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PARTICULATE MATTER (PM): AN ANALYSIS OF THE VISUAL CHARACTERISTICS OF PM FROM RESIDUAL BIODIESEL COMPARED TO S10 DIESEL IN AN MDGT-6500 CLE ENGINE

Material Particulado (MP): uma análise das características visuais de um biodiesel residual comparado com diesel S10 em um motor MDGT-6500 CLE

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Resumo: A crescente preocupação com a qualidade do ar tem incentivado pesquisas sobre combustíveis alternativos. O material particulado (MP), principal poluente da combustão de combustíveis fósseis como o diesel, afeta a saúde e contribui para as mudanças climáticas. Este estudo compara o MP gerado pela queima de biodiesel residual (B13, B20, B30 e B40) e diesel S10, utilizando o motor MDGT-6500 CLE. A análise visa não só quantificar o MP, mas também destacar a importância de combustíveis menos poluentes. A coleta de MP foi feita com um elemento têxtil em uma câmara de desaceleração, simulando condições do coletor de exaustão. Após o teste, o elemento foi pesando antes e depois da coleta, e o MP analisado com microscópio eletrônico (SEM). A quantificação de compostos voláteis foi realizada com forno de secagem e balança de precisão. O uso de papel revestido foi escolhido pela sua eficácia e baixo custo. A adição de biodiesel resultou em uma redução de 9,42% a 68,77% nas emissões de MP nas amostras B13 a B40, comparado ao S10. A análise morfológica do MP mostrou maior deposição em S10, B20 e B40, enquanto B13 e B30 apresentaram menos acúmulo, sugerindo que o biodiesel reduz significativamente as emissões.

Palavras-chave: Material Particulado; Biodiesel; Diesel 10; Meio Ambiente; Sustentabilidade

Abstract: The growing concern about air quality has driven research on alternative fuels. Particulate matter (PM), a major pollutant from the combustion of fossil fuels like diesel, affects health and contributes to climate change. This study compares the PM generated by the combustion of residual biodiesel (B13, B20, B30, and B40) and S10 diesel, using the MDGT-6500 CLE engine. The analysis aims not only to quantify PM but also to highlight the importance of less-polluting fuels. PM collection was done using a textile element in a deceleration chamber, simulating exhaust collector conditions. After the test, the element was weighed before and after collection, and the PM was analyzed using a scanning electron microscope (SEM). The quantification of volatile compounds was performed with a drying oven and a precision balance. Coated paper was chosen for its effectiveness and low cost. The addition of biodiesel resulted in a reduction of 9.42% to 68.77% in PM emissions in the B13 to B40 samples, compared to S10. The morphological analysis of PM showed greater deposition in S10, B20, and B40, while B13 and B30 showed less accumulation, suggesting that biodiesel significantly reduces emissions.

Keywords: Particulate Matter; Biodiesel; S10 diesel; Environment; Sustainability.

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1 INTRODUCTION

In recent years, the growing concern about air quality and the impacts of atmospheric pollution has driven intense research on alternative fuels. Particulate matter (PM) is one of the main pollutants resulting from the combustion of fossil fuels, such as diesel, and represents a serious threat to human health and the environment. These pollutants not only contribute to various respiratory and cardiovascular issues but also play a crucial role in climate change, directly influencing global warming.

Ideally, the products resulting from the combustion of fossil fuels, specifically diesel, should be only water (H_2O) and carbon dioxide (CO_2). Nitrogen (N_2) present in the air does not interact during the combustion process, being expelled by the exhaust system in the same way it entered the engine's combustion chamber, forming the air/fuel mixture. This phenomenon is known as ideal or complete combustion, as stated by Pustelnik (2019).

However, in practice, the situation differs from the ideal. According to Bosch (2005), diesel combustion rarely occurs completely under real conditions, often resulting in incomplete combustion that generates products such as paraffins, olefins, hydrocarbons, aldehydes, ketones, carboxylic acids, carbon monoxide, acetylenes, ethylene, hydrogen, and soot.

Albuquerque (2020) adds that the main air pollutants emitted from anthropogenic sources can be classified as conventional and non-conventional Arbex *et al.* (2012) propose another classification, distinguishing between primary and secondary pollutants. Primary pollutants are those emitted directly into the atmosphere by industries, power plants, and internal combustion engines, including sulfur dioxide, nitrogen oxides, particulate matter, carbon monoxide, and volatile organic compounds. Secondary pollutants, on the other hand, arise from chemical reactions caused by the photochemical oxidation of volatile organic compounds, catalyzed by nitrogen oxides in the presence of ultraviolet sunlight.

Particulate matter (PM), also known as soot, is defined by Heywood (1998 *apud* Lehmann, 2015) as a material resulting from the combustion of carbon that has absorbed organic compounds. PM is a product of the incomplete combustion of hydrocarbons in fuel, as well as from the engine's lubricating oil. It is generated at temperatures above 500 ºC and is primarily composed of carbon (C) and hydrogen (H), with a diameter ranging from 15 to 30 µm (Lehmann, 2015). The environmental effects of PM include damage to vegetation, reduced visibility, and soil contamination (Albuquerque, 2020).

Braun *et al.* (2004) emphasize that one of the major concerns regarding diesel cycle engines relates to their emissions, specifically nitrogen oxides and particulate matter, when compared to Otto cycle engines using gasoline or ethanol. In this context, there is encouragement for the use of vegetable oils, waste, and animal fats, aimed at reducing emissions of particulate matter, carbon monoxide, carbon dioxide, as well as nitrogen and sulfur oxides.

In this context, biodiesel stands out as a promising alternative, not only due to its less polluting properties but also because it can be produced from waste, promoting sustainability. The use of biofuels, such as biodiesel, can reduce dependence on fossil fuels and consequently decrease greenhouse gas (GHG) emissions, which are the primary drivers of climate change. Decarbonization, an urgent global objective, underscores the need for a transition to cleaner, renewable energy sources, highlighting the relevance of alternative fuels in combating the climate crisis.

One of the most interesting and innovative sources for biodiesel production is residual oil, especially used cooking oil, which, if improperly disposed of, can pose serious environmental risks. Using this waste for biodiesel production not only helps reduce environmental pollution but also promotes the reutilization of resources that would otherwise be improperly discarded. The transformation of residual oil into biodiesel follows a circular economy logic, where waste becomes a resource, contributing to the reduction of environmental impact.

