The Open European Journal of Engineering and Scientific Research (OEJESR)
Volume 1, Issue 2, 2025, Pages: 22-32
E-ISSN: 3062-3383
Journal homepage*:*
https://easdjournals.com/index.php/oejesr/index

Air-Fuel Ratio Calculation and Lambda (λ) Analysis for Biodiesel Oils Combustion

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Article history	Received 22 February 22025	Accepted 14 April 2025	Publishing 20 April 2025

Abstract

This paper discusses the study of biodiesel types such as canola oil, corn oil, sunflower oil, soybean oil and biodiesel. The paper covers composition, balance of equations, air-fuel ratio calculation, and lambda analysis for the combustion of these biodiesel types. This includes detailed information on the mathematical conversions required to convert weight per cent to molar per cent and subsequent estimation of the elemental concentrations in biodiesel. The figures are also presented. In addition, it focuses on other works related to the composition, characterization, and production of biodiesel. The research paper provides a comprehensive review of biodiesel types, composition and associated temperatures. It provides valuable insight into the chemical composition of canola oil, corn oil, sunflower oil, soybean oil and biodiesel, which is essential to understanding the potential of alternative fuels.

Keywords: Biodiesel, Air-fuel ratio, Oils, alternative fuels.

حساب نسبة الهواء إلى الوقود وتحليل معامل (λ) لامدا لاحتراق زيوت الديزل الحيوي

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الملخص

تتناول هذه الورقة دراسات حول أنواع مختلفة من وقود الديزل الحيوي، بما في ذلك زيت الكانولا وزيت الذرة وزيت عباد الشمس ووقود الديزل الحيوي لزيت فول الصويا. يناقش البحث تكوين وموازنة المعادلات وحسابات نسبة الهواء إلى الوقود وتحليل لامدا لاحتراق أنواع وقود الديزل الحيوي هذه. ويتضمن معلومات مفصلة عن التحويلات الرياضية المطلوبة لتحويل نسب الوزن إلى نسب مولية والحساب اللاحق لمتوسط محتوى العنصر في وقود الديزل الحيوي. تعرض الورقة أيضًا نسبة الهواء إلى الوقود المتكافئة وحسابات لامدا لكل نوع من أنواع وقود الديزل الحيوي. بالإضافة إلى ذلك، فهو يشير إلى أعمال أخرى تتعلق بتركيب وقود الديزل الحيوي وخصائصه وتوليفه.

تقدم الورقة البحثية تحليلاً شاملاً لأنواع وقود الديزل الحيوي المختلفة وتركيباتها ومعاملات الاحتراق المرتبطة بها. وهو يقدم رؤى قيمة حول الخواص الكيميائية وخصائص الاحتراق لزيت الكانولا وزيت الذرة وزيت عباد الشمس ووقود الديزل الحيوي لزيت فول الصويا، والتي تعتبر ضرورية لفهم إمكاناتها كوقود بديل.

الكلمات المفتاحية: وقود الديزل الحيوي، نسبة الهواء إلى الوقود، الزيوت، الوقود البديل.

Introduction

Fuels have an important industrial revolution and economic value worldwide. However, factors such as a reduction in fossil fuel resources and an increase in greenhouse gas releases into the atmosphere have augmented the alternative cleaner fuel studies in the world. Among these, biofuels are expected to reduce both dependence on fossil fuels and the accumulation of greenhouse gases, as well as other pollutants [1]

The growing concern related to the depletion of natural fossil fuel reserves affected by extensive usage necessitates the search for renewable energy sources and fuels. The depletion of the ozone layer and the consequent global warming-related warnings heighten the importance of discovering and developing alternative energy and fuel sources. The current shortage of oil and other fossil fuels is threatening not only economic performance but also the state of the environment. For 100 years, the atmosphere has seen a doubling of carbon dioxide concentration largely as result of industrialization and uncontrolled use of fossil fuels for transportation and energy generation [2].

