meets this with a flash point of 40.7°C, bovine fat biodiesel far exceeds this requirement, reaching 156.7°C. This higher flash point means the biodiesel is much less likely to catch fire, making it a safer option for storage and handling [36, 51]. Figure 6 shows the Pensky–Marten's apparatus to measure the flash point and fire point using a standard test method of ASTM D93.

Fig. 6. Pensky–Marten's apparatus for flash point measurement.

Figure 7 shows the variation of flash point of fuels. The experimental results shows that the value of flash point for MHBF is 1 ^{0}C decreasing, For B10 it is 6 ^{0}C increasing and for B20 it is 12 ^{0}C increasing compare to diesel. MHBF has slightly lower flash point. It is very close to diesel, leads to easier combustion, can improve cold start performance. B10 and B20 has higher flash point require more energy to ignite. Flash point does not directly affect power output, but influences fuel volatility, affects atomization and vaporization MHBF show slightly higher fuel evaporation while B10 and B20 shows reduced evaporation losses.

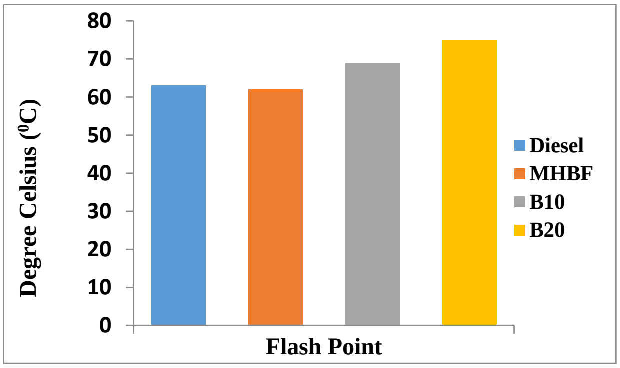

Fig. 7. Variation in fuel Flash Point for diesel, MHBF, B10 and B20.

A higher flash point shows the decreased volatility. Animal tallow-based biodiesel evaporates more slowly and the lower vapour generation improves vapour storage safety. The higher flash point of tallow biodiesel results from longer carbon chains, higher molecular weight methyl esters and greater proportion of saturated fatty acids.

2.4 Fire point

Fire point is the lowest temperature at which a fuel produces sufficient vapors to ignite and continue burning for at least 5 seconds after a test flame is applied [66, 67]. Biodiesel has one of the major limitations that is its poor behavior at low temperatures. In comparison with conventional diesel fuel, this issue is commonly indicated by higher cloud point (CP) and pour point (PP). Because of the formation of tiny wax crystals, the cloud point is the temperature at which biodiesel starts to become cloudy. When saturated fatty compounds begin to solidify the crystal starts to develop, which can negatively affect fuel flow and engine operation in cold weather conditions [64].

In the Pensky–Martens closed cup apparatus, the fuel sample is placed in a sealed cup and heated at a controlled rate with continuous stirring. At regular temperature intervals, a small test flame is introduced through an opening. The temperature at which vapors ignite and sustain combustion for at least 5 seconds is recorded as the fire point. Figure 8 shows the variation of fire point of fuels.

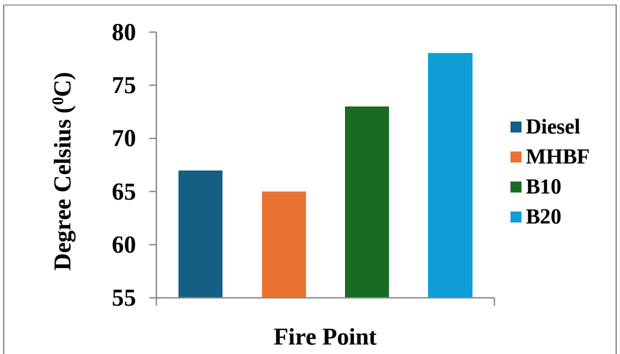

Fig. 8. Variation in fuel fire point for diesel, MHBF, B10 and B20.

The experimental results shows that the value of fire point for MHBF is 2 ^{0}C decreasing, For B10 it is 6 ^{0}C increasing and for B20 it is 11 ^{0}C increasing compare to diesel. MHBF shows decrease in fire point leads to higher volatility. B10 and B20 enhance safety, reduce evaporative losses, and improve environmental performance.

The fire point of any fuel is directly related to its boiling temperature and its volatility. Those fuels which have higher fire points, they are generally less volatile and they have saturated compounds in large proportion [68]. Such fuels often exhibit a higher cetane number, which promotes efficient combustion after the engine reaches operating temperature. However, due to their lower volatility, it can lead to poor fuel vaporization and reduced cold-flow performance in low-temperature conditions [68]. Tallow biodiesel has higher fire point, low toxicity and lower emissions are used as transport fuel, stationary engine fuel, boiler fuel and heating oil substitute [42]. Higher fire point has its primary significance is safety, handling and volatility. Diesel fuel has lower fire point than tallow-based biodiesel, therefore it is more volatile and more hazardous to store, However, it has better cold-weather flow. Low fire point of a fuel shows easier vapor formation at moderate temperatures, which can improve ignition of very cold engines, however, it increases storage and handling risk [69].

2.5 Pour point

Pour point is the lowest temperature at which an oil or fuel remains fluid enough to pour under specified conditions. It indicates low-temperature flow behavior and is critical for storage and engine performance [67]. Pour point represents the lowest temperature at which the fuel remains capable of flowing. Typically, the cloud point occurs at a higher temperature than the pour point. The low-temperature behavior of biodiesel is strongly influenced by its fatty acid composition. Saturated fatty acids possess higher melting temperatures than unsaturated fatty acids, causing them to crystallize earlier when the temperature decreases. Consequently, biodiesel produced from feedstocks containing a high proportion of saturated fatty compounds, such as animal fats, generally exhibits higher cloud and pour points, making it less suitable for operation in cold environments [42]. Using a pour point apparatus (ASTM D2500 method), the sample is placed in a test jar with a thermometer and cooled in a controlled bath at specified intervals. At every 3°C drop, the jar is removed and tilted. When the oil no longer flows, the temperature just above this is recorded as the pour point. Figure 9 shows the variation of pour point of fuels.