In this context, residual canola oil, *Brassica napus*, an oilseed widely cultivated in Brazil, has gai-

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REA - Revista de estudos ambientais (Online)
v. 26, n. 1, p.49-64, jan./jun. 2024

ned prominence as a raw material for biodiesel production. In addition to being a viable alternative for waste reutilization, canola oil has chemical characteristics that are favorable for biodiesel production, with a high oil content and low impurity levels. In the Brazilian scenario, where canola has become an important crop for agribusiness, the use of residual canola oil represents an opportunity to add value to an agricultural waste, while also promoting the development of a more sustainable and less fossil fuel-dependent energy sector.

The recent “Future Fuel Bill” in Brazil seeks to encourage the adoption of biofuels, such as biodiesel, through tax incentives and regulations that promote sustainable development. This legislation reinforces the need for investments in technologies that reduce GHG emissions, aligning with the global movement toward a cleaner energy matrix.

The analysis of the visual characteristics of particulate matter generated by the combustion of different types of fuels is fundamental to understanding their environmental and public health implications. Biodiesel, especially residual biodiesel, presents a distinct chemical composition compared to diesel S10, which can influence the formation and morphology of the particles emitted during combustion. This article proposes to investigate these differences through a comparative study, emphasizing the importance of less polluting fuels in mitigating climate change.

The MDGT-6500 CLE engine was selected for this analysis due to its relevance in the diesel engine market and the possibility of rigorous control of operational conditions. The choice of residual biodiesel, obtained from used oils, highlights its viability and eco-efficiency, aligned with the principles of the circular economy. The research aims not only to evaluate the quantity of particulate matter generated but also to investigate its physical and chemical characteristics.

Characterizing particulate matter is crucial to understanding its behavior and effects. Different fuels can result in varied particle morphologies and sizes, influencing their toxicity and deposition potential in human lungs. The visual analysis of PM, using microscopy techniques, will allow for a more precise evaluation of the differences between the two studied fuels.

Moreover, the comparison between residual biodiesel and diesel S10 opens avenues for discussions on public policies related to the use of alternative fuels and their implications for air quality. Although environmental regulations have encouraged the use of biodiesel, it is essential to understand how these fuels behave in terms of pollutant emissions to ensure the effectiveness of such policies.

Through this study, we hope to contribute to the understanding of particulate matter emissions in diesel engines, providing data that can inform decisions both in the industry and in the formulation of environmental policies. Analyzing the visual characteristics of PM generated by different fuels is an important step in the pursuit of more sustainable solutions for the transportation sector.

Thus, this article presents a detailed approach to the particulate matter resulting from the combustion of residual biodiesel, derived from residual oil of *Brassica napus*, and diesel S10 in an MDGT-6500 CLE engine, offering valuable insights for future research and practical applications in the field of biofuels and pollution control.

2 MATERIALS AND METHODS

The research uses residual biodiesel samples from *Brassica napus*, also known as canola, with different blend ratios. All the samples, B13 (13%), B20 (20%), B30 (30%), and B40 (40%), are compared with conventional Diesel S10 fuel oil. It is important to note that the blend percentages of the biodiesel samples refer to biodiesel/diesel mixtures. For example, B13 refers to a 13% biodiesel proportion in the biodiesel/diesel blend. The same logic applies to the other biodiesel samples.

The analysis of particulate matter (PM) retained in the samples was performed using a textile ele-

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v. 26, n. 1, p.49-64, jan./jun. 2024

ment. To quantify the weight of volatile compounds present in the textile material, nine specimens with the same length and width dimensions as the samples used in the particulate matter test were employed. All specimens were weighed on an analytical balance, model AUY220 from Shimadzu, and labeled in Petri dishes. Before collecting the particles, the filter is precisely weighed to determine its initial weight (m_0). The weight of the filter is crucial for the correct quantification of the collected particles. The filter is placed on a precision balance, usually with high sensitivity, to ensure the initial measurement is accurate, with precision in the milligram (mg) range.

The specimens were then simultaneously subjected to a microprocessor-controlled oven, model Q317M-23, manufactured by Quimis Scientific Equipment Ltda. The oven temperature was set to 260°C, simulating the conditions of the deceleration chamber at the beginning of the exhaust collector, with a dwell time of 17 minutes, the same duration adopted for the PM test.

The gravimetric process to determine the particle load in diesel engines involves measuring the number of particles present in the engine's exhaust gases using a direct weighing technique of a collected sample. The goal is to quantify the particulate matter (PM) emission generated by the fuel combustion in the diesel engine, which is essential for pollution control and compliance with environmental regulations.

The first step of the gravimetric process is the collection of particles generated by the diesel engine. For this, the sampling system usually consists of a high-efficiency filter placed in a sampling line connected to the exhaust gas outlet of the engine (usually in the exhaust pipe). The collection of particulate matter (PM) was performed using a deceleration chamber located at the beginning of the exhaust collector. To optimize the capture of PM, care was taken to avoid reducing the gas outlet pressure in the collector, as this could affect the measurement of combustion gases at the end of the exhaust pipe.

A textile element, placed inside the deceleration chamber, was used to retain the PM. This element was weighed before being placed in the chamber and, after the fuel test was completed, it was removed and weighed again. After the weighing process, the type of fuel used was identified, and the material was stored in an airtight container, protected from light. It is important to highlight that the deceleration chamber used in the research for particulate matter collection was adapted from the metal casing of an Otto cycle engine fuel filter, which was already available and no longer in use at the Motor Laboratory of the Federal Institute of Education, Science, and Technology of Rio Grande do Norte. This example illustrates the reuse of materials that, at first glance, would have no further utility, thus promoting the policy of resource recovery.

The diesel engine is then operated, and the exhaust gases are directed through the sampling system to the filter, where particles generated by the combustion of diesel are captured. The number of particles collected depends on various factors, such as the engine's operating regime, the type of fuel, and the operating conditions. During this process, the filter retains solid particles, which may include smoke, soot, and other materials generated by the incomplete combustion of fuel.

