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Original Article

Erythrina indica seed oil: sustainable biodiesel production

Salunke R. N[1], Rewatkar S. B[2], Nawkhare P.A[3]
[1]Assistant Professor, Dept. Chemistry, R. B. M. College, Chandgad, Kolhapur, (Maharashtra)
[2]Former Dean, Faculty of Science & Technology, Gondwana University, Gadchiroli
[3]Research scholar, Dr. Ambedkar college of arts, commerce & science, Chandrapur
Email-rajaramsalunke117@gmail.com

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Abstract

This study examines the viability of Erythrina indica (Indian Coral Tree) seed oil, a non-consumable resource, as a substrate for second-generation biodiesel production. The seeds exhibited a notable oil content of 38 % (w/w). Crude oil was transformed into Fatty Acid Methyl Esters (FAMEs), referred to as EISOMEs (Erythrina indica Seed Oil Methyl Esters), by a base-catalyzed transesterification process using 1% KOH, resulting in a substantial practical yield of 90.2%. ^{1}H-NMR spectroscopic investigation validated the conversion, with an estimated result of 92.46%. The produced biodiesel underwent a thorough assessment of its fuel characteristics. Significant discoveries encompass an extraordinarily elevated Cetane Number (58.2), a high Flash Point (172°C), and a kinematic viscosity of 3.6 mm²/s, all of which conform to the stipulations of international standards including ASTM D6751, BIS 15607, and EN 14214. The Higher Heating Value was established at 39.6 MJ/kg, while the Cloud Point was recorded at 2.6°C. This work offers a comprehensive examination of these features, linking them to the distinctive fatty acid profile of the feedstock, and compares them with recognized non-edible feedstocks. The findings strongly suggest that Erythrina indica is a very viable and competitive feedstock for the production of sustainable, high-quality biodiesel, necessitating further exploration of its agronomic and economic potential.

Keywords: Erythrina indica seed oil, Biodiesel, Fatty acids,Transesterification, Fuel properties

Introduction

The 21st-century global energy landscape is characterized by a significant reliance on fossil fuels, a situation that poses serious economic, geopolitical, and environmental difficulties. The transportation sector predominantly depends on petroleum-derived fuels, with oil anticipated to be the primary energy source for global fleets in the foreseeable future. This dependence engenders susceptibility to price fluctuations and supply chain interruptions, while also contributing to the exhaustion of limited geological resources. The combustion of fossil fuels is the primary catalyst for anthropogenic greenhouse gas (GHG) emissions, chiefly carbon dioxide (CO2), which is the foremost contributor to global climate change. The scientific consensus emphasizes the imperative to decarbonize the energy sector and shift towards clean, renewable, and sustainable energy sources to alleviate the most severe consequences of climate change and maintain global warming below the critical limit of 2°C.In response to this necessity, a collection of alternative fuels and innovative vehicle technologies has developed [3]. Liquid biofuels, particularly biodiesel, have attracted considerable interest as a direct, "drop-in" substitute or blending agent for traditional diesel fuel. Biodiesel is characterized as a fuel consisting of mono-alkyl esters of long-chain fatty acids obtained from renewable lipid sources, such vegetable oils or animal fats. Its advantages are numerous: it is renewable, biodegradable, non-toxic, and demonstrates a markedly enhanced emissions profile, characterized by reduced emissions of particulate matter, unburnt hydrocarbons, and carbon monoxide. Biodiesel functions within a "Carbon Neutral Cycle," where the CO2 emitted during combustion is theoretically balanced by the CO_2 absorbed from the atmosphere by the biomass feedstock during its growth, hence adding insignificantly to net greenhouse gas accumulation.

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Address for correspondence:
Salunke R. N,Assistant Professor, Dept. Chemistry, R. B. M. College, Chandgad, Kolhapur, (Maharashtra)

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The capacity to utilize biodiesel in current compression-ignition engines and fuel infrastructure with minimal modification renders it a technologically feasible and readily implementable solution for diminishing the carbon footprint of the transportation sector [4-7].

Non-Edible Oilseeds as a Promising Frontier for Biodiesel ProductionIn the varied realm of second-generation feedstocks, non-edible oilseeds constitute a notably advantageous and direct avenue for biodiesel production. These oilseeds are derived from plants whose oils are unfit for human consumption due to toxins or undesirable fatty acids, however they are abundant in triglycerides essential for biodiesel production. The principal motivator for their adoption is economic: feedstock costs are the predominant element of biodiesel production, representing 70-90% of the end price [8-11]. The use of inexpensive, non-consumable oils is crucial for attaining economic equivalence with traditional petrodiesel and securing the sustained commercial feasibility of the biofuel sector [12]. Several non-edible oilseed species have been thoroughly studied and are regarded as standards in the area. These encompass:

- Jatropha curcas (Ratan Jyot): A drought-resistant perennial shrub lauded for its ability to thrive on marginal lands with minimal inputs. Its seeds contain a high oil content, typically ranging from 27% to 40%, making it one of the most widely studied non-edible feedstocks globally.
- Pongamia pinnata (Karanja): A leguminous tree known for its high tolerance to salinity and drought, and its ability to fix atmospheric nitrogen, thereby enriching the soil. Its seeds yield an oil content of 30-40%, and its robust nature makes it suitable for cultivation in diverse agro-climatic zones.
- Other notable examples include Madhuca indica (Mahua), which is abundant in the tribal regions of India and produces seeds with 30-40% oil, and Melia azadirachta (Neem), a versatile tree whose oil has both biofuel and pesticidal applications. The exploration of this wide variety of species is crucial for identifying regionally appropriate and high-potential feedstocks for a decentralized and resilient biofuel economy [13, 14].