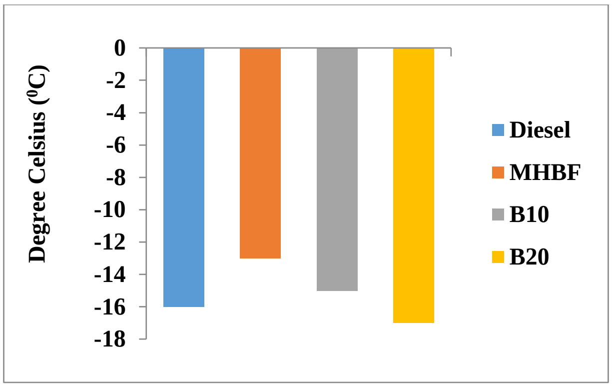

Fig. 9. Variation in fuel pour point for diesel, MHBF, B10 and B20.

The experimental results shows that the value of pour point for MHBF is 2 0C increasing, For B10 it is 1 0C increasing and for B20 it is 1 0C decreasing compare to diesel. MHBF and B10 show slightly higher pour point. B20 provides a good balance between engine performance and cold weather operability while maintaining environmental benefits. Slightly higher pour point fuels like MHBF and B10 may still operate well in moderate climates. Blending reduces extreme cold flow issues compared to pure biodiesel.

2.6 Cloud point

Cloud point is the temperature at which a clear petroleum product or biodiesel first becomes cloudy due to the formation of wax crystals when cooled. It indicates the onset of solidification and affects low-temperature fuel performance [67]. Figure 10 shows the apparatus to measure the cloud point and pour point using a standard test method of ASTM D2500.

Fig. 10. Cloud and pour point measuring apparatus.

Figure 11 shows the variation of cloud point of fuels.

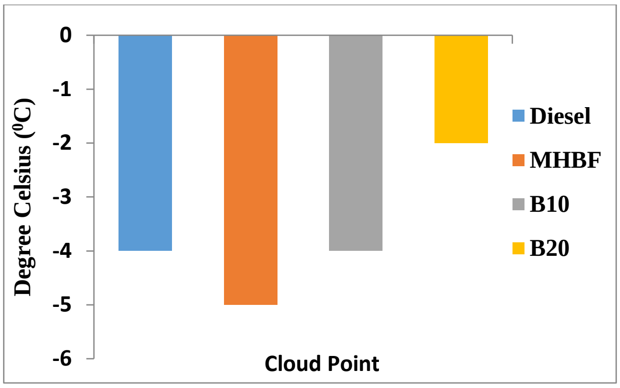

Fig. 11. Variation in fuel cloud Point for diesel, MHBF, B10 and B20.

The experimental results shows that the value of cloud point for MHBF is 1 ⁰C decreasing, For B10 it is same as diesel and for B20 it is 2 ⁰C decreasing compare to diesel. MHBF and B20 show reduced cloud point leads to better cold flow properties. B10 behaves similar to diesel. Lower cloud point delays wax crystal formation. It shows smooth fuel flow in cold conditions and easier ignition at low temperatures. Its lower CO and UHC emissions. Also reduced particulate matter. Slightly higher combustion temperature in biodiesel blends slightly increases Nox emissions. Animal fat contains a high proportion of saturated fatty acids such as palmitic and stearic acids so due to this reason tallow-based biodiesel has higher cloud point than diesel. Tallow based biodiesel cloud point typically ranges from 10°C to 20°C however values can vary and depending on feedstock composition and production conditions [70]. Cloud point shows the temperature at which wax crystals first seem. If atmospheric temperatures fall below cloud point, fuel flow difficulties may start [71]. Wax crystals formed near the cloud point can accumulate on fuel filters and eventually block fuel flow to the engine [72]. In winter conditions information about cloud point helps determine suitable storage temperatures and blending requirements [73]. Consequently, cloud point is a critical parameter for evaluating the suitability of tallow biodiesel in diesel engines operating under cold climatic conditions [70].

2.7 Calorific value

Calorific value represents the total heat energy that produces during when a unit mass of fuel undergoes complete combustion. Tallow based biodiesel has less calorific value than conventional diesel because biodiesel molecule contains oxygen which reduces their energy density [52]. Kosgei and colleague show in their research that the calorific value of beef tallow biodiesel was 36.5 MJ/kg, while conventional diesel typically ranges from 42-45 MJ/kg [74]. Diesel has hydrocarbons and therefore it possesses a greater carbon to oxygen ratio. Animal tallow-based biodiesel contains 10-12% oxygen approximately by weight, which lowers its energy content [52]. Calorific value is most important quality parameter because it determines the value of energy available for engine operation, brake output, fuel economy and engine operating cost. a higher calorific value fuel produces per unit mass, more useful work. Reducing fuel consumption, Conversely, lower calorific values fuel requires higher fuel injection quantities to achieve equivalent power output [74]. Bomb calorimeter is a high precision instrument used to determine the heating value of fuels by measuring the heat released during complete combustion in a sealed high-pressure chamber filled with oxygen [75]. It is widely used for biofuel analysis, coal and solid fuel testing [67]. Also used for determination of food energy [76]. The formula used for determination of calorific value is

$$CV=(M_w - W)(T_2 - T_1)/ m_f$$

Where:
Mw= Mass of water
W=Water equivalent of calorimeter
T_2- T_1= Temperature rise
m_f = Mass of fuel

Figure 12 shows the bomb calorimeter to determine the calorific value of biofuel using a standard method of ASTM D 240

Fig. 12. Bomb Calorimeter for calorific value measurement.

Figure 13 shows the variation of calorific value of fuels. The experimental results show that all alternative fuels show a decrease in calorific value. The calorific value for MHBF is 1.94% decreasing, for B10 it is 5.48 % decreasing and for B20 it is 6.66 % decreasing compare to diesel.