Air-fuel ratio (AFR) is a crucial parameter in combustion processes, including biodiesel and biomass applications. Studies have explored AFR optimization for various fuel mixtures, such as waste cooking oil and diesel [3], and rapeseed methyl ester [4]. The AFR affects exhaust gas composition, thermodynamic properties, and combustion efficiency. Monitoring oxygen concentration in flue gases is essential for controlling efficiency and emissions [5] . While expensive analyzers are often used, cost-effective alternatives like Arduino-based systems with lambda sensors have been developed for small-scale industries and developing countries [5]. Calculation methods for air ratio lambda consider multiple exhaust components, fuel properties, and mixture humidity [6]. Notably, measurement errors in exhaust gas components have a more significant impact on lambda in lean mixtures compared to rich mixtures [6]. These findings contribute to the understanding and optimization of AFR in various combustion applications.

Properties of Biodiesel

Biodiesel is a renewable fuel source originated from vegetables and oils, animal fats, or microalgae fats. It is an energy-efficient fuel that is widely accepted due t its non-toxicity, biodegradability, high flash point, and eco-friendly nature [12]. It has comparable properties to traditional diesel, but with lower emissions of exhaust gases. Besides, it exhibits properties, such as higher density and viscosity or thickness. However, it also has a high lubricity and biodegradability, while its cold flow behavior can be a challenge.

Biodiesel characteristics vary depending on the fatty acid ester composition of feedstock used, by-products, product purification, post-production, and storage issues. Some of its physicochemical properties impact the ignition and combustion efficiency of fuel, while structural features, such as degree of saturation, chain length of hydrocarbon, and branching impact the profile of fatty acid esters [13]. These directly influence the biodiesel properties, thus its features and performance as automotive fuel.

Combustion Process

Biodiesel combustion, similar to diesel fuel burning encompass a process of rapid burning (oxidation) of fuel with air in a controlled environment, releasing properties heat and power. Nonetheless, its unique properties, including increased oxygen content and decreased soot formation influence the combustion process and emissions.

Biodiesel combustion process encompasses several critical stages influenced by different factors, including fuel combustion, injection parameters, and combustion chamber design. Comprehending these dynamics is vital for optimizing performance and reducing emissions. The most common stages of biodiesel combustion include ignition delay, premixed combustion, diffusion combustion, and complete combustion [14].

Biodiesel typically exhibits shorter ignition delay than traditional diesel due to its superior cetane number and oxygen content, meaning it burns quicker. After ignition, the fuel-air mixture burns rapidly in a premixed staged. Followed by a diffusion combustion in which the burn rate is controlled by fuel-air mixing. In this diffusion combustion stage, the fuel and air mix and react, releasing heat and energy. The final stage, complete combustion is where the fuel is fully oxidized, mixing emissions of unburnt hydrocarbons, carbon monoxide, and soot [15].

Types of Biodiesel Oils

Biodiesel can be derived from different oils, grouped predominantly into edible and non-edible sources. Each category presents unique advantages and challenges for biodiesel production, impacting it viability as an alternative fuel.

The most common sources of edible oils include crude palm oil, soybean oil, and canola oil. Their key advantages encompass high availability and established processing methods. On the other hand, non-edible oils include jatropha oil, neem oil, mahua oil, and rubber oil, which can be sourced from plants growing in marginal lands, which reduces food supply concerns [16]. Today, they are increasingly recognized for their potential in biodiesel production because of reduced costs and environmental benefits. Lastly, microalgal oils can generate superior yield and can be cultivated on non-arable land. They offer a promising avenue for biodiesel production without competing for agricultural resources.

Biodiesel oils can be refined into Bintaro Oil, Hazelnut Oil, Corn Oil, Crude Palm Oil, Hydrotreated Vegetable Oil, Kapok Seed Oil, Rubber Seed Oil, Used Cooking Oil, Kesambi Oil, and Graphene Nanoplatelet biodiesels as illustrated in Table 1 below [17]:

Table 1: Comparison of Common Types of Biodiesels.

Type of Biodiesel	Explanation
Bintaro Oil Biodiesel Biodiesel	The most common source of Bintaro oil is a non-food crop, decreasing competition with food sources. Specific catalysts can affect its overall production process.
Hazelnut Oil Biodiesel	It has a low level of fatty acids, making it appropriate for biodiesel production.
Corn Oil Biodiesel	Corn oil is of high quality with high smoke point, making is appropriate for biodiesel. Besides, it widely available and prevalently used in different sectors. However, some concerns relating to using food crops for biodiesel production arise.

