

Exploring The Technical Feasibility Of The Combustion Of Dissolved Polystyrene Waste In Biodiesel

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Abstract

Polystyrene is one of the most commonly used plastics due to its versatility in various industries and inexpensive cost per unit weight. However, its inability to biodegrade is cause for controversy as it commonly finds itself in the form of environmentally hazardous litter. As this controversial polymer has prompted discussions on the possible routes of non-toxic disposal, it has been found that polystyrene readily dissolves in biodiesel, allowing the disposed waste to act as a beneficial fuel additive, increasing energy value and decreasing emissions. The Sustainable Energy Technologies Department at Brookhaven National Laboratory has been tasked with examining the feasibility of combusting polystyrene-biodiesel blends in residential boilers and the factors that must be taken into account for this fuel to be considered a viable energy source. After several preliminary tests, it was determined that the long polymer chains in polystyrene significantly lower the biofuel's ability to atomize well as it passes through a nozzle, unless a change in an experimental factor occurred such as pressure increase, lower blend concentration, or alteration of the fluid properties. Further steps in exploring these solutions that will allow higher concentrations of polystyrene-biodiesel blends to be used as a valuable alternative to biodiesel will continue into the future. It might also be practical to explore alternative combustion options that include the use of diesel engines or air atomized commercial boilers.

Keywords: Combustion, Residential boiler and burners, Polystyrene-Biodiesel blends

1. Introduction

Polystyrene, whose chemical structure is shown below, is one of the most commonly used plastics due to its versatility in various industries and inexpensive cost per unit weight. However, once it has been used and is discarded, polystyrene does not biodegrade for up to hundreds of years, leaving it to sit in a landfill or fill streets and waterways as litter. This poses an environmental hazard to animals that can easily mistake the plastic as food, introducing possible toxic chemicals into the food chain. Currently, this abundant plastic is not accepted in most curbside collection recycling programs, as it is not economical to collect¹. Despite this, it has been found that while polystyrene does not degrade on its own, it does readily dissolve in biodiesel, creating a polystyrene-biodiesel blend (PS-Biodiesel)².

Lately, biodiesel has attracted a great deal of attention as a preferred choice to replace petro-diesel and consequently reduce emissions³. This has led Brookhaven National Laboratory and the Sustainable Energy Technologies Department to partner with the Agricultural Utilization Research Institute and become one of the few groups trying to change the fate of polystyrene with the help of biodiesel. This study examines the possibility of burning polystyrene-biodiesel blends and the factors that must be taken into account in order for this fuel to be considered a viable energy source. Several tests were used in this study, including combustion and emission tests, atomization tests, and quartz chamber tests.

Combustion and emissions testing determines the ability of the fuels to burn and its stability in doing so in a realistic environment. If a fuel provides a stable combustion, smoke emissions resulting from the fuel combustion can be recorded.

Atomization tests measure particle and droplet size distributions of spray solutions. These measurements provide insight into fuel characteristics and the type of combustion that will be produced. Typically, smaller droplet sizes and a wider distribution angle are ideal for combustion with most fuels. For this study, only the average volume, the D[4,3], and mean surface area, the D[3,2], were calculated to compare average droplet sizes between various PS-Biodiesel blends.

Quartz chambers are beneficial in its ability to allow flame visualization. A burner is placed so that the flame flows into the quartz chamber, whose transparency lets viewers follow the flame as it continually burns. Studying flame behavior and stability assists in understanding and hypothesizing the roles of various factors in combustion.

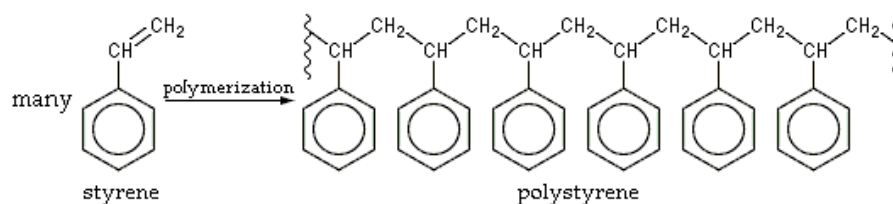


Figure 1. The chemical process of polymerization that results in the polystyrene molecule produced from several styrene molecules⁴.

2. Materials and Methods

The fuel created was composed of polystyrene dissolved in biodiesel at various concentrations. American Society for Testing and Materials (ASTM) D6751 approved biodiesel, which meets all the specification requirements that define the characterization of biodiesel, provided by Hero BX, was measured and weighed in grams before calculating a percent concentration by weight. The desired weight of standard 8.5 fl. oz. Styrofoam drinking cups were gathered and manually broken into pieces, increasing surface area and allowing the Styrofoam to dissolve easily in the biodiesel with minimal agitation. Initially, concentrations of 5% and up of polystyrene in biodiesel mixtures were created and the process recorded in Image 1 below. However, lower blend concentrations ranging from 0.1% to 1%, by weight, were also mixed.