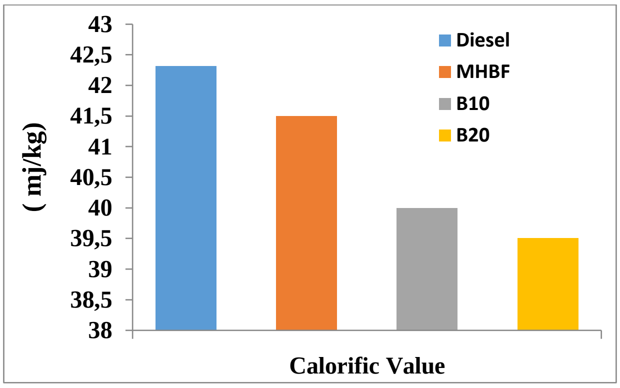

Fig. 13. Variation in fuel calorific value for diesel, MHBF, B10 and B20.

BSFC increase for MHBF, B10 and B20. Reason is that more fuel is required to produce the same power due to lower calorific value. Microemulsion improves atomization and combustion so MHBF show comparable efficiency and reduction in CO, UHC and smoke opacity and slight increase in NOx emission due to higher combustion temperature. Biodiesel blends show improved combustion due to higher oxygen content and better ignition quality.

2.8 Carbon residue

It is used to determine the tendency of petroleum products to form carbon deposits when subjected to high temperature in the absence of air. It is widely applied for fuels, lubricating oils, and heavy residues [27]. The quality of biodiesel and other fuels are evaluated by carbon residue because of their tendency to form carbonaceous deposits during combustion. A high carbon residue shows the presence of impurities such as free fatty acids, mono, di and triglycerides, soaps, polymerized esters, and inorganic contaminants [77]. However, carbon residue helps as an important indicator of fuel purity and overall quality. It helps in assessing the effectiveness of the transesterification process. In addition, it provides valuable information about the suitability of biodiesel for prolonged engine operation. Extreme carbon residue can lead to the formation of deposits on fuel injector nozzles, which unfavorably affects fuel atomization and produces bigger fuel droplets [78]. A known quantity of oil sample is placed in a silica or metal crucible. The crucible is heated strongly using a burner in a controlled manner. The sample first evaporates and then undergoes thermal decomposition. Volatile components burn off, leaving behind a carbonaceous residue. To measure the carbon residue, firstly weight the empty crucible (W_1). Add a known mass of sample and weigh (W_2). Heat the sample until vapors cease and residue forms. Heat the sample until vapors cease and residue forms. Cool the crucible in a desiccator and weigh again (W_3). Now carbon residue is calculated by the formula

$$\text{Carbon Residue (\%)} = W_2\text{-}W_1/W_3\text{-}W_1 \times 100$$

Figure 14 shows the Conradson Carbon Residue Apparatus to measure the carbon residue using a standard method of ASTM D189.

Fig. 14. Conradson Carbon Residue Apparatus.

The experimental results show that diesel has lowest carbon residue value which represents the least tendency to form carbon deposits. Diesel shows the highly refined nature which contains less oxygenated compounds and impurities that can contribute to residue formation. MHBF shows a carbon residue value of 0.052%. The increment in MHBF can be attributed to the presence of long chain fatty acid esters and other heavier molecular constituents. During combustion these compounds may undergo thermal cracking and polymerization. This will result in greater amount of carbonaceous residue. B10 shows a carbon residue value of 0.050% higher than diesel but slightly lower than MHBF. The dilution effect of diesel decreases the heavy ester molecules concentration thereby limiting deposit formation. B20 shows the highest carbon residue value i.e. 0.060%. The increment introduces a larger proportion of high molecular weight fatty acid esters which can contribute to greater carbon residue formation.

When tallow-based biodiesel properly produced and purified it exhibits low carbon residue [79]. It shows cleaner combustion compared with diesel due to its high cetane number, oxygen content, and low sulfur concentration [80]. However, carbon residue can be increased by oxidation, poor storage conditions and incomplete transesterification [78]. This can lead to injector fouling, deposit formation, reduced engine efficiency, and increased particulate emissions. Therefore, carbon residue serves as a critical indicator of fuel quality and long-term engine durability [81]

3. LIMITATIONS, CHALLENGES AND POTENTIAL RISKS

Banković and colleague show in their study that tallow-based biodiesel has high cloud and pour points, which can lead to gelling or solidification at lower temperatures. This limits its usability in colder climates without additives or blending with petro-diesel. The availability of raw tallow is limited compared to plant oils. Processing tallow into biodiesel requires pre-treatment which increases costs [44]. Older engines may be less tolerant of high fatty acid methyl ester content. Long-term usage without modification may lead to wear and deposit issues. Tallow biodiesel generally has lower energy higher density than petroleum diesel. This results in higher fuel consumption for the same power output [10]. Binhweel and co-authors reported that differences in the chemical makeup of animal fats can influence biodiesel quality and performance. Due to higher viscosity of tallow-based biodiesel, it reduces atomization, reduces combustion efficiency and impact injector operation [82]. Ambaye and co-author states in their research that due to lower oxidative stability results in gum formation, filter clogging, and storage issues. Under certain conditions it can lead to increased NOx emissions. Combustion characteristics may differ, requiring engine tuning. Due to its solvent properties, it may degrade rubber seals and hoses in older engines [83]. Baribeau and colleague show in their study that, in colder weather, solidification can lead to starting issues. Fats or impurities that are not converted, clog fuel filters or form deposits on injectors and combustion chambers. Biodiesel including animal tallow-based is more hygroscopic than diesel, promoting water absorption and microbial growth, which can damage fuel systems. Without proper monitoring or maintenance, the long-term use, increase maintenance needs or shorten engine lifespan. Depending on animal fat as a resource may create ethical and environmental concerns, particularly if it reduces food availability or encourages large-scale livestock farming practices [84].