Crude Palm Oil Biodiesel	Crude palm oils are often used as industrial raw material for biodiesel generation as it is a product from milling factories.
Hydrotreated Vegetable Oil Biodiesel	Also known as renewable diesel is a biofuel produced by hydro-processing vegetable oils and fats, providing a cleaner-burning, low-emission fuel that can be utilized as a direct replacement for conventional diesel.
Kapok Seed Oil Biodiesel	Kapok Oil is a non-edible feedstock regarded a better source due to abundant availability and high oil yield among other non-edible feedstocks [18].
Rubber Seed Oil Biodiesel	Rubber seed oil is a non-edible oil source, which is a promising feedstock for biodiesel generation, providing a sustainable alternative to fossil fuels, particularly in regions with rubber plantations.
Used Cooking Oil Biodiesel	Used cooking oil can be transformed into biodiesel, a renewable fuel source associated with benefits, such as reduced emissions and equipment lifespan.
Kesambi Oil Biodiesel	Kesambi oil has been tested a source of biodiesel generate by synthesizing it using different kinds of base catalyst through transesterification.
Graphene Nanoplatelet Biodiesel	Graphene Nanoplatelet are carbon-based nanomaterials that can advance biodiesel performance and emissions by promoting burning and decreasing pollutants.

Combustion Characteristics of Fuel

Combustion characteristics of fuels include properties, such as ignition temperatures, flame speed, and chemical reaction pathways that are influenced by fuel composition and molecular structured. These features are central in comprehending fuel quality, combustion efficiency, and emissions. Biodiesels burn more efficiently with superior combustion effectiveness and exhaust temperature [19]. Generally, biodiesels have a superior heat of vaporization that diesel, which can result in slightly lower fuel atomization and potentially impact cold start performance. Besides, biodiesel has a superior cetane number compared to conventional diesel, leading to smoother combustion, reduced engine noise, and inferior emissions of unburned hydrocarbons and carbon monoxide [20].

Biodiesel contains inherent oxygen (approximately 10-12%), which promotes more complete burning, reducing particulate matter emissions [20]. Moreover, it generally has higher viscosity than diesel, particularly at lower temperatures, which can impact fuel atomization, spray pattern, and fuel pump performance, while it also has a significantly higher flash point than diesel. Overall, biodiesel offers several advantages concerning combustion characteristics, such as higher cetane number, inherent oxygen content, and decreased emissions of certain pollutants. Nonetheless, its increased viscosity and potential for higher nitrogen oxide emissions demand careful consideration and optimisation in engine design and operation [21].

Properties, Combustion Performance, and Emissions Analysis of Biodiesel

Today, biodiesel has emerged as a viable alternative to traditional diesel, offering multiple benefits concerning properties, combustion performance, and emissions. Biodiesel exhibits superior density, viscosity, and cetane numbers, slightly decreasing engine performance. Biodiesel combustion decreases carbon monoxide by 30%, unburned hydrocarbons by 50%, and smoke by 70% [20]. The cetane number of biodiesels is typically reduces, resulting in longer ignition delays, whereas different biodiesel blends, such as B20 and B40 maintain acceptable combustion properties while being compatible with present diesel engines [22]. In terms of performance, biodiesel blends often slightly lower thermal efficiency and superior specific fuel consumptions compared to traditional diesel [23]. Their heat release rates can be significantly higher compared to traditional diesel, suggesting more effective combustion processes. Augmented biodiesel rations cause earlier combustion start and decreased ignition delays. Concerning emission analysis, biodiesel use has been linked with a decrease in carbon monoxide, unburned hydrocarbons, and soot emissions by up to 70% [20]. Nonetheless, nitrogen oxides emissions can raise up to a 45.5% rise when utilizing certain biodiesel blends. The overall emissions profile varies with the biodiesel source and blend ration, demanding cautious selection for ideal performance. The Demand of bio gasoline and biodiesel in the period of 1980 to 2022 is demonstrated in Figure 1.