After the collection, the filter is carefully removed from the system and weighed again (m_1). The final weight of the filter, after collecting the particles, will be higher than the initial weight due to the amount of particulate matter retained. The final weight should be taken under controlled temperature and humidity conditions to avoid environmental factors influencing the measurement.

The amount of particles collected is then calculated by the difference between the final weight (with the particles) and the initial weight (of the empty filter):

$$\textit{Particle Load (g)} = \textit{Final Weight (g)} - \textit{Initial Weight (g)}$$

This calculation provides the amount of particles retained in the filter. This difference represents the mass of collected particulate matter and can be expressed in units such as milligrams (mg) or grams (g).

Morphological analyses of the particulate matter retained in the textile element were carried out

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REA - Revista de estudos ambientais (Online)
v. 26, n. 1, p.49-64, jan./jun. 2024

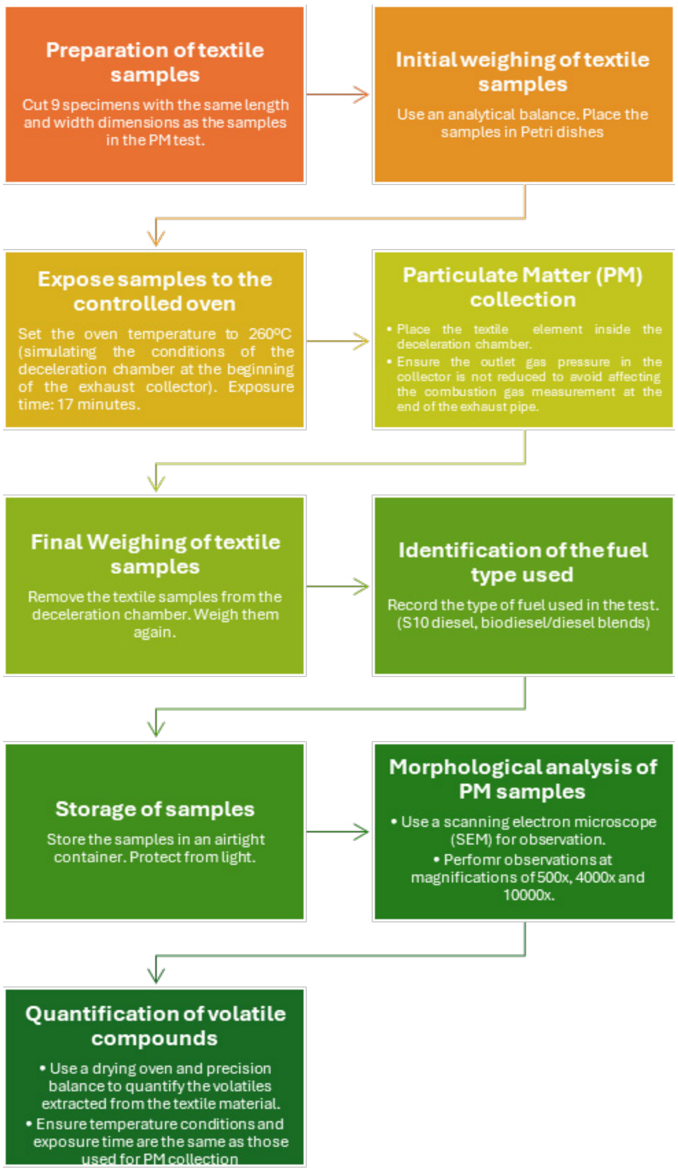
using a scanning electron microscope (SEM) available at the Mineral/Materials Characterization Laboratory - DIAREN of the same institute. Observations of the textile element samples containing the particulate matter (PM) resulting from the combustion of S10 diesel and the biodiesel/diesel blends B13, B20, B30, and B40 were conducted at magnifications of 500x, 4000x, and 10000x.

To evaluate the initial and final weight of the textile material used for capturing the PM, coated paper was employed, which was inserted into an adapted collection device attached to the exhaust system of the generator. The choice of coated paper was justified not only by the effectiveness of the method, which has been widely used in various studies, but also by its easy availability and low cost.

The quantification of the weight of the volatiles extracted from the textile material was performed using a drying oven and a precision balance in a controlled temperature laboratory environment. The temperature conditions and exposure time were kept the same as those to which the particulate matter collection apparatus was subjected.

In this sense, briefly and summarized, the methodological process for the analysis of particulate matter from the S10 diesel sample and the B13, B20, B30 and B40 samples of residual *Brassica napus* biodiesel can be described according to the following Flowchart:

Flowchart: Simplified diagram of the methodological process for the analysis of particulate matter from the S10 sample and the biodiesel samples.



Source: Authors, 2024.

3 RESULTS AND DISCUSSION

As described in the previous flowchart, the first step consists of preparing the textile samples. In this sense, it can be seen that Table 1 demonstrates the values obtained by the method used to quantify the loss of volatile materials in the textile elements present in the deceleration chamber.

Table 1 - Analysis of the Weighing of Samples of Virgin Textile Material Before and After Submission to the Drying Process.

Specimen	Weight at room temperature (g)	Weight after drying (g)	Total losses in (g)	Percentage of loss (%)
1	0,350	0,320	0,030	8,619
2	0,351	0,322	0,028	8,237
3	0,346	0,313	0,033	9,654
4	0,354	0,319	0,035	9,903
5	0,352	0,318	0,034	9,785
6	0,356	0,323	0,032	9,239
7	0,373	0,331	0,041	11,173
8	0,374	0,333	0,040	10,946
9	0,353	0,314	0,038	10,968

Source: Research Data, 2024.

With the determination of the percentage of loss of the textile material, considering the volatile components of each textile element and the results presented in Table 1, it was possible to calculate the mean and standard deviation of the percentage of loss, as recorded in Table 2. It is noted that the compounds that volatilized were analyzed under the same temperature and exposure time conditions as the textile elements subjected to the particulate deceleration apparatus.

Table 2 - Weight Loss of Textile Material Due to Volatiles Compared to Its Initial Weight.

	Weight of the textile material at room temperature (g)	Weight loss of the textile material (%)
Mean	0,357	9,836
Standard Deviation	0,009	1,044

Source: Research Data, 2024.