4. CONCLUSION

Physicochemical properties influence fuel quality, stability, and engine performance, are essential in biofuel formulation. The injection and combustion efficiency are affected by density and viscosity. Flash point and fire point ensure safe storage. The cold weather usability is determined by cloud point and pour point. The value of energy output is indicated by calorific value and the deposit formation tendency is shown by carbon residue. The optimization of these properties reduces emissions, ensures compatibility with existing engines, enhances safety and improves efficiency. Experimentally this study examines the physicochemical properties of MHBF, B10 and B20 and compared with conventional diesel fuels. The results are given as

- All biofuels show physicochemical properties in the range of EN14214/ASTMD6751 standard.
- MHBF, B10 and B20 has slightly higher density and kinematic viscosity than diesel. This increment in properties can slightly affect atomization but it improves lubrication characteristics.
- MHBF, B10, and B20 shows higher flash point and fire point than conventional diesel. The increment indicating safer storage and handling. Mixed behavior is shown by cold flow properties.
- In some cases, MHBF and B20 demonstrate improved cloud point and pour point while slight deterioration in others suggests the need for cold-flow optimization depending on climate.
- The heating value or calorific value of MHBF, B10 and B20 is marginally lower than conventional diesel, results into a small increase in fuel consumption.
- MHBF, B10 and B20 shows slightly higher carbon residue, indicating a tendency for deposit formation. The presence of inherent oxygen promotes cleaner combustion reduction in CO, HC, and PM with a slight increase in NOx.

Without major modifications in CI engines MHBF, B10 and B20 can be considered as viable alternative fuels. MHBF and biodiesel blends offers the best balance between fuel properties and engine compatibility, with acceptable performance and environmental benefits.

Future Perspective

The study of animal tallow as a feedstock for liquid biofuels has gained momentum due to its cost-effectiveness and sustainability. However, future research must focus on enhancing the physicochemical properties of animal tallow based microemulsion hybrid biofuel for improvement in performance and emissions in modern engines. Oxidation stability is improved by combining tallow biofuel with algae-based biodiesel or bioethanol and reduction in NOx emissions. To support better fuel production and performance there is a need to develop affordable, and eco-friendly catalysts. To enhance stability, spray quality and cold flow property, microemulsion fuel needed effective additives, surfactants and co-surfactants. Air fuel mixing through CFD, spray behavior and advanced diagnose study helps in greatly understanding the behavior of combustion. The use of bifunctional catalysts enables, transesterification and esterification making it easier to process animal tallow with high free fatty acid (FFA) content. Working under mild conditions the enzyme-based catalysts minimize soap formation and may reduce energy use. The optimization of this catalyst can improve yield and reduce costs. Issues like high viscosity, ignition delay, and emissions are overcome by studying physicochemical properties and adjusting engine parameters such as injection timing and pressure. These hybrid fuels can narrow the gap between diesel and biofuels while remaining environmentally friendly.

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REFERENCES

[1] S. Sudalai *et al.*, "A review on oilcake biomass waste into biofuels: Current conversion techniques, sustainable applications, and challenges: Waste to energy approach (WtE)," *Energy Conversion and Management*, vol. 314, p. 118724, Jun. 2024, doi: 10.1016/j.enconman.2024.118724.

[2] L. S. G. Teixeira *et al.*, "Comparison between conventional and ultrasonic preparation of beef tallow biodiesel," *Fuel Processing Technology*, vol. 90, no. 9, pp. 1164–1166, May 2009, doi: 10.1016/j.fuproc.2009.05.008.

[3] L. S. G. Teixeira *et al.*, "Characterization of beef tallow biodiesel and their mixtures with soybean biodiesel and mineral diesel fuel," *Biomass and Bioenergy*, vol. 34, no. 4, pp. 438–441, Jan. 2010, doi: 10.1016/j.biombioe.2009.12.007.

[4] P. R. Muniyappa, S. C. Brammer, and H. Noureddini, "Improved conversion of plant oils and animal fats into biodiesel and co-product," *Bioresource Technology*, vol. 56, no. 1, pp. 19–24, Apr. 1996, doi: 10.1016/0960-8524(95)00178-6.

[5] Y. Devarajan, D. Munuswamy, D. Arunkumar, T. Raja, and R. Mishra, "Application of potential green algal for power generation as a likely and fractional alternative," *Biomass Conversion and Biorefinery*, vol. 15, no. 2, pp. 2081–2096, Sep. 2023, doi: 10.1007/s13399-023-04870-x.

[6] M. F. Russell, M. Sandhu, M. Vail, C. Haran, U. Batool, and J. Leo, "Tallow, rendered animal fat, and its biocompatibility with skin: a scoping review," *Cureus*, vol. 16, no. 5, p. e60981, May 2024, doi: 10.7759/cureus.60981.

[7] S. Lowengard, "On the Disappearance of the Animal Body," *Historical Studies in the Natural Sciences*, vol. 53, no. 3, pp. 242–255, Jun. 2023, doi: 10.1525/hsns.2023.53.3.242.

[8] R. Chakraborty and H. Sahu, "Intensification of biodiesel production from waste goat tallow using infrared radiation: Process evaluation through response surface methodology and artificial neural network," *Applied Energy*, vol. 114, pp. 827–836, May 2013, doi: 10.1016/j.apenergy.2013.04.025.

[9] G. A. C. Jayaseelan, A. Anderson, M. K. Poduva, P. V. Sudheesh, and Roshith, "Synthesis and performances characteristics of biodiesel from animal fat," *Materials Today Proceedings*, vol. 45, pp. 6053–6056, Nov. 2020, doi: 10.1016/j.matpr.2020.10.002.

[10] P. Adewale, M.-J. Dumont, and M. Ngadi, "Recent trends of biodiesel production from animal fat wastes and associated production techniques," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 574–588, Feb. 2015, doi: 10.1016/j.rser.2015.02.039.