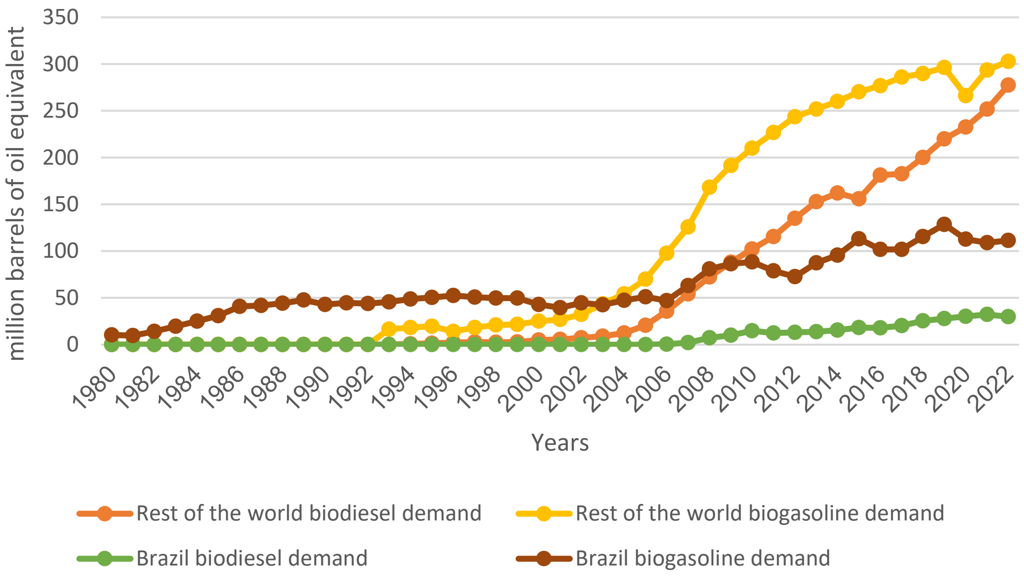

Figure 1: Demand of bio gasoline and biodiesel, 1980-2022.

Oil Biodiesel Composition

We have the following formula for biodiesel produced from Canola Oil:

$$C_{18}H_{33}O_2$$

The paper provided weight % for all different methyl esters that constitute the Canola Oil Biodiesel and therefore some mathematical transformation was required.

First, the formulas for each of the 5 constituents were mapped. Second, molar weight for each methyl ester was calculated to proceed to changing the wet% to molar %. Once we have molar % a weighted sum was conducted to calculate average element content on the biodiesel. The result is the following formula: [7] , [8]

$$\mathrm{C_{18}H_{33}O_2}$$

Balancing the Equation

The unbalanced equation is as follows:

$$\mathrm{C_{18}H_{33}O_2} + O_2 \rightarrow CO_2 + H_2O$$

To balance this equation, we will use the algebraic method. First let's write our unknowns:

$$\mathrm{aC_{18}H_{33}O_2} + bO_2 \rightarrow cCO_2 + dH_2O$$

Now, let's write all equations:

$$18a = c \qquad (i)$$

$$33a = 2d \qquad (ii)$$

$$2a + 2b = 2c + d \qquad (iii)$$

Since we will be calculating Air Fuel Ratio, we need to burn 1 mol of fuel which means $a = 1$ and, by solving the equations i-iii, $b = \frac{109}{4}$, $c = 18$ and $d = 33/2$.

Air-Fuel Ratio

Molar mass of biodiesel and Oxygen is 281.46 $\frac{gram}{mol}$ and 31.998 $\frac{gram}{mol}$.

Mass of air required for total combustion will be:

$$m_{air}\frac{101/4}{0.21} * 28.85 = 3468.92\ grams = 3.468\ Kg$$

Where 28.85 is the molecular weight of air. There we assumed a composition of air of 79% N_2 and 21% O_2.

On the other side, 1 mol of canola oil biodiesel is equivalent to $0.281Kg$.

The stoichiometric Air-Fuel Ratio (AFR_{stoich}) is calculated:

$$AFR_{stoich} = \frac{m_{air}}{m_{fuel}} = \frac{3.468}{0.281} = 12.34$$

$$\lambda = \frac{AFR}{AFR_{stoich}} = \frac{3.07}{12.34} = 0.25$$

As expected, λ is very low since the air-fuel mix is rich in biodiesel.

Now, for a mix with excess of air and for one mol of biodiesel we have:

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{(28.85) * (300)}{281.46} = 30.75$$

Given AFR we can compute λ,

$$\lambda = \frac{AFR}{AFR_{stoich}} = \frac{30.75}{12.34} = 2.49$$

In this case λ is higher than 1 because the mix is poor on fuel and rich on air.