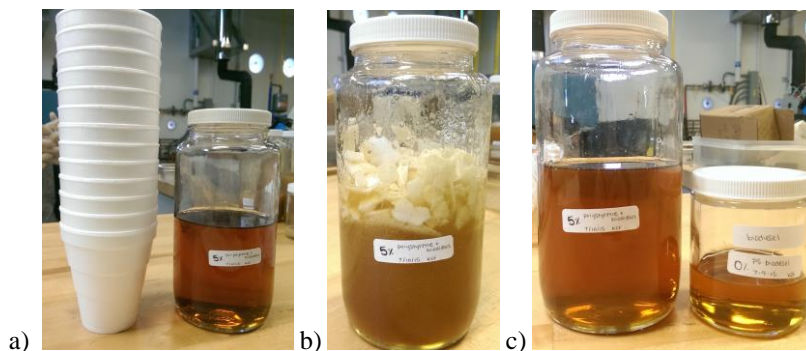


Image 1. Process of creating a 5% PS-Biodiesel blend, highlighting the a) beginning, b) middle, and c) end stages.

The combustion tests consisted of a Dunkirk residential boiler and a Carlin fuel oil burner attachment (Image 2). A two-fuel flow allowed the boiler to run 100% biodiesel during warm up and to gather control data, before switching to the various PS-Biodiesel test fuels. During the fuel combustion, a Testo 350 combustion emissions analyzer was used to record O_2 , an indication of air-fuel ratio, and CO and NO_x emissions produced from combustion.



Image 2. Dunkirk residential boiler and Carlin fuel oil burner apparatus.

Two nozzles were used for the duration of this study: a 0.65 70-degree angle Danfoss nozzle in preliminary combustion and atomization experiments, before changing to a 0.4 70-degree angle, model DoF nozzle for secondary combustion and quartz chamber tests.

A quartz chamber attachment to the Carlin burner was used for flame visualization to observe the differences in flame stability and behavior of a 100% biodiesel and a 0.5% PS-Biodiesel blend. Flame visualization was used to determine fuel characteristics through the observation of the fuel combustion. The quartz chamber apparatus is shown below in Image 3.



Image 3. Quartz chamber attachment to the Carlin fuel oil burner. The burner in this apparatus was set at 400 psi and the nozzle used was the 0.4 70-degree angle DoF nozzle.

Atomization tests were also conducted to measure and compare spray particle size and droplet size distributions between pure biodiesel (0% PS-Biodiesel), a 0.2% blend, and a 1% blend. In this test, a Malvern Spraytec Measurement Instrument was used to measure and plot average particle size distributions (PSD) as well as calculate volume mean diameter, $D[4,3]$, and surface area mean, $D[3,2]$ using laser diffraction. During this process, a low level laser shined towards a set of detectors. As a spray was sent through the beam, the small droplets caused a diffraction

of the laser beam, telling the detectors the size of the droplets. Smaller droplets created a larger diffraction while larger ones caused a smaller diffraction of the light. This process is shown in Image 5.

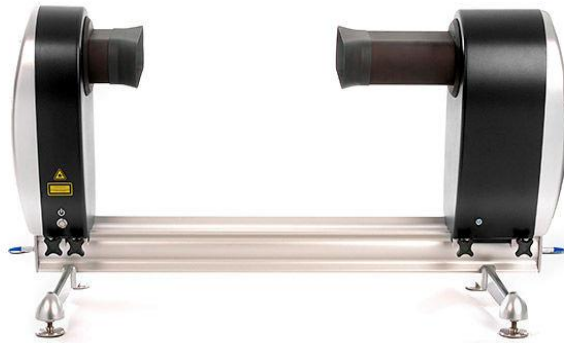


Image 4. Side view of the Malvern Spraytec measurement instrument⁵.

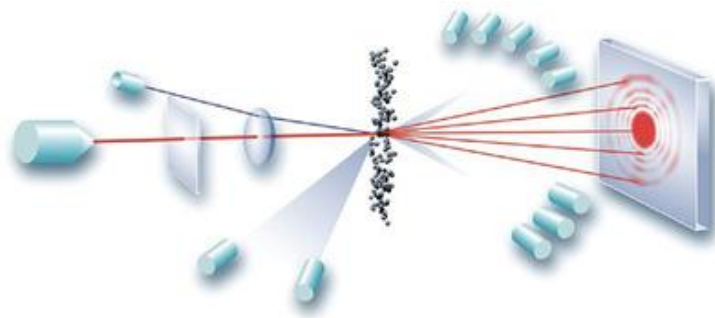


Image 5. Depiction demonstrating a laser using light diffraction to measure spray particle size in the Malvern Spraytec⁶.