[11] H. Tian, C. Li, C. Yang, and H. Shan, "Alternative processing technology for converting vegetable oils and animal fats to clean fuels and light olefins," *Chinese Journal of Chemical Engineering*, vol. 16, no. 3, pp. 394–400, Jun. 2008, doi: 10.1016/s1004-9541(08)60095-6.

[12] N. Shalaby, S. A. Hanafi, Elmelawy, and H. A. El-Syed, "Hydrocracking of waste cooking oil as renewable fuel on NIW/SIO2-AL2O3 catalyst," *Journal of Advanced Catalysis Science and Technology*, vol. 2, no. 1, pp. 27–37, Mar. 2015, doi: 10.15379/2408-9834.2015.02.01.3.

[13] S. A. Hanafi, M. S. Elmelawy, N. H. Shalaby, H. A. El-Syed, G. Eshaq, and M. S. Mostafa, "Hydrocracking of waste chicken fat as a cost effective feedstock for renewable fuel production: A kinetic study," *Egyptian Journal of Petroleum*, vol. 25, no. 4, pp. 531–537, Dec. 2015, doi: 10.1016/j.ejpe.2015.11.006.

[14] M. C. Hernández-Cruz, R. Meza-Gordillo, B. Torrestiana-Sánchez, A. Rosales-Quintero, L. M. C. Ventura-Canseco, and J. H. Castañón-Gonzáles, "Chicken fat and biodiesel viscosity modification with additives for the formulation of biolubricants," *Fuel*, vol. 198, pp. 42–48, Dec. 2016, doi: 10.1016/j.fuel.2016.12.039.

[15] R. Ravikumar, K. Kiran, M. H. Kumar, G. S. Hebbar, and A. S. D. Shetty, "A Comparative Analysis of Biodiesel Properties Derived from Meat Stall Wastes through Optimized Parameters," *IOP Conference Series Materials Science and Engineering*, vol. 1065, no. 1, p. 012005, Feb. 2021, doi: 10.1088/1757-899x/1065/1/012005.

[16] R. Ravikumar, M. H. Kumar, K. Kiran, G. S. Hebbar, "Extraction and Characterization of Biofuel from Industrial Waste organic Pupae-Silkworm," *International Journal of Recent Technology and Engineering (IJRTE)*, vol. 8, no. 3, pp. 1603–1607, Sep. 2019, doi: 10.35940/ijrte.c4422.098319.

[17] M. U. Kaisan, G. Y. Pam, and D. M. Kulla, "Physico-chemical properties of biodiesel from wild grape seeds oil and petrodiesel blends," *American Journal of Engineering Research*, vol. 2, no. 10, pp. 291–297, 2013.

[18] R. Ravikumar, G. Sujaykumar, S. Divakar, and K. Basavaraj, "Investigation of effect of chicken biodiesel blended diesel on engine performance," *International Journal of Advances in Scientific Research and Engineering*, vol. 3, no. 1, pp. 1–6, 2017.

[19] R. Ravikumar, K. Kiran, and S. H. G. Moorthy, "Experimental analysis of biofuel produced from fat derivatives of bird and animal as an additive fuel in CI engine," *International Journal of Renewable Energy Research*, vol. 10, no. 3, pp. 1226–1233, 2020.

[20] R. A. Soldi, A. R. S. Oliveira, L. P. Ramos, and M. A. F. César-Oliveira, "Soybean oil and beef tallow alcoholysis by acid heterogeneous catalysis," *Applied Catalysis a General*, vol. 361, no. 1–2, pp. 42–48, Apr. 2009, doi: 10.1016/j.apcata.2009.03.030.

[21] R. G. Nelson and M. D. Schrock, "Energetic and economic feasibility associated with the production, processing, and conversion of beef tallow to a substitute diesel fuel," *Biomass and Bioenergy*, vol. 30, no. 6, pp. 584–591, Mar. 2006, doi: 10.1016/j.biombioe.2005.09.005.

[22] F. Ma, L. D. Clements, and M. A. Hanna, "Biodiesel Fuel from Animal Fat. Ancillary Studies on Transesterification of Beef Tallow," *Industrial & Engineering Chemistry Research*, vol. 37, no. 9, pp. 3768–3771, Aug. 1998, doi: 10.1021/ie980162s.

[23] Y. T. Ge, A. M. Fsadni, and H. S. Wang, "Bubble dissolution in horizontal turbulent bubbly flow in domestic central heating system," *Applied Energy*, vol. 108, pp. 477–485, Apr. 2013, doi: 10.1016/j.apenergy.2013.03.055.

[24] R. Yahyaee, B. Ghobadian, and G. Najafi, "Waste fish oil biodiesel as a source of renewable fuel in Iran," *Renewable and Sustainable Energy Reviews*, vol. 17, pp. 312–319, Nov. 2012, doi: 10.1016/j.rser.2012.09.025.

[25] T. M. Mata, N. Cardoso, M. Ornelas, S. Neves, and N. S. Caetano, "Evaluation of Two Purification Methods of Biodiesel from Beef Tallow, Pork Lard, and Chicken Fat," *Energy & Fuels*, vol. 25, no. 10, pp. 4756–4762, Oct. 2011, doi: 10.1021/ef2010207.

[26] T. Kraiem, A. B. Hassen-Trabelsi, S. Naoui, H. Belayouni, and M. Jeguirim, "Characterization of the liquid products obtained from Tunisian waste fish fats using the pyrolysis process," *Fuel Processing Technology*, vol. 138, pp. 404–412, Jun. 2015, doi: 10.1016/j.fuproc.2015.05.007.

[27] A. B. Hassen-Trabelsi, T. Kraiem, S. Naoui, and H. Belayouni, "Pyrolysis of waste animal fats in a fixed-bed reactor: Production and characterization of bio-oil and bio-char," *Waste Management*, vol. 34, no. 1, pp. 210–218, Oct. 2013, doi: 10.1016/j.wasman.2013.09.019.