Corn Oil Biodiesel Composition

Based on the work of [9] we have the following formula for biodiesel produced from corn Oil:

$$C_{17}H_{32}O_2$$

On this paper we find weight % for all different methyl esters that constitute the corn Oil Biodiesel and therefore some mathematical transformation was required as explained on a previous report.

Balancing the Equation

The unbalanced equation is as follows:

$$\mathrm{C_{17}H_{32}O_2} + O_2 \rightarrow CO_2 + H_2O$$

To balance this equation, we will use the algebraic method. First let's write our Unknowns:

$$\mathrm{aC_{18}H_{33}O_2} + bO_2 \rightarrow cCO_2 + dH_2O$$

Now, Let's write all equations:

$$17a = c(i)$$

$$32a = 2d(ii)$$

$$2a + 2b = 2c + d(iii)$$

Since we will be calculating Air Fuel Ratio, we need to burn 1 mol of fuel which means $a = 1$ and, by solving the equations i-iii, $b = 24$, $c = 17$ and $d = 16$.

Air-Fuel Ratio

Molar mass of biodiesel and Oxygen is 268.441 $\frac{gram}{mol}$ and 31.998 $\frac{gram}{mol}$.
Mass of air required for total combustion will be:

$$m_{air}\frac{24}{0.21} * 28.85 = 3297.14 grams = 3.297 Kg$$

Where 28.85 is the molecular weight of air. There we assumed a composition of air of 79% N_2 and 21% O_2.

On the other side, 1 mol of corn oil biodiesel is equivalent to $0.268 Kg$.

The stoichiometric Air-Fuel Ratio (AFR_{stoich}) is calculated:

$$AFR_{stoich} = \frac{m_{air}}{m_{fuel}} = \frac{3.297}{0.268} = 12.30$$

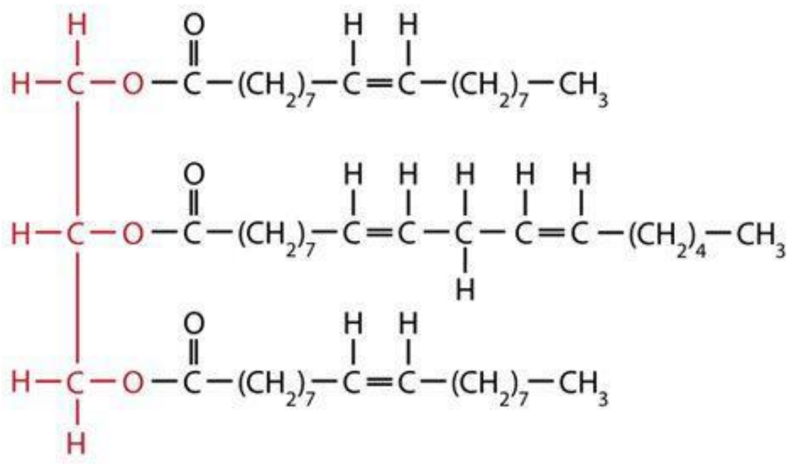

Figure 2: Typical Canola oil triglyceride**.**

Lambda Calculations

Based on the explanations given on one of the previous documents let's proceed with a couple of examples.

Suppose we have 1 mol of canola oil biodiesel, and we are going to use 30 mol of air to burned it. That means that our measured AFR will be:

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{(28.85) * (30)}{281.46} = 3.07$$

Given AFR we can computeλ,

Lambda Calculations

Based on the explanations given on one of the previous documents let's proceed with a couple of examples.

Suppose we have 1 mol of canola oil biodiesel, and we are going to use 30 mol of air to burned it. That means that our measured AFR will be:

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{(28.85) * (30)}{268.441} = 3.22$$

Given AFR we can compute λ,

$$\lambda = \frac{AFR}{AFR_{stoich}} = \frac{3.22}{12.30} = 0.26$$

As expected, λ is very low since the air-fuel mix is rich in biodiesel.

Now, for a mix with excess of air and for one mol of biodiesel we have:

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{(28.85) * (300)}{268.441} = 32.24$$

Given AFR we can compute that in this case λ is higher than 1 because the mix is poor on fuel and rich on air.