3. Results

Initial combustion tests used the Danfoss nozzle in a fuel pump at approximately 100 psi, the standard pressure for home boilers. It was predicted that up to a 5% PS-Biodiesel concentration would combust easily based on prior diesel engine research, however, almost immediately the flame became unstable and shut down on flame failure. The blends were reduced to 2.5%, where the system reset again before data could be taken, and soon 1% blend concentrations, which was able to run for enough time to collect data. Figure 2(a) and 2(b) show the Oxygen levels in the chamber, detailing the flame strength and stability. These results showed Carbon Monoxide emissions from the 1% blend reached toxic levels, as shown in Figure 2(b) and 2(d).

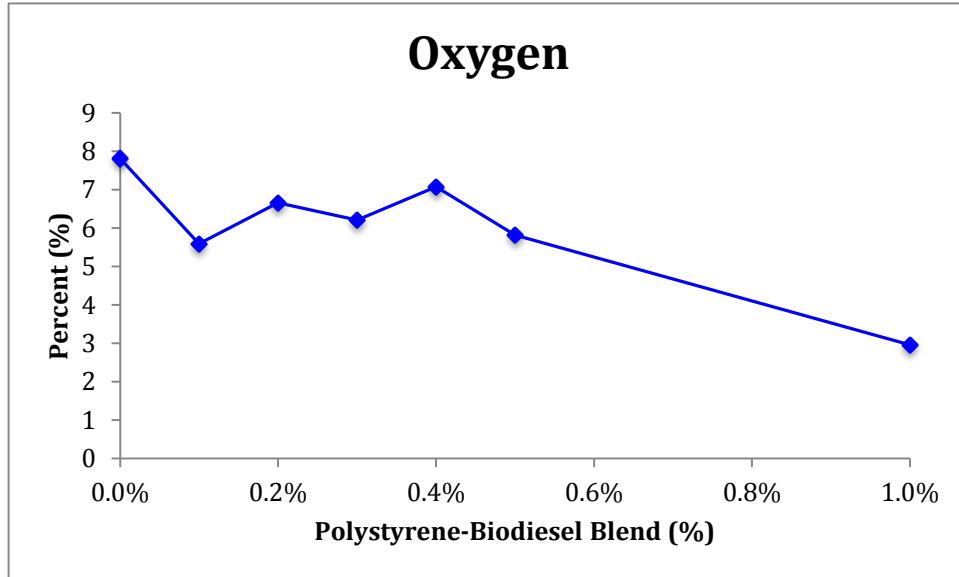


Figure 2(a). Oxygen levels, in percent, for PS-Biodiesel blends that were combusted at 100 psi through a 0.65 70-degree angle Danfoss nozzle.

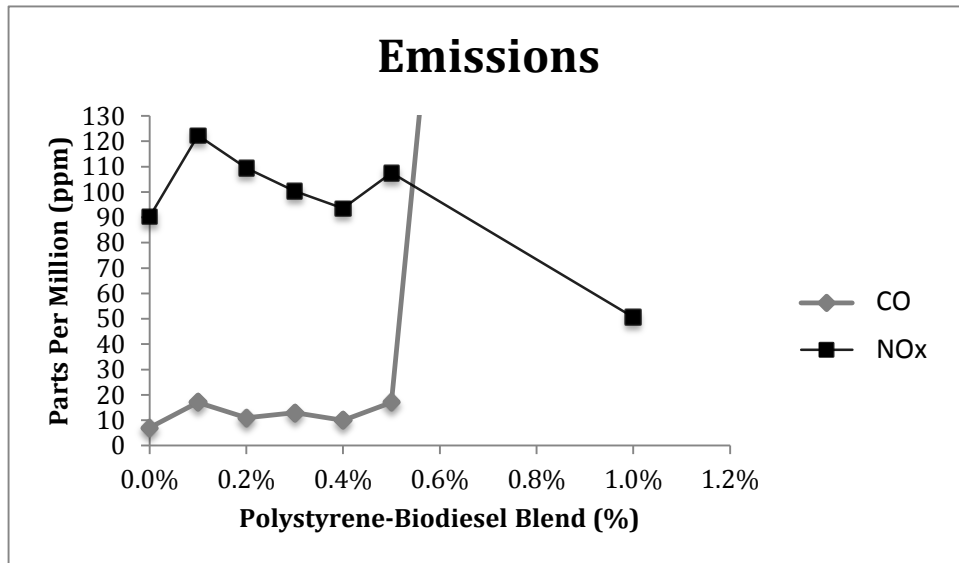


Figure 2(b). CO and NOx emissions, in ppm, for PS-Biodiesel blends that were combusted at 100 psi through a 0.65 70-degree angle Danfoss nozzle.