In this context, the mass of the textile material, previously sized in the appropriate proportions for the test, was measured before and after the capture of the emitted particulate matter, as shown in Table 3:

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REA - Revista de estudos ambientais (Online)
v. 26, n. 1, p.49-64, jan./jun. 2024

Table 3 - Analysis of the Weighing of Textile Elements Before and After the Combustion of the Evaluated Fuels.

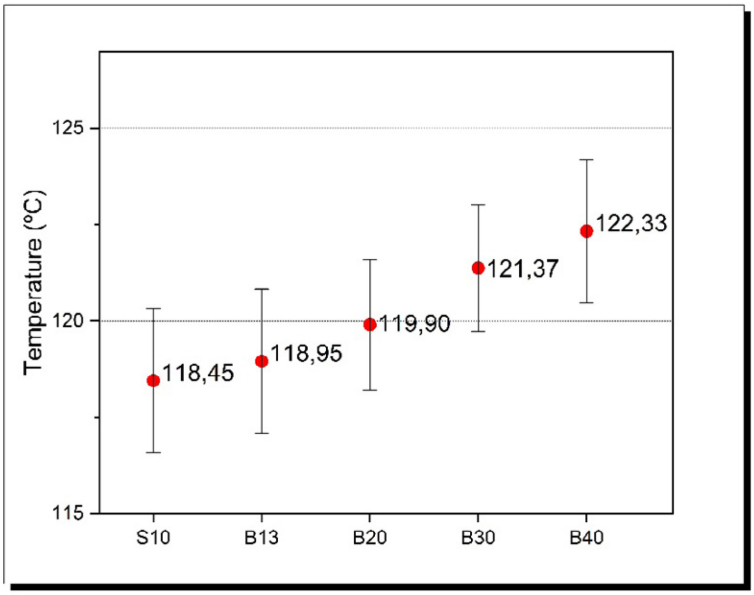
Fuel	Before (g)	After (g)	Total losses in (g)	Average temperature (ºC)	Standard Deviation of Temperature
S10	0,361	0,350	0,011	118,4	1,86
B13	0,353	0,340	0,013	118,9	1,87
B20	0,365	0,346	0,019	119,9	1,69
B30	0,358	0,334	0,024	121,3	1,64
B40	0,363	0,335	0,028	122,3	1,86

Source: Research Data, 2024.

According to what is observed in Table 1, there is evidence of mass loss of the textile material after the combustion of the evaluated fuel samples. This event characterizes the vaporization of volatile constituents present in the production process of the textile material when subjected to the temperatures of the exhaust gases in the generator's exhaust system.

This phenomenon can be visualized, as shown in Figure 1, through the average temperatures of the exhaust gases during the test.

Figure 1 - Exhaust gas temperature at the outlet of the exhaust.



Source: Research Data, 2024.

In Figure 2, it can be seen that the greatest weight loss of the textile element occurred in the test with fuel B40, resulting in approximately a 7.71% reduction compared to the weight of the textile element before being subjected to the experiment. It is noteworthy that the average temperature recorded in the apparatus where the textile element was housed was 122.3 ± 1.86°C for B40 and 118.4 ± 1.86°C for the S10 sample, as shown in Figure 1. However, the maximum difference between the temperatures recorded in both tests was 7.6°C, and the minimum difference did not exceed 0.2°C, which does not justify the substantial difference in the volatile weight loss between the S10 and B40 samples, especially considering the weight reduction observed in the textile element during the drying evaluation at

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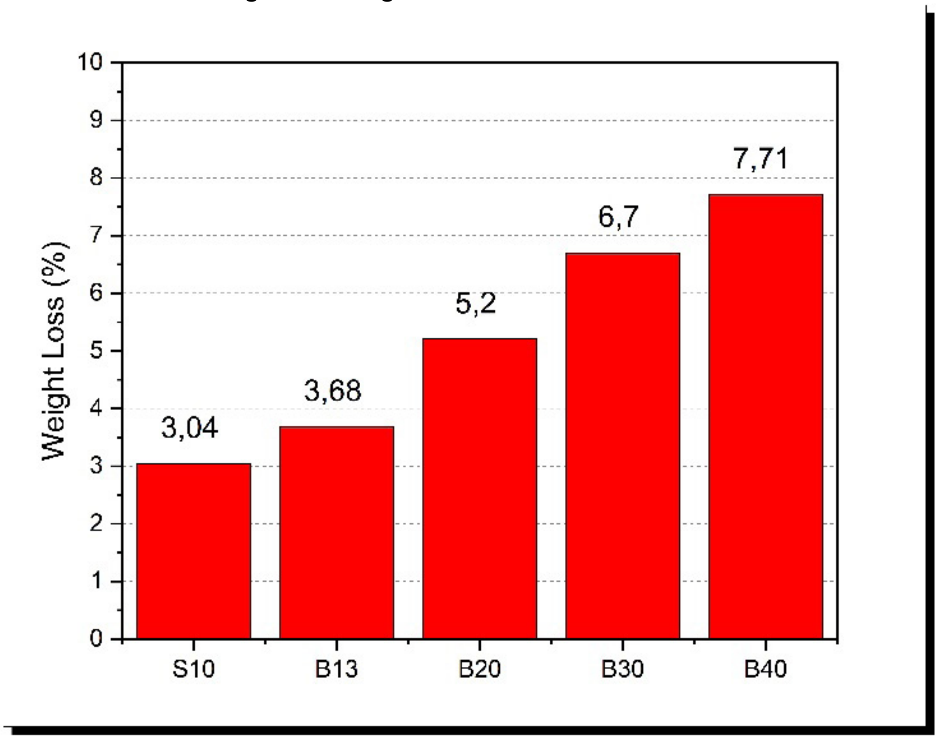
REA - Revista de estudos ambientais (Online)
v. 26, n. 1, p.49-64, jan./jun. 2024

260°C, as shown in Table 2. The hypothesis is that the temperatures found in the testing device for the analyzed fuels are close enough to be considered identical. Therefore, the influence of temperature on the elimination of volatile compounds, represented by the reduction in the weight of the textile element, is equivalent for the tested fuels. However, the difference in the results is due to the accumulation of particulate material on the textile element. On the other hand, the test with S10 fuel showed the smallest weight reduction, which was 60.6% lower than the loss observed with B40.