Sunflower Oil Biodiesel Air-Fuel Ratio Calculation

Sunflower Oil Biodiesel Composition To determine the formula of the biodiesel 3 different papers where consulted. All 3 papers agree that biodiesel produced from sunflower oil has different compounds in it.

Reference number one [10]uses Gas-Chromatography (GC) to determine composition of the synthesized sunflower oil biodiesel showing 11 different compounds. Reference number [2]uses GC as well but in a less sophisticated way. Reference 3 uses Nuclear Magnetic Resonance (NMR).

By cross-referencing data from all 3 papers, it was decided to use the formula found on reference number: [11] $C_{20}H_{38}O_2$.

Balancing the Equation

The unbalanced equation is as follows:

$$\mathrm{C_{20}H_{38}O_2} + O_2 \rightarrow CO_2 + H_2O$$

To balance this equation, we will use the algebraic method. First let’s write our unknowns:

$$\mathrm{aC_{20}H_{38}O_2} + bO_2 \rightarrow cCO_2 + dH_2O$$

Now, let's write all equations:

$$20a = c \qquad (i)$$

$$38a = 2d \qquad (ii)$$

$$2a + 2b = 2c + d \qquad (iii)$$

Since we will be calculating Air Fuel Ratio, we need to burn 1 mol of fuel which means $a = 1$, and by solving eq. i-iii we have: $b = \frac{57}{2}$, $c = 20$ and $d = 19$.

Air-Fuel Ratio

Molar mass of biodiesel and Oxygen are 310.522 $\frac{gram}{mol}$ and 31.998 $\frac{gram}{mol}$.

Mass of air required for total combustion will be:

$$m_{air} \frac{57/2}{0.21} * 28.85 = 3915.23\ grams = 3.9152\ Kg$$

On the other side, 1 mol of sunflower oil biodiesel is equivalent to $0.3105 Kg$.

The stoichiometric Air-Fuel Ratio (AFR_{stoich}) is calculated:

$$AFR_{stoich} = \frac{m_{air}}{m_{fuel}} = \frac{3.9152}{0.3105} = 12.61$$

Lambda Calculations

Lambda (λ) is defined as follows:

$$\lambda = \frac{AFR}{AFR_{stoich}}$$

Where AFR is the measured value in a particular system.

This definition has a couple of implications, first a $\lambda = 1$ will be reached when measured AFR is equal to AFR_{stoich}.

Second, High values of λ or $\lambda > 1$ are defined as lean and low values of λ or $\lambda < 1$ are defined as rich making reference to richness or lack of fuel. Let's ilustrate this with an example. Suppose we have 1 mol of sunflower oil biodiesel, and we are going to use 30 mol of air to burned it. That means that our measured AFR will be:

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{(28.85) * (30)}{310.522} = 2.79$$

Given AFR we can compute λ,

$$\lambda = \frac{AFR}{AFR_{stoich}} = \frac{2.79}{12.61} = 0.22$$

As expected, λ is very low since the air-fuel mix is rich in biodiesel.

Now, for a mix with excess of air and for 1 mol of biodiesel we have:

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{(28.85) * (300)}{310.522} = 27.87$$

Given AFR we can compute λ,

$$\lambda = \frac{AFR}{AFR_{stoich}} = \frac{27.87}{12.61} = 2.21$$

In this case λ is higher than 1 because the mix is poor on fuel and rich on air.

Soybean Oil Biodiesel Composition

As mentioned before, the article [3] showed us the percentage of all different Fatty Acid Methyl Esters that formed biodiesel. The percentages for Soybean oil biodiesel is tabulated in Table 2:

Table 2: The percentages for Soybean oil biodiesel.

Substance	**Wt %**
Palmitic Acid	10.32
Stearic Acid	3.99
Oleic Acid	22.42
Linoleic Acid	53.48
Linolenic Acid	7.82
Arachidic Acid	0.54
Icosenoic Acid	0.30
Behenic Acid	0.56

When averaged they gives the same result as Canola Oil.

$$C_{18}H_{33}O_2$$

Balancing the Equation

The unbalanced equation is as follows:

$$\mathrm{C_{18}H_{33}0_2} + O_2 \rightarrow CO_2 + H_2O$$

To balance this equation, we will use the algebraic method. First let's write our Unknowns:

$$\mathrm{aC_{18}H_{33}0_2} + bO_2 \rightarrow cCO_2 + dH_2O$$

Now, let's write all equations:

$$18a = c \qquad (i)$$

$$33a = 2d \qquad (ii)$$

$$2a + 2b = 2c + d \qquad (iii)$$

Since we will be calculating Air Fuel Ratio, we need to burn 1 mol of fuel which means $a = 1$ and, by solving the equations i-iii, $b = \frac{109}{4}$, $c = 18$ and $d = 33/2$.