  This study examines a new and mostly uninvestigated possibility for biodiesel production: Erythrina indica, or the Indian Coral Tree. This deciduous tree, part of the Leguminosae family, is native to the tropical jungles of India and can reach a height of 18 meters. Its seeds are inedible, categorizing it as a second-generation feedstock and therefore circumventing the food-versus-fuel dilemma. Initial observations indicate that its seeds possess a significant oil content, rendering it a strong candidate for systematic assessment as a biodiesel source. Notwithstanding its ubiquity, a thorough characterisation of its seed oil and the fuel characteristics of its resultant biodiesel has not been thoroughly documented in the scientific literature [15, 16].



Figure.1 Erythrina indica seeds

This study aims to address this knowledge gap by providing a thorough and systematic analysis of Erythrina indica as a biodiesel feedstock. The specific objectives of this research are:

- To perform solvent extraction of oil from Erythrina indica seeds and accurately quantify the oil content.
- To characterize the fundamental physicochemical properties (e.g., acid value, viscosity, density) and the detailed fatty acid profile of the crude Erythrina indica seed oil (EISO).
- To synthesize biodiesel in the form of Erythrina indica Seed Oil Methyl Esters (EISOMEs) via a base-catalyzed transesterification process and to determine the conversion yield using both gravimetric and spectroscopic methods.
- To conduct a comprehensive evaluation of the critical fuel properties of the produced EISOMEs, including cetane number, kinematic viscosity, flash point, cloud point, density, and higher heating value.
- To critically assess the viability of Erythrina indica as a competitive biodiesel feedstock by benchmarking the properties of EISOMEs against established international fuel standards (ASTM, BIS, EN) and other prominent non-edible oil sources.

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Material and Methods

1 Feedstock material

The principal raw material for this study, the seeds of Erythrina indica, were collected from the Etapalli & Armori forest area in Gadchiroli district (Maharashtra), India. Subsequent to collecting, the seeds underwent a standardized preparation technique to guarantee optimal oil extraction. This entailed extensively desiccating the seeds in direct sunshine to diminish moisture levels, essential for averting hydrolytic reactions and enhancing storage stability. The desiccated seeds were further subjected to mechanical grinding to produce a fine powder, hence augmenting the surface area for solvent interaction [17-21]. Oil extraction was conducted via the Soxhlet method, a recognized and highly effective laboratory technique for continuous solid-liquid extraction. A specified mass of powdered seed material was placed in a thimble and subjected to continuous extraction using 95% n-Hexane (boiling range 55-65°C) as the solvent. Upon completion of the extraction procedure, the solvent was retrieved using distillation, resulting in the residual crude Erythrina indica seed oil (EISO). The oil content percentage was determined gravimetrically utilizing Equation (1):

$$\text{Oil content (w/w \%)} = \frac{\text{Weight of the oil obtained}}{\text{Weight of the seeds taken}} \times 100 \qquad (1)$$

The examination indicated a significant oil content of 38 % on a weight/weight ratio. The elevated yield is a fundamental and essential attribute, as it directly affects the economic viability of a feedstock. An oil content of 38 % positions E. indica competitively against other notable non-edible feedstocks, such Jatropha curcas (27-40%) and Pongamia pinnata (30-40%), hence highlighting its substantial potential as a feedstock [22].

2 Physicochemical Analysis of Crude Erythrina indica Seed Oil (EISO)

Prior to biodiesel conversion, the crude EISO underwent a series of physicochemical analyses in accordance with the standard protocols established by the American Oil Chemists' Society (AOCS). These preliminary characterizations are essential for assessing the quality of the crude oil, choosing the suitable conversion method, and forecasting the characteristics of the ultimate biodiesel product. The key characteristics are encapsulated in Table 1.The Acid Value (AV) of the oil was determined to be 6.5 mg KOH/g, equating to a Free Fatty Acid (FFA) concentration of 3.25%. The Free Fatty Acid (FFA) level is a crucial factor in biodiesel generation, especially when employing a base catalyst. Elevated free fatty acid (FFA) levels (>1–2%) may interact with the alkaline catalyst, resulting in soap formation through a process termed saponification. This side reaction depletes the catalyst, diminishes biodiesel yield, and poses considerable difficulties in separating biodiesel from the glycerol phase due to emulsion formation. The recorded FFA of 3.25% is beneath the frequently referenced threshold of 5%, rendering a single-step base-catalyzed transesterification process viable, yet sufficiently elevated to necessitate meticulous process management.The Saponification Value (SV), indicative of the average molecular weight of fatty acids, was established at 195.6 mg KOH/g. The saponification value (SV) is inversely related to the chain length of fatty acids; a greater SV signifies a lower average molecular weight. The moderate EISO value indicates a predominance of medium-to-long-chain fatty acids, characteristic of vegetable oils [23–24].The Iodine Value (IV) of EISO was 74.8 g of I2 per 100 g. The IV quantifies the extent of unsaturation, namely the quantity of double bonds, in the oil. This is a vital determinant of the ultimate stability of biodiesel. Oils with elevated iodine values are more prone to oxidation, resulting in polymerization and the accumulation of gums and deposits during storage and engine running. The European biodiesel standard EN 14214 establishes a maximum limit of 120 for the iodine value of the finished fuel. The relatively low IV of the raw EISO is a highly advantageous attribute, indicating that the resultant biodiesel will exhibit superior oxidative stability [25].