[28] P. Bora, L. J. Konwar, J. Boro, M. M. Phukan, D. Deka, and B. K. Konwar, "Hybrid biofuels from non-edible oils: A comparative standpoint with corresponding biodiesel," *Applied Energy*, vol. 135, pp. 450–460, Sep. 2014, doi: 10.1016/j.apenergy.2014.08.114.

[29] P. Nautiyal, K. A. Subramanian, and M. G. Dastidar, "Experimental investigation on performance and emission characteristics of a compression ignition engine fueled with biodiesel from waste tallow," *Clean Technologies and Environmental Policy*, vol. 19, no. 6, pp. 1667–1677, Apr. 2017, doi: 10.1007/s10098-017-1355-8.

[30] V. K. Shahir, C. P. Jawahar, P. R. Suresh, and V. Vinod, "Experimental investigation on performance and emission characteristics of a common Rail Direct InjectionEngine using animal fat biodiesel blends," *Energy Procedia*, vol. 117, pp. 283–290, Jun. 2017, doi: 10.1016/j.egypro.2017.05.133.

[31] L. M. S. Freire *et al.*, "Evaluation of the oxidative stability and flow properties of quaternary mixtures of vegetable oils for biodiesel production," *Fuel*, vol. 95, pp. 126–130, Nov. 2011, doi: 10.1016/j.fuel.2011.11.014.

[32] R. Behçet, H. Oktay, A. Çakmak, and H. Aydin, "Comparison of exhaust emissions of biodiesel–diesel fuel blends produced from animal fats," *Renewable and Sustainable Energy Reviews*, vol. 46, pp. 157–165, Mar. 2015, doi: 10.1016/j.rser.2015.02.015.

[33] J. M. Encinar, N. Sánchez, G. Martínez, and L. García, "Study of biodiesel production from animal fats with high free fatty acid content," *Bioresource Technology*, vol. 102, no. 23, pp. 10907–10914, Sep. 2011, doi: 10.1016/j.biortech.2011.09.068.

[34] E. E. Kwon, E.-C. Jeon, H. Yi, and S. Kim, "Transforming duck tallow into biodiesel via noncatalytic transesterification," *Applied Energy*, vol. 116, pp. 20–25, Dec. 2013, doi: 10.1016/j.apenergy.2013.11.043.

[35] H. Kumar, A. K. Sarma, and P. Kumar, "A comprehensive review on preparation, characterization, and combustion characteristics of microemulsion based hybrid biofuels," *Renewable and Sustainable Energy Reviews*, vol. 117, p. 109498, Oct. 2019, doi: 10.1016/j.rser.2019.109498.

[36] H. Kumar, H. Kumar, H. Kumar, and H. Kumar, "To Enhance the Performance of CI Engine with Using of Additives Based Hybrid Bio Fuel—A Review," *Macromolecular Symposia*, vol. 413, no. 5, Oct. 2024, doi: 10.1002/masy.202400067.

[37] H. Kumar, A. K. Sarma, and P. Kumar, "A novel approach to study the effect of cetane improver on performance, combustion and emission characteristics of a CI engine fuelled with E20 (diesel – bioethanol) blend," *Sustainable Chemistry and Pharmacy*, vol. 14, p. 100185, Oct. 2019, doi: 10.1016/j.scp.2019.100185.

[38] H. Kumar, H. Kumar, H. Kumar, and H. Kumar, "Microemulsification-based hybrid oxygenated biofuel for CI engine locomotives: with special reference to 'preparation' techniques and 'performance' analysis," *Environmental Science and Pollution Research*, vol. 33, no. 6, pp. 2133–2159, Jan. 2025, doi: 10.1007/s11356-025-35960-0.

[39] H. Kumar and H. Kumar, "Experimental investigation of Alcohol-Based hybrid biofuel from used cooking oil fueled in a CI engine," in *Advances in chemical and materials engineering book series*, 2024, pp. 253–272. doi: 10.4018/979-8-3693-5320-2.ch012.

[40] H. Kumar, H. Kumar, M. Aslam, A. K. Sarma, M. H. Salmani, and K. Singh, "Performance and emission characteristics of CI engine using bio-crude derived biofuels," in *Biofuel and biorefinery technologies*, 2025, pp. 361–377. doi: 10.1007/978-3-031-85036-3_15.

[41] H. Kumar, A. K. Sarma, and P. Kumar, "Experimental investigation of 2-EHN effects upon CI engine attributes fuelled with used cooking oil-based hybrid microemulsion biofuel," *International Journal of Environmental Science and Technology*, vol. 19, no. 11, pp. 11051–11068, Oct. 2021, doi: 10.1007/s13762-021-03751-y.

[42] H. Kumar and H. Kumar, "Experimental investigation of animal tallow-based microemulsion hybrid biofuel on CI engine parameters," *Journal of Renewable and Sustainable Energy*, vol. 18, no. 2, Mar. 2026, doi: 10.1063/5.0303247.

[43] R. Khalifeh and H. Esmaeili, "Biodiesel production from goat fat using calcium oxide nanocatalyst and its combination with diesel fuel to improve fuel properties," *International Journal of Sustainable Engineering*, vol. 14, no. 5, pp. 1122–1131, Jun. 2020, doi: 10.1080/19397038.2020.1780336.

[44] I. B. Banković-Ilić, I. J. Stojković, O. S. Stamenković, V. B. Veljkovic, and Y.-T. Hung, "Waste animal fats as feedstocks for biodiesel production," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 238–254, Feb. 2014, doi: 10.1016/j.rser.2014.01.038.

[45] E. Alptekin and M. Canakci, "Optimization of transesterification for methyl ester production from chicken fat," *Fuel*, vol. 90, no. 8, pp. 2630–2638, Apr. 2011, doi: 10.1016/j.fuel.2011.03.042.

[46] H. Esmaeili, G. Yeganeh, and F. Esmaeilzadeh, "Optimization of biodiesel production from Moringa oleifera seeds oil in the presence of nano-MgO using Taguchi method," *International Nano Letters.*, vol. 9, no. 3, pp. 257–263, Jul. 2019, doi: 10.1007/s40089-019-0278-2.