Air-Fuel Ratio

Molar mass of biodiesel and Oxygen is 281.46 $\frac{gram}{mol}$ and 31.998 $\frac{gram}{mol}$.
Mass of air required for total combustion will be:

$$m_{air}\frac{101/4}{0.21} * 28.85 = 3468.92\ grams = 3.468\ Kg$$

Where 28.85 is the molecular weight of air. There we assumed a composition of air of 79% N_2 and 21% O_2.

On the other side, 1 mol of soybean oil biodiesel is equivalent to $0.281Kg$.

The stoichiometric Air-Fuel Ratio (AFR_{stoich}) is calculated:

$$AFR_{stoich} = \frac{m_{air}}{m_{fuel}} = \frac{3.468}{0.281} = 12.34$$

Lambda Calculations

Based on the explanations given on one of the previous documents let's proceed with a couple of examples.
Suppose we have 1 mol of soybean oil biodiesel, and we are going to use 30 mol of air to burned it. That means that our measured AFR will be:

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{(28.85) * (30)}{281.46} = 3.07$$

Given AFR we can compute λ,

$$\lambda = \frac{AFR}{AFR_{stoich}} = \frac{3.07}{12.34} = 0.25$$

As expected, λ is very low since the air-fuel mix is rich in biodiesel.

Now, for a mix with excess of air and for one mol of biodiesel we have:

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{(28.85) * (300)}{281.46} = 30.75$$

Given AFR we can compute λ,

$$\lambda = \frac{AFR}{AFR_{stoich}} = \frac{30.75}{12.34} = 2.49$$

In this case λ is higher than 1 because the mix is poor on fuel and rich on air.

Advantages of biodiesel Combustion

Environmental Benefits

Biodiesel combustion presents multiple environmental benefits by reducing harmful emissions and mitigating climate change. As a renewable fuel derived from organic sources, it significantly reduces greenhouse gas emissions compared to conventional fossil fuels, improving air quality and public health. More specifically, biodiesel combustion significantly reduces carbon dioxide emissions as feedstock plants absorb carbon dioxide during their growth, creating a closed carbon cycle [17]. Besides, they can decrease total hydrocarbons, polycyclic hydrocarbons, and sulfur emissions by 67%, 80%, and 100% respectively, which essentially improves urban air quality and public health [24]. Biodiesel is biodegradable, posing less pollution risk. Besides, its non-toxic, which makes it safer for handling and decreases pollution hazards. Biodiesel combustion lowers nitrogen oxide emissions and particulate matter, which are associated with respiratory sicknesses. Consequently, it contributes to a healthier environment for urban populations.

Engine Performance Enhancement

Biodiesel combustion enhance engine performance, identifying it as a viable alternative to traditional diesel fuels. Its unique properties, including its superior cetane number and better lubrication improves combustion efficiency and decreases emissions. Existing studies indicate that biodiesel's increased cetane number improves ignition quality, leading to more effective combustion [25]. Similarly, biodiesel combustion considerably decreases harmful emissions when optimized with unique engine designs, whiles its unique molecular structure lowers particulate matter emissions, improving environmental benefits [26]. Mixing biodiesel with additives, such as eco-diesel can optimize engine performance, realizing notable increases in torque and power output. Preheating biodiesel using exhaust gas energy improves engine power and decreases specific fuel consumption by up to 8.27% [27].

Renewable Resource

As a renewable resource, biodiesel combustion has many environmental benefits and sustainability. Biodiesel is often derived from organic materials; thus, reduces greenhouse gas emissions and offers a cleaner alternative to fossil fuels. Biodiesel is biodegradable and non-toxic, which makes it safer for the environment in case of spills. On the other hand, the carbon released during diesel combustion is offset by the carbon absorbed during biomass growth, contributing less to global warming [28]. Biodiesel is generated from renewable sources, including animal fats, vegetable oils, and waste cooking oils, promoting sustainable supply. Moreover, it has superior cetane number, enhancing combustion efficiency compared to traditional diesel. Lastly, biodiesel has a higher flash point (150ºC), which makes it less volatile and safer to transport and handle compared to petroleum diesel.