It was established that the crude oil had a kinematic viscosity of 28.9 mm^2/s when it was heated to 40 °C. When compared to the value of regular diesel fuel, this value is around ten to twelve times higher. One of the primary factors that makes the direct utilization of vegetable oils in modern diesel engines problematic is the elevated viscosity of these oils. This leads to insufficient fuel atomization, incomplete combustion, and carbon deposition on the components of the engine. This result demonstrates very clearly how important it is for the transesterification process to reduce the viscosity to a level that is suitable for use in engine applications [26].

Table 1. Physicochemical properties of EISO

Property	***Erythrina indica* seed oil**
Oil content (%)	38
Molecular weight (gm/mol)	879.42
Density at 25°C (Kg/m^3)	902
Viscosity at 40°C (mm^2/s)	28.9
Iodine value (mg I_2 gm/oil)	74.8
Saponification value (mg KOH gm/oil)	195.6
Acid value (mg KOH gm/oil)	6.5

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2.3Fatty Acid Profile of EISO

The fatty acid content of a feedstock is the fundamental chemical fingerprint of the feedstock, and it is the major factor that determines the fuel qualities of the finished biodiesel. An analysis of the fatty acid profile of EISO was carried out, and the results are presented in Table 2.Following the completion of the examination, it was discovered that the oil is primarily made up of monounsaturated and saturated fatty acids. The monounsaturated acid oleic acid (C18:1), which accounts for 45.5% of the total, is the fatty acid found in the greatest quantity. This is a highly desirable quality, as oleic acid offers a favorable balance between cold-flow properties (superior to those of saturated acids) and oxidative stability (superior to those of polyunsaturated acids) [27–28].Additionally, the oil has a substantial proportion of saturated fatty acids, which collectively amount to around 36.4% of the total. Behenic acid (C22:0) accounts for 14.2%, palmitic acid (C16:0) for 9.8%, stearic acid (C18:0) for 7.4%, arachidic acid (C20:0) for 4.0%, and hexadecanoic acid (C16:0) for 3.4% of the total composition. The presence of these long-chain saturated fatty acids is expected to have a positive effect on the cetane number and contribute significantly to the oxidative stability of the biodiesel [29].Linoleic acid (C18:2) is found at just 6.8% of the total, which is important because the proportion of polyunsaturated fatty acids remains quite low. Since these molecules are the most prone to oxidation and polymerization—processes that can deteriorate fuel quality over time—low levels of polyunsaturated fatty acids (with two or more double bonds) are advantageous for fuel stability.One of the most important findings of this research is the identification of a distinctive and well-balanced fatty acid profile, which will be further examined in relation to the key qualities of the resulting biodiesel fuel.

Table 2. Fatty Acid Composition of Erythrina indica Seed Oil (EISO)

S.No.	Fatty Acid	Composition (%)	Molecular Frmulao	MolecularWeight (g/mol)
1	Oleic acid	45.5	$C_{18}H_{34}O_2$	282.50
2	Behenic acid	14.2	$C_{22}H_{44}O_2$	340.59
3	Eicosenoic acid	8.9	$C_{20}H_{38}O_2$	310.40
4	Palmitic acid	9.8	$C_{16}H_{32}O_2$	256.40
5	Stearic acid	7.4	$C_{18}H_{36}O_2$	284.60
6	Linoleic acid	6.8	$C_{18}H_{32}O_2$	280.45
7	Arachidic acid	4.0	$C_{20}H_{40}O_2$	312.60
8	Hexadecanoic acid	3.4	$C_6H_{12}O_2$	116.40
	Total	**100.0**		

Data sourced from Kadam et al., 2023 and Pathak & Dey, 1956. Note: The original table in the source document contained some inconsistencies in molecular formulas and ordering. The data has been corrected and reordered by composition for clarity. Hexadecanoic acid is another name for Palmitic acid; the distinct entry is retained from the source.

3 Production of Biodiesel

The process of transesterification was utilized in order to accomplish the transformation of the high-viscosity EISO into the low-viscosity biodiesel. Through the utilization of an alcohol (methanol) and the presence of a catalyst, this chemical reaction facilitates the transformation of the triglycerides present in the oil into fatty acid methyl esters (FAMEs) and glycerol. In light of the fact that the FFA content of the EISO was 3.6%, which is lower than the 5 percent standard, a base-catalyzed procedure with a single step was utilized. The reaction was carried out under the conditions that were optimized as follows:

- Reactant Molar Ratio: An oil-to-methanol molar ratio of 1:6 was used. The stoichiometric requirement is 1:3, but a significant excess of methanol is used to shift the equilibrium of the reversible reaction towards the product side, thereby maximizing the conversion of triglycerides to FAMEs.
- Catalyst: Potassium hydroxide (KOH) was used as the homogeneous base catalyst, at a concentration of 1% by weight of the oil. KOH is a highly effective and commonly used catalyst for this process.
- Reaction Conditions: The oil was preheated, and the reaction mixture was maintained at a temperature of 65°C, which is close to the boiling point of methanol, to ensure a high reaction rate. The mixture was continuously stirred at 500 rpm for a duration of 3 hours to ensure proper mixing and mass transfer between the immiscible oil and

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methanol phases [30].