[47] L. F. Ramírez-Verduzco, J. E. Rodríguez-Rodríguez, and A. Del Rayo Jaramillo-Jacob, "Predicting cetane number, kinematic viscosity, density and higher heating value of biodiesel from its fatty acid methyl ester composition," *Fuel*, vol. 91, no. 1, pp. 102–111, Jul. 2011, doi: 10.1016/j.fuel.2011.06.070.

[48] T. M. Mata, N. Cardoso, M. Ornelas, S. Neves, and N. S. Caetano, "Sustainable production of biodiesel from tallow, lard and poultry fat and its quality evaluation," *Chemical Engineering Transactions*, vol. 19, pp. 13–18, 2010, doi: 10.3303/CET1019003.

[49] A. Saydut, M. Duz, C. Kaya, A. Kafadar, and C. Hamamci, "Transesterified sesame (Sesamum indicum L.) seed oil as a biodiesel fuel," *Bioresource Technology*, vol. 99, no. 14, pp. 6656–6660, Feb. 2008, doi: 10.1016/j.biortech.2007.11.063.

[50] A. P. S. Chouhan and A. K. Sarma, "Modern heterogeneous catalysts for biodiesel production: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 9, pp. 4378–4399, Sep. 2011, doi: 10.1016/j.rser.2011.07.112.

[51] M. E. Da Cunha *et al.*, "Beef tallow biodiesel produced in a pilot scale," *Fuel Processing Technology*, vol. 90, no. 4, pp. 570–575, Feb. 2009, doi: 10.1016/j.fuproc.2009.01.001.

[52] C. Öner and Ş. Altun, "Biodiesel production from inedible animal tallow and an experimental investigation of its use as alternative fuel in a direct injection diesel engine," *Applied Energy*, vol. 86, no. 10, pp. 2114–2120, Feb. 2009, doi: 10.1016/j.apenergy.2009.01.005.

[53] Z. Yaakob, B. N. Narayanan, S. Padikkaparambil, S. U. K, and M. A. P, "A review on the oxidation stability of biodiesel," *Renewable and Sustainable Energy Reviews*, vol. 35, pp. 136–153, Apr. 2014, doi: 10.1016/j.rser.2014.03.055.

[54] H. Çamur and E. Alassi, "Physicochemical Properties Enhancement of Biodiesel Synthesis from Various Feedstocks of Waste/Residential Vegetable Oils and Palm Oil," *Energies*, vol. 14, no. 16, p. 4928, Aug. 2021, doi: 10.3390/en14164928.

[55] B. E. Olubunmi, A. F. Alade, S. O. Ebhodaghe, and O. T. Oladapo, "Optimization and kinetic study of biodiesel production from beef tallow using calcium oxide as a heterogeneous and recyclable catalyst," *Energy Conversion and Management X*, vol. 14, p. 100221, Apr. 2022, doi: 10.1016/j.ecmx.2022.100221.

[56] K. Hellström, A. Diószegi, and L. Diaconu, "A broad literature review of density measurements of liquid cast iron," *Metals*, vol. 7, no. 5, p. 165, May 2017, doi: 10.3390/met7050165.

[57] S. Van Vlierberghe, G. -j. Graulus, S. K. Samal, I. Van Nieuwenhove, and P. Dubruel, "Porous hydrogel biomedical foam scaffolds for tissue repair," in *Elsevier eBooks*, 2014, pp. 335–390. doi: 10.1533/9780857097033.2.335.

[58] Y. A. Çengel and M. A. Boles, *Thermodynamics : an Engineering Approach*. 1989. [Online]. Available: http://www.loc.gov/catdir/toc/ecip0616/2006021201.html

[59] P. Felizardo, M. J. N. Correia, I. Raposo, J. F. Mendes, R. Berkemeier, and J. M. Bordado, "Production of biodiesel from waste frying oils," *Waste Management*, vol. 26, no. 5, pp. 487–494, Jun. 2005, doi: 10.1016/j.wasman.2005.02.025.

[60] Z. Feng, J. Zhang, J. Gu, X. Leng, Z. He, and K. Nishida, "Improving biodiesel atomization performance in CI engines: a review of spray behavior, droplet impingement, and advanced techniques," *Processes*, vol. 13, no. 8, p. 2527, Aug. 2025, doi: 10.3390/pr13082527.

[61] M. A. Ghazavi, M. Fallahipanah, and H. S. Jeshvaghani, "A feasibility study on beef tallow conversion to some esters for biodiesel production," *International Journal of Recycling of Organic Waste in Agriculture*, vol. 2, no. 1, Mar. 2013, doi: 10.1186/2251-7715-2-2.

[62] G. Sánchez-Rodríguez, J. Domenzaín-González, F. J. Verónico-Sánchez, H. I. Pérez-López, A. Zúñiga-Moreno, and O. Elizalde-Solis, "Density and Viscosity in Biodiesel + Diesel Mixtures from Recycled Feedstocks," *Applied Sciences*, vol. 15, no. 7, p. 3812, Mar. 2025, doi: 10.3390/app15073812.

[63] M. K. Moro, D. Andreatta, B. C. Oliveira, R. M. Bimbato, and G. Simonelli, "Application of central composite rotational delineation (ccrd) in the study of biodiesel properties," *Brazilian Journal of Petroleum and Gas*, vol. 11, no. 4, pp. 187–195, Dec. 2017, doi: 10.5419/bjpg2017-0016.

[64] M. S. A. Moraes *et al.*, "Tallow Biodiesel: properties evaluation and consumption tests in a diesel engine," *Energy & Fuels*, vol. 22, no. 3, pp. 1949–1954, Mar. 2008, doi: 10.1021/ef7006535.

[65] I. M. Atadashi, M. K. Aroua, and A. A. Aziz, "High quality biodiesel and its diesel engine application: A review," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 7, pp. 1999–2008, Mar. 2010, doi: 10.1016/j.rser.2010.03.020.