According to Neeft *et al.* (1996), the emission of particulate matter is attributed to sulfur, which, for example, in the case of S10 diesel fóssil fuel, up to 10 ppm of súlfur may exist. Under certain combustion conditions, sulfur becomes reactive with the oxygen generated at the end of the process, competing with the carbon that has not fully reacted. The measurement of the weight of the particulate matter deposited in the textile element is possible due to the difference between the weight of the textile after the combustion of the evaluated fuel (as shown in Figure 2) and the weight of the material lost as volatiles when exposed to the temperatures of the exhaust gases, compared to the initial weight (Figure 3).

Moreover, it was observed that there was little variation in the average temperatures of the gases with the addition of biodiesel; the largest difference recorded was between the fuels S10 and B40, with only 3.88 ºC. This small temperature variation in the tests provided similar conditions for the volatile compounds of the textile element across all samples, allowing us to conclude that there was a greater deposition of particulate matter in S10 and less in B40, as illustrated in Figure 3.

Figure 2 - Weight Loss of Textile Material.



Source: Research Data, 2024.

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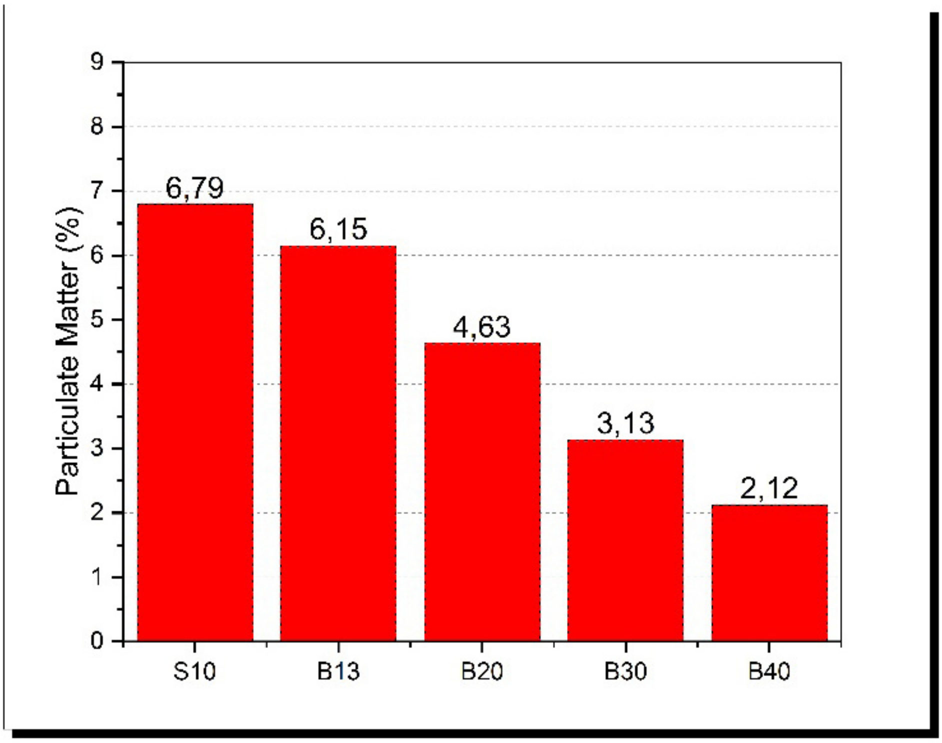
REA - Revista de estudos ambientais (Online)
v. 26, n. 1, p.49-64, jan./jun. 2024

Figure 3 - Percentage of Accumulated PM on the Textile Element.



Source: Research Data, 2024.

After performing the drying test of the textile element samples in the oven, an average reduction in the weight loss of the textile material (in %) of around 9.83% was observed in all the samples, as presented in Table 2. However, when comparing the textile material losses with the PM accumulations, represented in Figures 2 and 3, respectively, it was observed that the samples experienced increasing losses of textile material as the biodiesel proportion in the mixture increased, as illustrated in Figure 2. On the other hand, the percentage of PM accumulated in the samples decreased with the increase in the biodiesel blend, especially when compared to Diesel S10.

To make the comparison more evident, the Table 4 presents the results obtained from the weight loss of the textile material alongside the accumulated particulate matter percentage in the textile material for each residual biodiesel sample (B13, B20, B30, and B40) and for Diesel S10. It also shows the percentage reduction of PM in the residual biodiesel samples using the results obtained from S10 diesel as a reference.

Table 4 - Comparison between the weight loss of the textile material, the accumulated particulate matter percentage in the textile material and percentagem of reduction of PM.

Fuel	Weight Loss of Textile Material (%)	Percentage of Accumulated PM (%)	Percentage of reduction of PM (%)
S10	3,04	6,79	-
B13	3,68	6,15	9,42
B20	5,20	4,63	31,81
B30	6,70	3,13	53,90
B40	7,71	2,12	68,77

Source: Research Data, 2024.

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REA - Revista de estudos ambientais (Online)
v. 26, n. 1, p.49-64, jan./jun. 2024

The reduction of PM in the samples B13, B20, B30, and B40 was 9.42%, 31.81%, 53.90%, and 68.77%, respectively, compared to S10 diesel, indicating a clear decrease in particulate emissions as the proportion of biodiesel increased.