The mixture was then moved to a separating funnel after the reaction was complete, and it was left to settle for the entire night. There were two separate layers that formed as a result of changes in density: the upper layer was composed of the crude biodiesel (EISOMEs), while the lower layer was composed of glycerol, excess methanol, and dissolved catalyst. The glycerol layer that was lower was removed by draining. After that, the remaining layer of crude biodiesel was put through a purification process, which consisted of multiple washings with warm distilled water. This essential stage eliminates any soap, catalyst, and methanol that may have been left behind, so assuring that the finished fuel satisfies the quality requirements.

5 Spectroscopic Confirmation and Yield Calculation

Using Proton Nuclear Magnetic Resonance (1H-NMR) spectroscopy, the purified product was examined in order to verify that the conversion of triglycerides into methyl esters was successful. The ^{1}H-NMR spectrum is an effective instrument for determining the conversion efficiency and gives definitive information regarding the structure of the substance studied.The spectrum that was produced as a result exhibited two important signals that indisputably confirm the synthesis of FAMEs. Figure 2 in the source paper is an example of this. The signal that was the most distinctive was a crisp singlet that appeared at a chemical shift of 3.59 parts per million. This peak is a representation of the protons that are associated with the methoxy group (−OCH3) of the methyl esters, which is not present in the initial structure of the triglyceriding compound. Furthermore, a multiplet that was found at a concentration of 2.13 parts per million was attributed to the protons of α-carbonyl methylene ($-CH_2-COOCH_3$), which further validated the structure of the ester.A quantitative determination of the conversion percentage was made by utilizing the established Equation (2), which was derived from the integrated areas of the pertinent peaks in the 1H-NMR spectrum:

$$C = 100 \times \frac{\text{2x Area intergation of methoxy protons}}{\text{3 x Area intergation of methylene protons}} \qquad (2)$$

Where, C = conversion percentage of triglycerides to methyl esters.

In this equation, the variable C represents the percentage conversion, AMe represents the integration area of the methoxy protons (at a concentration of 3.59 ppm), and ACH2 represents the integration area of the α-methylene protons (an amount of 2.13 ppm).

A conversion of 92.46% was obtained by the computation that was based on the spectroscopic data collection. This result demonstrated a high degree of concordance with the gravimetric yield of 90.2% that was practically realized. This yield was calculated by weighing the finished purified biodiesel product. It is clear that the synthesis and purification technique that was used in this investigation was quite effective, as evidenced by the strong connection that exists between the spectroscopic yields and the practical yields [31].

3. Results and discussion

1 Analysis of Key Fuel Properties of EISOMEs

The successful synthesis of EISOMEs was followed by an in-depth analysis of the important fuel qualities that these compounds possessed respectively. The performance, emissions, and safety features of the biodiesel are determined by these attributes, which also decide whether or not the biodiesel is suitable for integration into contemporary compression-ignition engines. Following the presentation and discussion of the findings, comparisons are made between the results and the major international biodiesel standards as well as conventional petrodiesel.

1.2 Ignition Quality: Cetane Number (CN)

Due to the fact that it evaluates the autoignition characteristics of diesel fuel, the Cetane Number (CN) is widely considered to be the most significant feature that determines the quality of diesel fuel. 58.2 was discovered to be the value of the CN that was estimated for EISOMEs as shown in Figure 2. This number is not only much higher than that of normal petrodiesel (CN ~46) but also comfortably exceeds the minimum requirements of all major international standards, including ASTM D6751 (minimum 47) and the more demanding EN 14214 (minimum 51).There is a clear correlation between a high cetane number and a shorter ignition delay period. The ignition delay period refers to the amount of time that passes between the injection of fuel into the combustion chamber and the beginning of combustion. A shorter delay results in a combustion process that is smoother and more controlled, which translates into several tangible benefits for the performance of the engine and the emissions it produces on the road. The engine will make less noise and "knock," it will be easier to start the engine cold, and the combustion process will be more complete. A higher CN leads to an increase in the efficiency of combustion, which in turn results to a reduction in the emissions of dangerous pollutants from the tailpipe. These pollutants include unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM). The very high CN of 58.2 is a main indicator that EISOMEs have the potential to act as a premium-quality diesel alternative, potentially giving greater combustion performance in comparison to conventional diesel. Because the feedstock contains a high concentration of long, straight-chain saturated and monounsaturated fatty acids, this high value is a direct result of the feedstock's fatty acid profile [32-35].

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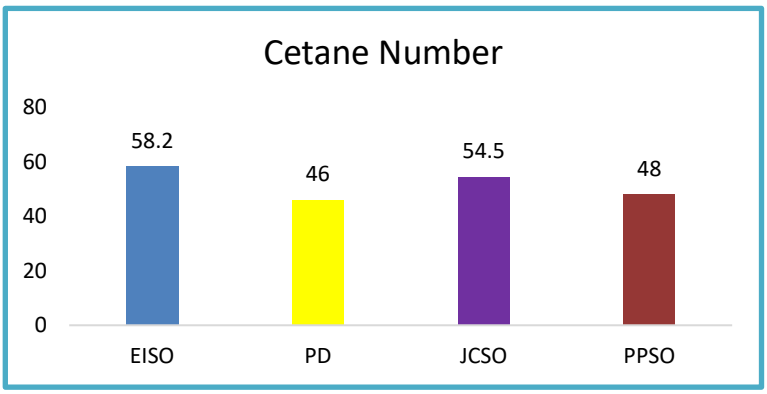