[66] M. Lapuerta, O. Armas, and R. Ballesteros, "Diesel Particulate Emissions from Biofuels Derived from Spanish Vegetable Oils," *SAE Technical Papers on CD-ROM/SAE Technical Paper Series*, vol. 1, May 2002, doi: 10.4271/2002-01-1657.

[67] G. Knothe, "Biodiesel and renewable diesel: A comparison," *Progress in Energy and Combustion Science*, vol. 36, no. 3, pp. 364–373, Dec. 2009, doi: 10.1016/j.pecs.2009.11.004.

[68] D. Babu and R. Anand, "Influence of fuel injection timing and nozzle opening pressure on a CRDI-assisted diesel engine fueled with biodiesel-diesel-alcohol fuel," in *Elsevier eBooks*, 2019, pp. 353–390. doi: 10.1016/b978-0-08-102728-8.00013-9.

[69] J. Gandure, C. Ketlogetswe, and M. Jonas, "Production, composition and fuel properties of tallow biodiesel: a case of Botswana," *Energy and Power Engineering*, vol. 09, no. 07, pp. 355–365, Jan. 2017, doi: 10.4236/epe.2017.97024.

[70] Y. S. Pradana, I. G. B. N. Makertihartha, A. Indarto, T. Prakoso, and T. H. Soerawidjaja, "A review of Biodiesel cold flow Properties and its improvement Methods: Towards Sustainable Biodiesel Application," *Energies*, vol. 17, no. 18, p. 4543, Sep. 2024, doi: 10.3390/en17184543.

[71] L. Leng, W. Li, H. Li, S. Jiang, and W. Zhou, "Cold Flow Properties of Biodiesel and the Improvement Methods: A review," *Energy & Fuels*, vol. 34, no. 9, pp. 10364–10383, Aug. 2020, doi: 10.1021/acs.energyfuels.0c01912.

[72] A. Bouaid, G. Iliuta, and J. M. Marchetti, "Cold flow properties of biodiesel from waste cooking oil and a new improvement method," *Heliyon*, vol. 10, no. 17, p. e36756, Aug. 2024, doi: 10.1016/j.heliyon.2024.e36756.

[73] S. Tamrat, Y. Seifu, V. R. Ancha, R. Gopal, and R. B. Nallamothu, "Performance and emission interaction analysis of biodiesel–diesel blends with CeO_2 nanoparticles and diethyl ether in a compression ignition engine," *Scientific Reports*, vol. 16, no. 1, p. 2750, Dec. 2025, doi: 10.1038/s41598-025-32508-7.

[74] C. Kosgei and F. L. Inambao, "A comprehensive review of low-cost biodiesel production from waste beef tallow," *International Journal of Mechanical Engineering and Technology*, vol. 10, no. 7, pp. 285–305, 2019.

[75] A. Demirbas, "Importance of biodiesel as transportation fuel," *Energy Policy*, vol. 35, no. 9, pp. 4661–4670, May 2007, doi: 10.1016/j.enpol.2007.04.003.

[76] S. Jain and M. P. Sharma, "Stability of biodiesel and its blends: A review," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 2, pp. 667–678, Nov. 2009, doi: 10.1016/j.rser.2009.10.011.

[77] A. E. Atabani *et al.*, "Valorization of spent coffee grounds recycling as a potential alternative fuel resource in Turkey: An experimental study," *Journal of the Air & Waste Management Association*, vol. 68, no. 3, pp. 196–214, Aug. 2017, doi: 10.1080/10962247.2017.1367738.

[78] P. Sujin, A. J. Kings, L. R. M. Miriam, and A. Saravanan, "Comprehensive Review of Biodiesel Production from Nonedible Feedstocks: Environmental Impacts and Sustainable Solutions," *Journal of Environmental Nanotechnology*, vol. 13, no. 4, pp. 257–271, Jan. 2025, doi: 10.13074/jent.2024.12.243860.

[79] F. Posada, C. Malins, and A. Baral, "Biodiesel carbon intensity, sustainability and effects on vehicles and emissions," International Council on Clean Transportation, Jan. 17, 2012. [Online]. Available: https://theicct.org/publication/biodiesel-carbon-intensity-sustainability-and-effects-on-vehicles-and-emissions/

[80] N. Mhetras and D. Gokhale, "Sustainable biodiesel production: importance of feedstock resources and production methods," *RSC Advances*, vol. 15, no. 33, pp. 26739–26754, Jan. 2025, doi: 10.1039/d5ra03084f.

[81] M. Ramos, A. P. S. Dias, J. F. Puna, J. Gomes, and J. C. Bordado, "Biodiesel production processes and sustainable raw materials," *Energies*, vol. 12, no. 23, p. 4408, Nov. 2019, doi: 10.3390/en12234408.

[82] F. Binhweel, Md. S. Hossain, and M. I. Ahmad, "Recent Trends, Potentials, and Challenges of Biodiesel Production from Discarded Animal Fats: a Comprehensive Review," *BioEnergy Research*, vol. 16, no. 2, pp. 778–800, Oct. 2022, doi: 10.1007/s12155-022-10527-w.

[83] T. G. Ambaye, M. Vaccari, A. Bonilla-Petriciolet, S. Prasad, E. D. Van Hullebusch, and S. Rtimi, "Emerging technologies for biofuel production: A critical review on recent progress, challenges and perspectives," *Journal of Environmental Management*, vol. 290, p. 112627, May 2021, doi: 10.1016/j.jenvman.2021.112627.

[84] A.-M. Baribeau, R. Bradley, P. Brown, J. Goodwin, U. Kihm, E. Lotero, D. O'Connor, M. Schuppers, and D. Taylor, *Biodiesel from Specified Risk Material Tallow: An Appraisal of TSE Risks and Their Reduction*. Ottawa, ON, Canada: Advanced Technology Fuels Canada, 2006.