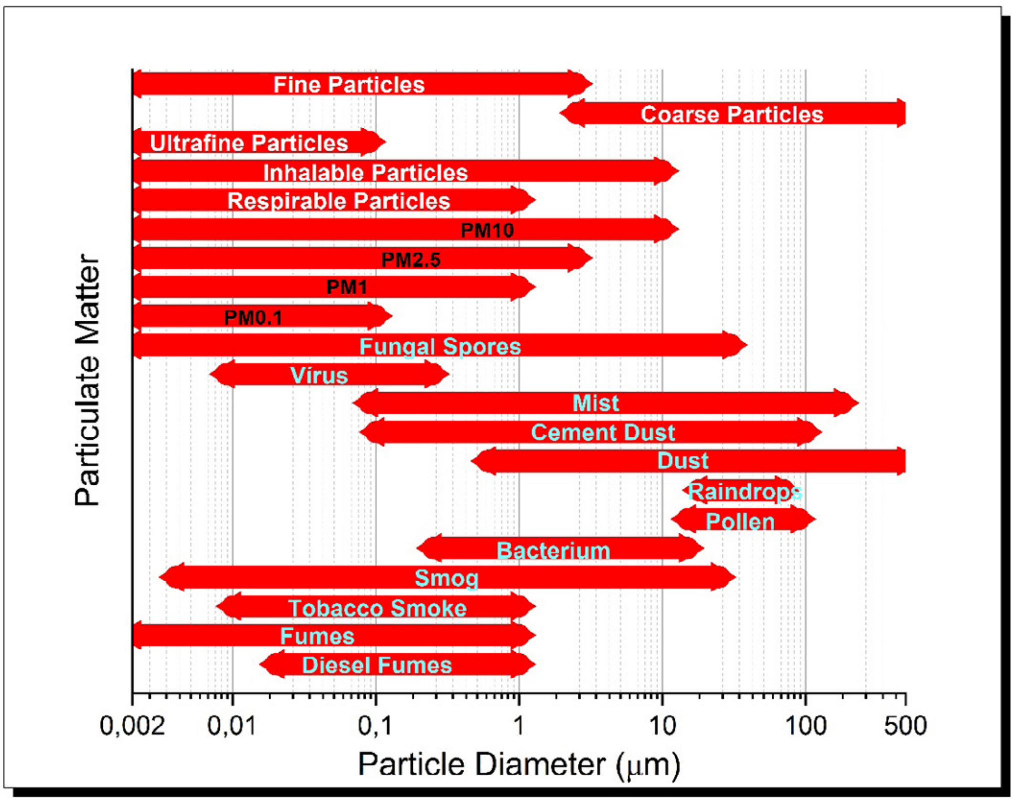
The analysis of particulate matter in the textile element, which should have included morphological observation and EDS testing, was limited to the morphological analysis of the S10 diesel samples and the biofuels B13, B20, B30, and B40. For better visualization of the retained material, the analysis of the coated paper in its virgin state was also conducted. This means that the morphological verification process applied to the samples was repeated on the pure textile element, without any traces of residues from the combustion of the fuel.

It is important to emphasize that the textile material was not used as a filter for capturing PM with specific dimensions, but rather as a support that retains particles through deposition in its structure during the combustion of the analyzed samples.

Figure 4, which illustrates the classification, size, and origin of particulate matter, is crucial for understanding the behavior of the PM generated during the combustion of the analyzed fuels — residual biodiesel and S10 diesel. Particulate matter is primarily classified by its size, which can be divided into PM2.5 (particles with a diameter smaller than 2.5 micrometers), PM10 (smaller than 10 micrometers), and other groups, each with different effects on human health and the environment.

For a better understanding of the dimensions, classifications, and sources of PM, Brito *et al.* (2018) present the following information in Figure 4:

Figure 4 - Classification, Size, and Source of Atmospheric Particulate Matter.



Source: Adapted from Brito *et al.* 2018.

In Figure 5, the samples of textile material containing PM captured after the combustion of fuels S10, B13, B20, B30 and B40 are presented at 500x magnification. It is worth noting that the samples analyzed in the SEM correspond to the same samples from all previous tests. Only fragmentation of

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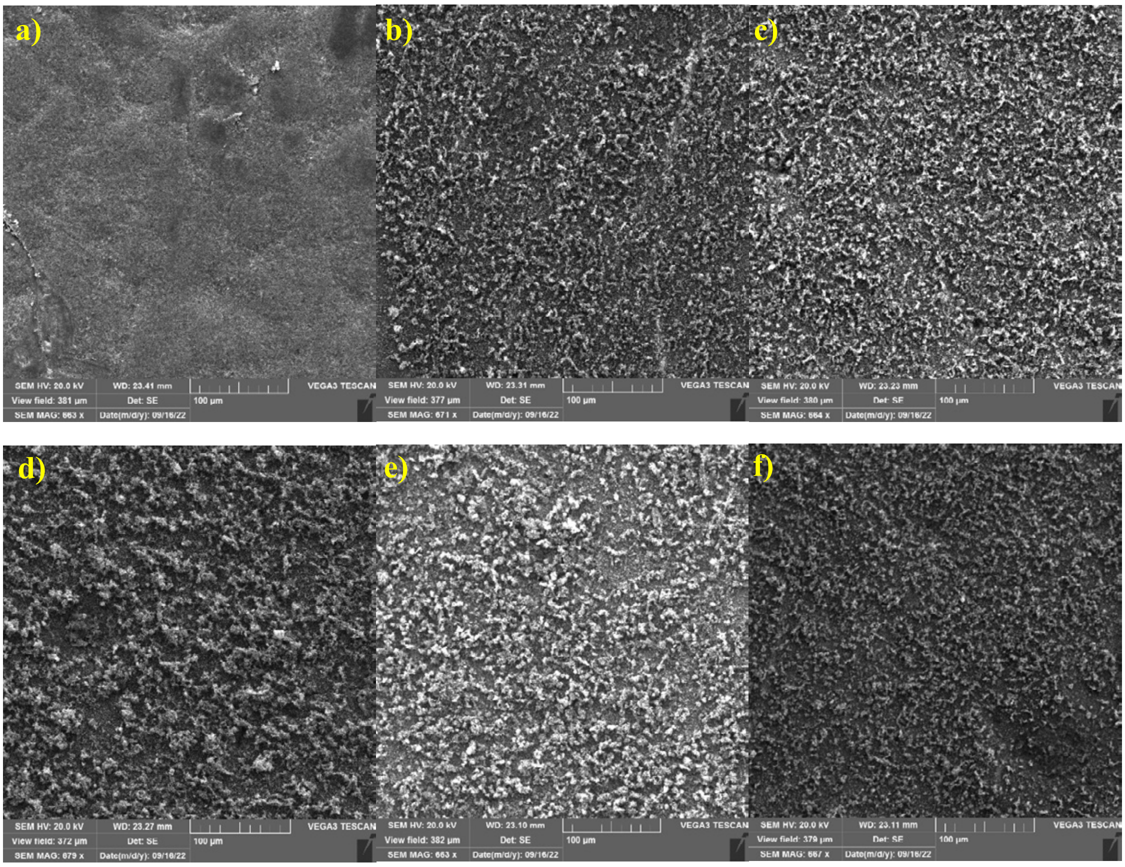
REA - Revista de estudos ambientais (Online)
v. 26, n. 1, p.49-64, jan./jun. 2024

the sample for analysis occurs. The SEM is capable of providing clear images of the accumulation of particulate material on the textile element, highlightinh the surface topography of a material. It is worth noting that the sample aligned in the SEM represents a fragment of the textile element. The fragmented sample represents the part with the highest visual accumulation of particulate matter (PM). Thus, it does not represent the total sample of the textile element.