Figure.2 Cetane Number of EISO in comparision with petrodiesel and reported biodiesel

1.2 Flow Characteristics: Kinematic Viscosity

The transesterification procedure resulted in a significant reduction of the fuel's kinematic viscosity by more than 90 percent. This reduction went from 30.25 mm^2/s for the raw oil to 3.6 mm^2/s for the final EISOMEs when they were heated to 40 ^{0}C. This figure is quite close to the lower limit of the BIS 15607 standard, which is within the range of 2.0 to 4.62 mm^2/s as shown in Figure 2. It is also well within the range that is prescribed by ASTM D6751, which is between 1.9 and 6.0 mm^2/s. It is slightly lower than the range that is specified by EN 14214, which is between 3.5 and 5.5 mm2/s. There is a crucial parameter known as viscosity that is responsible for regulating the flow behavior of the gasoline within the injection system of the engine. It is difficult for the fuel to produce a thin spray when it is injected because of its very high viscosity, as can be observed in the raw EISO. This results in poor atomization, which in turn causes larger fuel droplets that do not mix well with air. This leads to incomplete combustion, which in turn leads to increased fuel consumption and the creation of carbon deposits on injectors and cylinder walls. One of the key goals of biodiesel manufacturing is to successfully reduce the viscosity of the fuel to a level that is acceptable for diesel engines. The fact that EISOMEs have a value of 3.6 mm2/s suggests that they will have flow qualities that are acceptable for contemporary high-pressure fuel injection systems, which will ensure that atomization and combustion are carried out effectively. It is anticipated that this will not result in substantial operational concerns and may even contribute to finer atomization, despite the fact that it is somewhat below the minimum required by EN 14214.

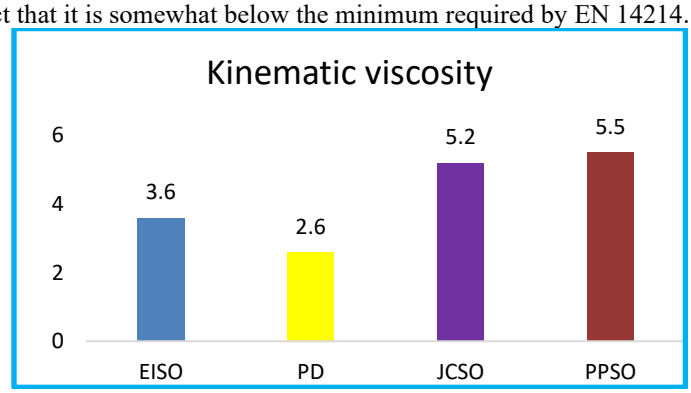


Figure.2 Kinematic viscosity of EISO in comparision with petrodiesel and reported biodiesel

1.3 Safety and Handling: Flash Point (FP)

It was established that the Flash Point (FP) of the EISOMEs that were created was 172 ^{0}C. This is a significant increase in comparison to the flash point of petrodiesel, which is normally somewhere around 70 ^{0}C as shown in Figure 3. The most significant thing is that it surpasses the minimal safety limits that are established by international biodiesel standards, such as ASTM D6751 (>130°C) and both BIS 15607 and EN 14214 (>120°C).The flash point is the lowest temperature at which a liquid creates sufficient vapor to make an ignitable mixture with air. This is the standard definition of the flash point. The fire hazard that is connected with the storage, transportation, and handling of a fuel is evaluated using this parameter, which is an essential evaluation tool. Due to the extremely high flash point of EISOMEs, it is classified as a material that is not flammable and does not pose any hazards. As a result, it is substantially safer to handle than normal diesel fuel. In addition, the flash point is an essential quality control indication that is utilized in the context of the manufacture of biodiesel. In the event that residual methanol from the transesterification process is not completely eliminated, it has the potential to significantly reduce the flash point of the final biodiesel. Methanol having a flash point of roughly 11 ^{0}C is extremely low. The extraordinarily high value of 168 ^{0}C that was measured provides strong indication that the purification technique, which consisted of washing with warm

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water, was highly effective in eliminating unreacted methanol, which ultimately resulted in a product that was both pure and safe [36].

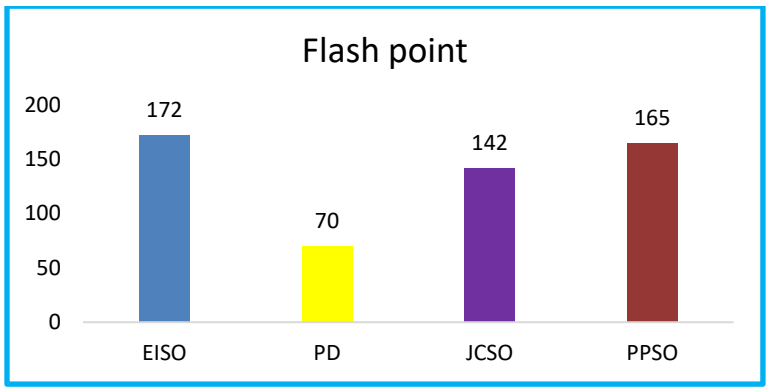


Figure 3. Flash point of EISO in comparision with petrodiesel and reported biodiesel