Improved Combustion Efficiencies

Biodiesel has many advantages when used as an alternative for traditional diesel. One of the most significant advantages of biodiesel combustion is positively impacting the environment. Due to its biodegradable and non-toxic nature, it decreases the risk of environmental contamination compared to petroleum-based diesel. More specifically, biodiesel combustion emits no sulfur and fewer carbon monoxides, particulate matter, smoke, and hydrogen carbon [29].

Challenges and Limitations

Trade and Policy Constraints

Trade and policy constraints concerning biodiesel combustion can hinder its prevalent adoption, such as non-tariff barriers, feedstock competition, and the necessity for strong regulatory frameworks to ensure sustainable and fair practices [30]. A lack of clear and consistent regulations concerning biodiesel generation, quality standards, and environmental impact assessments creates uncertainty and hinder investment. Non-tariff barriers, including quality standards, labelling requirements, and phytosanitary regulations can considerably influence biodiesel trade, particularly emerging economies [31].

Economic and Infrastructure Barriers

Emerging economies may encounter difficulties in accessing international markets because of increased production costs, lack of infrastructure, and competition from market leaders. Besides, some feedstocks are highly perishable and demand specialized infrastructure for biodiesel generation and storage, which limits trade opportunities.

Land Use and Environmental Impact

Expanding biodiesel production can result in deforestation, land degradation, and other environmental concerns, demanding vigilant policy planning and sustainable practices. Besides, greenhouse gases can be emitted by direct or indirect land-use changes triggered by increased biofuel production [33].

Technological and Regulatory Challenges

The technology necessary for producing specific types of biofuels, such as second-generation biofuels, is comparatively new and not fully commercialized, demanding further to advance efficiency and decrease costs R&D [32].

Combustion and Emissions Considerations

Future Prospective

Looking into the future, biodiesel combustion faces considerations concerning feedstock accessibility, production costs, environmental impacts, and the need for technological advancements to improve effectiveness and deal with challenges, such as oxidative stability and cold-flow properties. These technological advancements provide a pathway to promote production efficacy and raise quality standards [34]. Opportunities for market expansion exist due to growing awareness concerning sustainable energy sources, nurturing a conducive environment for biodiesel uptake. Government help via supportive policies, subsidies, and incentives can considerably bolster market prospects. Besides, partnership approaches with industries generating waste animal fat can guarantee a consistent and reliable supply chain for feedstock, offering a strategic advantage.

Conclusion

In conclusion, the analysis of air-fuel ratio (AFR) and lambda (λ) is essential for optimizing biodiesel combustion in internal combustion engines. The distinctive oxygenated composition of biodiesel results in a stoichiometric air-fuel ratio (AFR) of about 13.8:1, marginally leaner than conventional diesel's 14.7:1, facilitating more complete combustion and diminishing particulate matter (PM) and carbon monoxide (CO) emissions. Nevertheless, accurate lambda regulation is crucial, as biodiesel combustion presents a compromise between efficiency and emissions. A stoichiometric mixture ($\lambda=1$) optimizes power and emissions but may elevate nitrogen oxides (NOx), whereas lean combustion ($\lambda>1$) further diminishes carbon monoxide (CO) and particulate matter (PM) but intensifies NOx production at elevated temperatures. Rich blends ($\lambda<1$) reduce NOx emissions but elevate soot and CO levels. To mitigate these issues, it is advisable to implement techniques including exhaust gas recirculation (EGR), optimal injection timing, and the utilization of wideband oxygen sensors for real-time lambda monitoring. Moreover, using biodiesel (e.g., B20-B100) and investigating advanced combustion methodologies such as homogeneous charge compression ignition (HCCI) can enhance cold-start efficacy and emissions management. Future developments in AI-driven AFR calibration and sustainable feedstocks, such as algae-based biodiesel, are expected to improve combustion efficiency and mitigate environmental effects. Biodiesel is a feasible, sustainable substitute for diesel; however, its effective application relies on meticulous regulation of AFR and lambda to get optimal performance, efficiency, and emission reduction.

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