Figure 5 shows that sample “a”, corresponding to the textile element in its virgin state, presents a visibly smooth and clean surface, without residue, when compared to the other samples. Samples “b” (S10), “c” (B13), “e” (B30) and “f” (B40) reveal the retention of particulate matter in an aggregated and close manner. Sample “d”, referring to B20, showed a more dispersed distribution, suggesting a possible release of PM in smaller quantities compared to the others.

It is important to highlight that the morphological observation has a partially qualitative nature, focusing on morphology, dimensions, and sizes, but does not allow for the identification of the components, substances, or the quantity (mass) present in the samples. The amount of PM emitted during the combustion process is related to the time the internal combustion engine (ICE) is in operation. Additionally, in the image, it is not possible to measure the sizes and dimensions of the particulate matter due to the level of magnification used.

Figure 5 – a) Morphological sample of virgin textile material at 500x magnification; b) Morphological sample of S10 textile material at 500x magnification; c) Morphological sample of B13 textile material at 500x magnification; d) Morphological sample of B20 textile material at 500x magnification; e) Morphological sample of B30 textile material at 500x magnification; f) Morphological sample of B40 textile material at 500x magnification.



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v. 26, n. 1, p.49-64, jan./jun. 2024

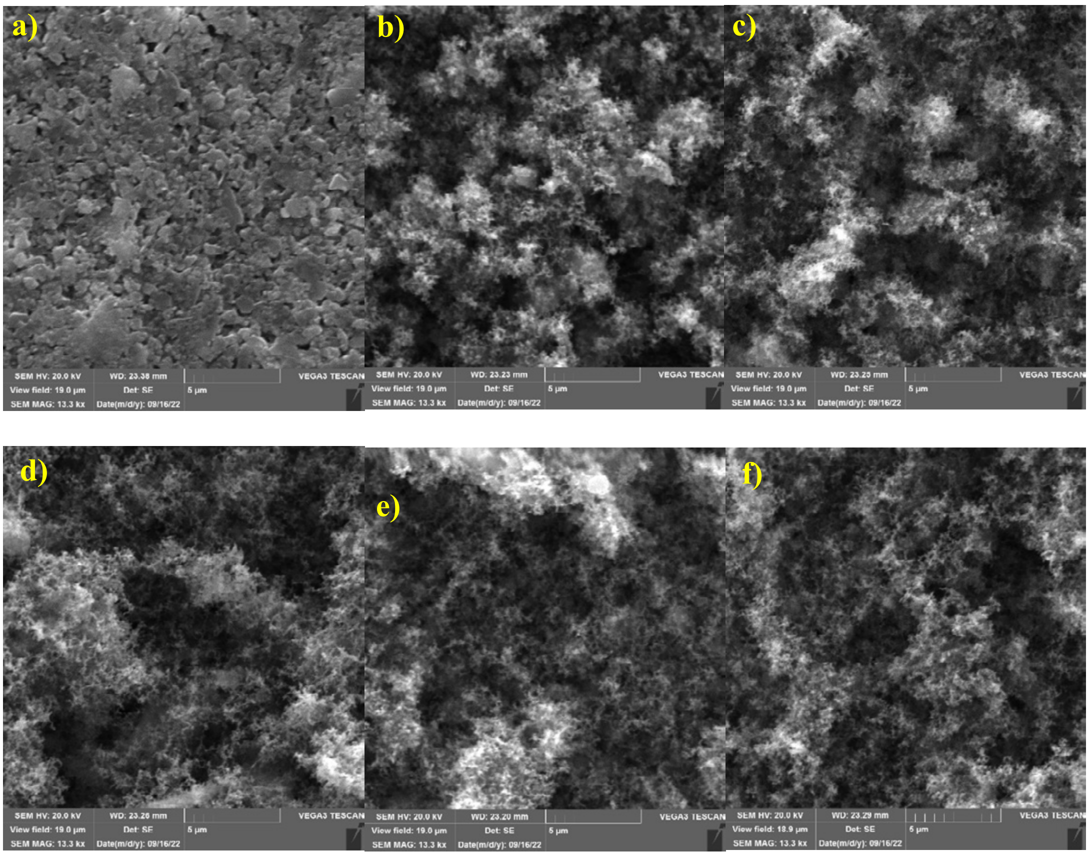
In Figure 5, especially in samples “b,” “c,” “d,” “e,” and “f,” the formation of small spheres grouped in chains, with little separation between them, is observed, characterizing particles emitted by biofuels, as described by Micic *et al.* (2003 *apud* Rosasco *et al.* 2011).

In Figure 6, it can also be observed that the PM retained in the textile component was distributed uniquely for each fuel sample subjected to the combustion process. At a magnification of 10,000x, the morphological characteristics of samples “b,” “c,” “d,” “e,” and “f” maintain a similar pattern. Generally, at this level of magnification, the particulate matter (PM) exhibits undefined dimensions. Brito *et al.* (2018) note that the particles released from diesel emissions are fine and ultrafine, allowing for the analysis of their shapes and dimensions through high magnifications.

Samples “c,” “d,” “e,” and “f,”, in Figure 6, corresponding to fuels B13, B20, B30, and B40, showed similarities, with records of some peak areas, although in smaller quantities compared to sample “b” (S10), which exhibited a greater presence of gray-colored regions. This indicates a lower deposition of PM in samples “c,” “d,” “e,” and “f.”

Sample “b,” as illustrated in Figure 6, related to S10 diesel, revealed areas with a greater clustering of PM, suggesting a significant accumulation of particulate matter. It is worth noting that the lighter-colored regions indicate areas with a higher concentration of particulate matter, considering that the image captured by the SEM provides a sense of depth of the analyzed element.