1.4 Cold Weather Performance: Cloud Point (CP)

It was determined that the Cloud Point (CP) of the EISOMEs was 2.6 ^{0}C. This figure is higher than the range that is recommended by the ASTM D6751 standard for usage in temperate areas, which is -3 to -12 ^{0}C as shown in Figure 4. However, this value is within the average range for petrodiesel, which is -15 to 5 ^{0}C.The temperature at which wax crystals first begin to form as the fuel is cooled is referred to as the cloud point. These crystals give the fuel a cloudy or hazy look. These crystals have the potential to clump together and clog fuel lines and filters, which can impede the flow of fuel and result in serious problems with the engine's capacity to function when the temperature is low. Because of this, the cloud point is a significant element that reduces the amount of biodiesel that may be used in colder climates [37]. At a temperature of 3.1 ^{0}C, it appears that pristine EISOMEs (B100) would be adequate for use in tropical regions throughout the entire year. However, in order to ensure dependable operation during the winter months in temperate countries, it may be necessary to incorporate cold flow improver additives or blend with winter-grade petrodiesel (for example, in B20 blends). This attribute is a direct trade-off that is related to the chemical structure of the fuel; the same long, saturated fatty acid chains that contribute favorably to the high cetane number also have higher melting points and are responsible for the creation of wax crystals at relatively higher temperatures when the temperature is relatively higher [38].

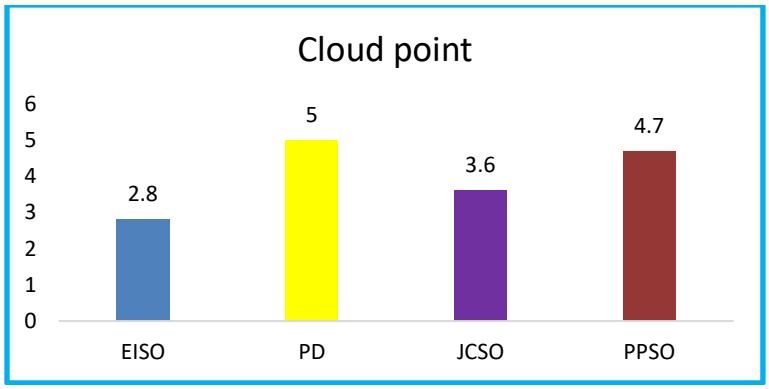


Figure 4. Cloud point of EISO in comparision with petrodiesel and reported biodiesel

1.5 Fuel Injection and Combustion: Density

At a temperature of 15 ^{0}C, the density of the EISOMEs was determined to be 865 kg/m^3. This is slightly higher than the density of petrodiesel, which is 850 kg/m^3, and it comes neatly within the permitted range that is stated by the Bureau of Indian Standards (BIS 15607), which is between 820 and 860 kg/m^{3}as shown in Figure 5.The density of the fuel is an important property that has an effect on the performance of the engine as well as the process of fuel injection. Given that diesel fuel injection systems measure fuel by volume, a fuel with a higher density will result in a slightly greater quantity of fuel being delivered into the combustion chamber for a given injection volume. This is because diesel fuel injection systems measure fuel by volume. As a result of this greater mass of fuel, biodiesel's reduced energy content can be somewhat compensated for, which provides assistance in maintaining engine power output. It is also the case that density, in conjunction with viscosity and surface tension, has an effect on the properties of the fuel spray. These qualities include droplet size and penetration depth, which in turn have an effect on the process of air-fuel mixing and the overall efficiency of combustion. The density of 859 kg/m3 that was observed is well within the standard range for biodiesels and shows that it is also fully compatible with the fuel systems that are already in place for engines [39].

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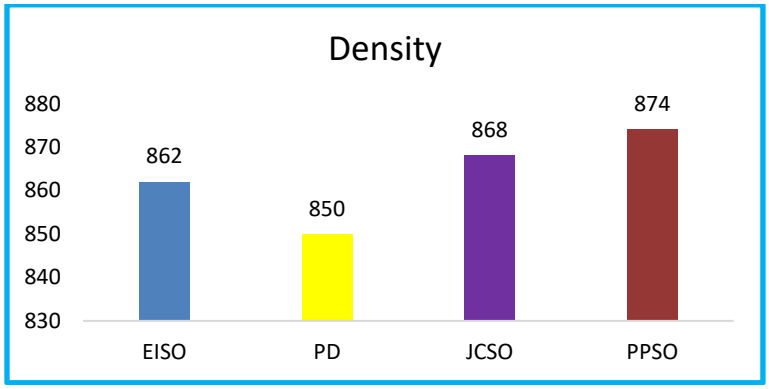


Figure.5 Density of EISO in comparision with petrodiesel and reported biodiesel

1.6 Energy Content: Higher Heating Value (HHV)

After doing the calculation, the Higher Heating Value (HHV), which is also referred to as the calorific value, was determined to be 39.6 MJ/kg for EISOMEs. Compared to the HHV of petrodiesel, which is roughly 46.0 MJ/kg, this is significantly lower, as was to be expected as shown in Figure 6.During the process of complete combustion of a unit mass of fuel, the HHV is the total quantity of thermal energy that is released into the atmosphere. Compared to their petroleum-based competitors, biodiesel fuels have a lower energy content by their own nature, often ranging from 10 to 12 percent less. The presence of oxygen atoms inside the molecular structure of methyl esters of fatty acids is the reason for this phenomenon. These oxygen atoms contribute to the molecular weight of the methyl esters, but they do not contribute to the energy that is produced during combustion. Despite the fact that this molecular oxygen is advantageous for lowering emissions of soot and carbon monoxide and facilitating more complete combustion, the lower energy density that it produces is a consequence of its presence. There is a little rise in the brake-specific fuel consumption (BSFC) as a practical consequence of a lower HHV. This means that a slightly larger volume of biodiesel is required to be used in order to generate the same amount of engine power as petrodiesel. The high-heat value (HHV) of 40.1 MJ/kg is common for a biodiesel that is based on vegetable oil. This value represents a fundamental and well-understood trade-off for the environmental and performance benefits that the fuel provides [40].

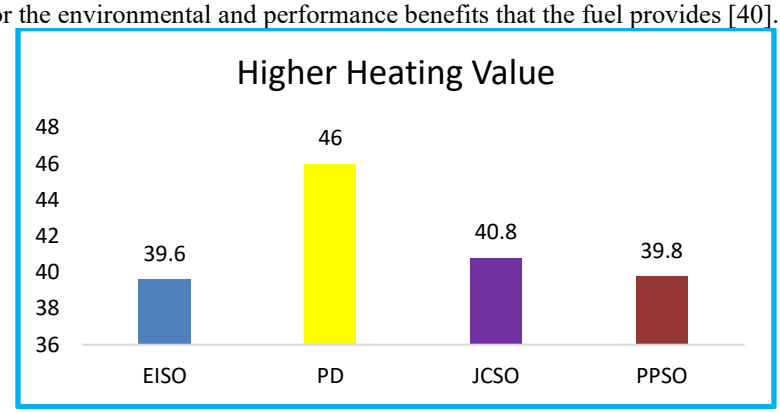


Figure 6.HHV of EISO in comparision with petrodiesel and reported biodiesel

2 Correlating Feedstock Characteristics with Biodiesel Properties

It is not enough to just characterize the end fuel in order to conduct a comprehensive evaluation of a novel biodiesel feedstock; rather, it is necessary to have a fundamental understanding of how the inherent qualities of the raw oil affect the performance of the biodiesel that is produced. There is no coincidence behind the exceptional quality of EISOMEs; rather, it is a direct result of the one-of-a-kind chemical makeup of the seed oil derived from the Erythrina indica plant.

The fatty acid profile of EISO, which may be found in Table 2, indicates a composition that achieves a profoundly favorable equilibrium between qualities that are frequently in conflict with one another. The considerable fraction of long-chain saturated fatty acids, which accounts for around 33.8% of the total, is the primary contributor to the high cetane number of 58.2. This is due to the fact that compressed molecules that are longer and more saturated are more likely to ignite. On the other hand, a high concentration of saturated fats often results in very poor cold-flow characteristics, which in turn leads to a high cloud point. On the other hand, feedstocks that are abundant in polyunsaturated fats may have excellent cold-flow qualities; nonetheless, they are characterized by low cetane numbers and poorly stable oxidative processes. Through the use of the EISO profile, this trade-off is avoided. As a natural moderator, the monounsaturated oleic acid, which makes up 45.5% of its composition, is the predominant component. It makes a positive contribution to the cetane number while having a melting point that is significantly lower than that of its saturated counterparts. As a result, it prevents the cloud point from getting overly high. When this occurs, a

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"balanced profile" is produced, which means that the fuel is able to reach outstanding ignition quality without significantly affecting its performance in cooler temperatures.

Furthermore, the characteristics of the raw oil can be used to make a direct prediction regarding the oxidative stability of the fuel, which is an essential criterion for the long-term storage of the fuel and the health of the engine. The most important factor that contributes to the instability of biodiesel is the oxidation of double bonds, which is especially prevalent in polyunsaturated fatty acids. The total amount of double bonds can be directly measured using the Iodine Value (IV), which is an abbreviation. There is a clear indication that the final biodiesel will be extremely resistant to oxidation because to the low amount of polyunsaturated linoleic acid (6.8%) and the low IV of the raw EISO, which is 70.6 grams of ionizing radiation per one hundred grams. Due to the intrinsic stability of EISOMEs, they are less likely to come into contact with gums, sediments, and acidic compounds while being stored. These substances have the potential to clog filters and cause engine components to corrode. The findings of this study suggest that a straightforward and low-cost method of determining the iodine and saponification values of an unidentified raw oil can function as an effective instrument for making predictions. It makes it possible to conduct a speedy screening of potential new feedstocks, finding those that have the greatest promise for producing stable biodiesel with a high cetane content. This is accomplished without the requirement for a comprehensive synthesis and testing methodology for each and every candidate under consideration. This approach has the potential to considerably speed up the process of discovering and validating previously unknown biofuel resources that are sustainable [41].

3 Comparative Assessment with International Standards and Other Feedstocks

The features of EISOMEs were benchmarked against worldwide fuel standards as well as other prominent non-edible biodiesel feedstocks in order to contextualize the performance of EISOMEs and thoroughly analyze its quality. In Table 3, a direct comparison is made between EISOMEs and petrodiesel, as well as the standards of ASTM D6751, BIS 15607, and EN 14214.