Figure 6 – a) Morphological sample of virgin textile material at 10000x magnification; b) Morphological sample of S10 textile material at 10000x magnification; c) Morphological sample of B13 textile material at 10000x magnification; d) Morphological sample of B20 textile material at 10000x magnification; e) Morphological sample of B30 textile material at 10,000x magnification; f) Morphological sample of B40 textile material at 10000x magnification.



Source: Research Data, 2024.

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REA - Revista de estudos ambientais (Online)
v. 26, n. 1, p.49-64, jan./jun. 2024

Guimarães *et al.* (2018) emphasize that the opacity of particulate matter generated during the combustion of fuels is directly related to the ability of light to pass through this material. In simple terms, the darker and more opaque the emitted smoke, the greater the amount of particulate matter released during the combustion process.

The morphological analysis of the particulate matter retained in the textile component, resulting from the combustion of the fuels, revealed that the S10, B20, and B40 samples, as shown in Figure 5, exhibited darker colors, indicating a greater deposit of particulate matter. In contrast, the B13 and B30 samples displayed lighter shades. According to Duarte *et al.* (2003), the electronic image obtained in the SEM (Scanning Electron Microscope) is represented in grayscale, which involves the mapping and counting of secondary electrons (SE) and backscattered electrons (BSE) emitted by the analyzed material.

The mechanism of soot particle formation in diesel engines follows a sequence that starts with pyrolysis, the decomposition of molecules due to the high combustion temperatures. This process results in the formation of platelets that transform into microscopic crystals, known as crystallites. The union of these crystallites gives rise to turbostratic particles. Next, coagulation and surface growth occur. The subsequently grown particles form an aggregation. There is absorption and condensation of hydrocarbons. The increase in particle size throughout the formation mechanism starts with 0.35 nm as platelets and reaches from 0.1 to 10 μm in the aggregation of the grown surface particles (Olmos, *et al,* 2018; SMITH, 1981).

Upon observing the enlarged images in Figure 6, it was possible to note that the B13, B20, B30, and B40 samples appeared similar in terms of the clustering and spacing of the retained particulate matter, suggesting a lower amount of deposited material.

In contrast, the S10 sample, illustrated in Figure 5 “a,” stood out due to the higher number of peaks of particulate matter, with a light gray color and a reduced presence of dark regions compared to the other samples. It is important to emphasize that the analyses of the clustering and spacing of the particulate matter were conducted based on the image generated by the SEM.

When relating the analysis of exhaust gas temperatures to the deposit of particulate matter on the textile element, it is observed, through a 10,000x magnification that there was a greater deposition of particulate matter in the S10 sample of the textile element and less in the B40—when comparing biodiesel B40 with all other samples.

4 CONCLUSION

The use of residual oil for biodiesel production represents a practice aligned with the Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). The use of residual oils from sources such as used frying oil provides a sustainable solution for waste management, while promoting the reduction of dependence on fossil fuels.

From the perspective of the 5 R’s, the use of residual oils follows the principles of reduce and reuse. By converting discarded oil into biodiesel, we are reducing the amount of waste generated, minimizing the environmental impact associated with improper disposal. This process also reuses a material that would otherwise be considered waste, turning it into a renewable energy source.

Furthermore, the conversion of residual oil into biodiesel contributes to recycling, one of the pillars of the 5 R’s, as biodiesel is a renewable form of fuel that can replace fossil fuels. In doing so, we not only reduce greenhouse gas emissions but also contribute to the sustainability of energy processes.

Research into alternative fuels, especially biodiesel, is essential in light of growing concerns about air quality and the impacts of air pollution. This study revealed that the particulate matter (PM) generated by the combustion of residual biodiesel has different emission levels compared to S10 diesel. Measurements demonstrated that the addition of biodiesel not only reduces PM emissions, but also highlights its ability to mitigate adverse effects on human health and the environment, thus in line with Saldiva (2016), professor at USP, when stating that "the greater the blend of biodiesel without mineral diesel, the lower the emission of greenhouse gases, with a global effect, as well as toxic particulate matter, with a local impact."

The results, which showed decreases in PM emissions ranging from 9.42% to 68.77% in the biodiesel samples, reinforce the relationship between fuel composition and its emissions. This reduction is crucial, considering the role of PM in public health and climate change. The morphological analysis highlighted that residual biodiesel, obtained from used oils, is not only viable but also eco-efficient, aligning with the principles of the circular economy.

When relating the analysis of exhaust gas temperatures to the deposit of particulate matter on the textile element, it is observed, through a 10,000x magnification, that there was a greater deposition of particulate matter in the S10 sample of the textile element and less in the B40. The reduction of particulate matter in the B13, B20, B30, and B40 samples represented, in that order, the following percentages in relation to the record obtained from diesel S10: 9.42%, 31.81%, 53.90%, and 68.77%. Thus, this indicates a clear reduction in particulate emissions as the biodiesel mixture increased.

In summary, the research demonstrated the potential for using residual *Brassica napus* biodiesel in diesel cycle internal combustion engines without the need for engine modifications for fuel compatibility. Therefore, there may be the possibility of a viable opportunity to use a renewable fuel oil with a lower environmental impact compared to S10 diesel. However, it is important to verify in future studies if the use of biodiesel in concentrations higher than the current specifications could cause damage to the engines.

Moreover, public policies, such as the "Future Fuel Bill" in Brazil, emphasize the importance of encouraging the use of biofuels, reinforcing the need for investments in technologies that promote sustainability and decarbonization. Understanding PM emissions from different fuels is essential for formulating effective environmental policies and promoting more sustainable solutions in the transportation sector.

Lastly, by rethinking our approaches to waste disposal and energy production, we can move towards a circular economy model where waste is seen as a resource, not a problem. The concept of refusing can also be applied to the use of non-renewable alternatives, such as fossil fuels, favoring instead solutions based on clean, renewable energy sources.

Therefore, the production of biodiesel from residual oil is a strategy that is not only environmentally responsible but also aligned with a sustainable and resilient economy, promoting the reduction of environmental impact and advancing global sustainability goals.

Therefore, this study contributes to the understanding of the environmental and public health impacts related to the combustion of fuels, providing valuable data for future research and practical applications in the field of biofuels.

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