Table 3: Comparison of Fuel Properties of EISOMEs with Petrodiesel and International Biodiesel Standards

Property	**EISOMEs (Modified Data)**	**Petrodiesel**	**ASTM D6751**	**BIS 15607**	**EN 14214**
Cetane Number	58.2	46	47 min.	51 min.	51 min.
Kinematic Viscosity @ 40°C (mm^2/s)	3.6	2.6	1.9- 6.0	2.0 – 4.62	3.5 – 5.5
Density @ 15°C (Kg/m^3)	865	850	880	820 – 860	900
Flash Point (°C)	172	70	>130.	>120 .	>120
Cloud Point (°C)	2.6	–15 to 5	–3 to –12	Report	Report
Higher Heating Value (MJ/Kg)	39.6	46.0	Report	Report	Report

Data for EISOMEs, Petrodiesel, and standards sourced from Kadam et al., 2023. Note: "Report" or "ND" in original sources indicates the standard does not specify a limit for this property.

The information shown in Table 3 makes it abundantly evident that EISOMEs either reach or surpass the requirements for all of the essential parameters that are established by the major standards. The fuel is of a premium quality, as evidenced by the fact that both the cetane number and the flash point are significantly higher than the minimum criteria. Both the viscosity and the density are well within the ranges that are often used for specifications. The cloud point is the single distinguishing feature that should be mentioned; although it is acceptable in many areas, it would need to be managed in order to be used in colder climes. This is a trait that is shared by many high-quality biodiesels [42].In Table 4, Erythrina indica is compared to two of the non-edible feedstocks that have received the most attention from researchers: Jatropha curcas and Pongamia pinnata. This comparison is made in order to evaluate the competitiveness of Erythrina indica within the field of second-generation biofuels.

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Table 4: Comparative Analysis of Key Fuel Properties of Biodiesel from Erythrina indica, Jatropha curcas, and Pongamia pinnata

Parameter	Erythrina indica	Jatropha curcas	Pongamia pinnata
Feedstock Oil Content (%)	38	28 – 42	32 – 41
Biodiesel Yield (%)	~91	~87 – 97	~92
Cetane Number	58.2	53.0 – 54.5	~48
Flash point (^{0}C)	172	142	165
Higher heating value (MJ/Kg)	39.6	40.8	39.83
Kinematic Viscosity @ 40°C (mm^2/s)	3.6	4.1 – 5.2	5.5
Density @ 15°C (Kg/m^3)	862	~868	874
Cloud Point (°C)	2.8	1.9 – 3.6	4.7

According to the findings of this comparison investigation, Erythrina indica is a feedstock that is not only exceptionally competitive but also outstanding. Its oil content and biodiesel yield are comparable to those of other sources that have been established. The quality of its fuel, and particular the cetane number, is, nevertheless, the component that offers the most significant advantage. It is superior to the typical values that are recorded for both Jatropha and Pongamia biodiesel, with a value of 58.2, which indicates that it has greater ignition quality. Furthermore, its kinematic viscosity of 3.5 mm2/s is significantly lower than that of both Jatropha and Pongamia biodiesels, which indicates that it has superior atomization and flow characteristics. Both its density and cloud point are comparable to those of Jatropha, with Pongamia being slightly superior in both respects. The information shown here clearly shows that Erythrina indica is not only another possible choice; rather, it is a high-potential candidate that requires major attention for the purpose of further development and commercialization [43].

In the course of this exhaustive inquiry, it was effectively proved that the non-edible seeds of Erythrina indica may be used to produce and characterize high-quality biodiesel. According to the findings of the study, the seed oil content was found to be 38 % (w/w), and it was successfully transformed into Erythrina indica Seed Oil Methyl Esters (EISOMEs) with a practical yield of 90.2% by the utilization of a standard single-step, base-catalyzed transesterification process. In order to prove the high conversion efficiency, which was 92.46%, spectroscopic confirmation using ^{1}H-NMR was performed. As a result of the subsequent study of the fuel qualities of the biodiesel, it was discovered that EISOMEs are a high-performance fuel that either fulfills or surpasses the specifications of important international standards. These standards include ASTM D6751, BIS 15607, and EN 14214. Notable discoveries include a high flash point of 172 ^{0}C, which guarantees safe handling and storage, and a very high cetane number of 58.2, which indicates excellent ignition quality. Both of these findings are extremely significant. Other essential characteristics, such as kinematic viscosity (3.6 mm^2/s) and density (865 kg/m^3), were found to be well within acceptable limits, so demonstrating that the fuel is suitable for use in contemporary diesel engines.

Conclusion

In the course of this exhaustive inquiry, it was effectively proved that the non-edible seeds of Erythrina indica may be used to produce and characterize high-quality biodiesel. According to the findings of the study, the seed oil content was found to be 38 % (w/w), and it was successfully transformed into Erythrina indica Seed Oil Methyl Esters (EISOMEs) with a practical yield of 90.2% by the utilization of a standard single-step, base-catalyzed transesterification process. In order to prove the high conversion efficiency, which was 92.46%, spectroscopic confirmation using 1H-NMR was performed. As a result of the subsequent study of the fuel qualities of the biodiesel, it was discovered that EISOMEs are a high-performance fuel that either fulfills or surpasses the specifications of important international standards. These standards include ASTM D6751, BIS 15607, and EN 14214. Notable discoveries include a high flash point of 172 ^{0}C, which guarantees safe handling and storage, and a very high cetane number of 58.2, which indicates excellent ignition quality. Both of these findings are extremely significant. Other essential characteristics, such as kinematic viscosity (3.6 mm^2/s) and density (865 kg/m^3), were found to be well within acceptable limits, so demonstrating that the fuel is suitable for use in contemporary diesel engines.

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