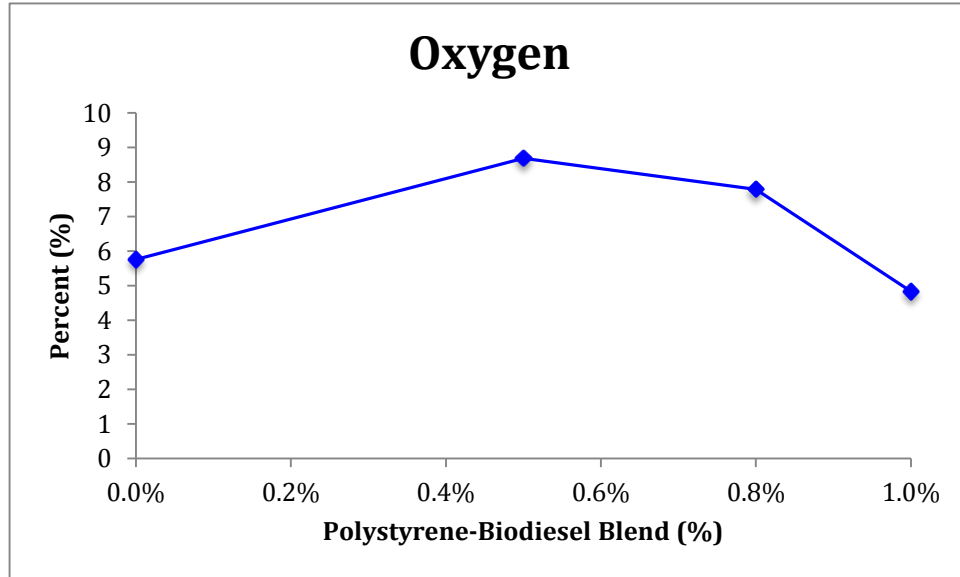


Figure 2(c). Oxygen levels, in percent, for PS-Biodiesel blends that were combusted at 400 psi through a 0.4 70-degree angle DoF nozzle.

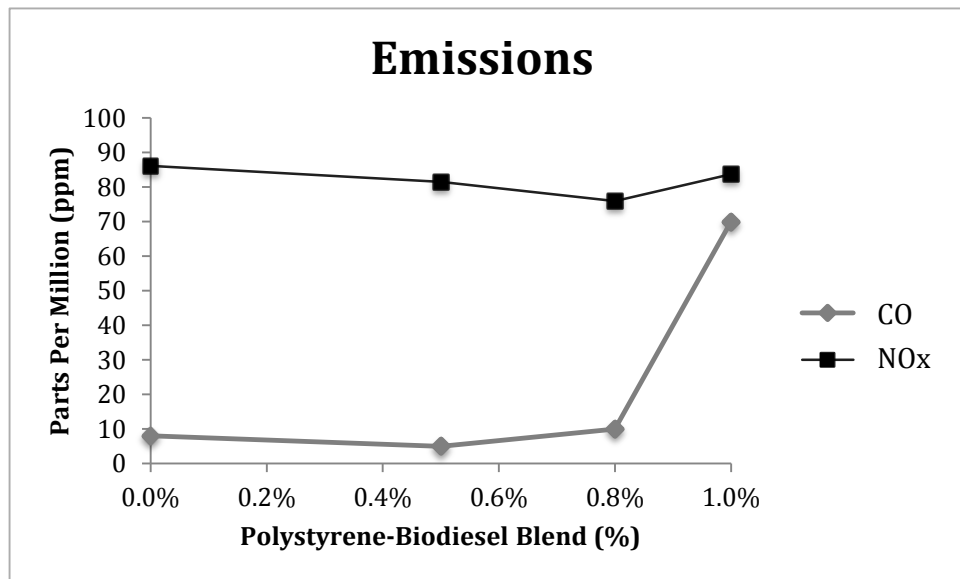


Figure 2(d). CO and NOx emissions, in ppm, for PS-Biodiesel blends that were combusted at 400 psi through a 0.4 70-degree angle DoF nozzle.

Atomization tests were run using 1% blends to measure the droplet size distribution to investigate the issues with the previous combustion tests. Using this fuel concentration, it was observed that atomization did not occur at this concentration and a cylindrical jet was expelled from the nozzle, shown in Image 6(a). A lower PS-Biodiesel concentration blend of 0.2% was mixed for testing and the average particle size obtained was compared to that of pure biodiesel (0% PS-Biodiesel), with the PSD shown in Figure 3 and calculated D[4,3] and D[3,2] comparisons in Table 1. Visual for the 0.2% PS-Biodiesel blend atomization at room temperature is provided in Image 6(b). This test used a 0.65 70-degree angle Danfoss nozzle at a system pressure of 100 psi.

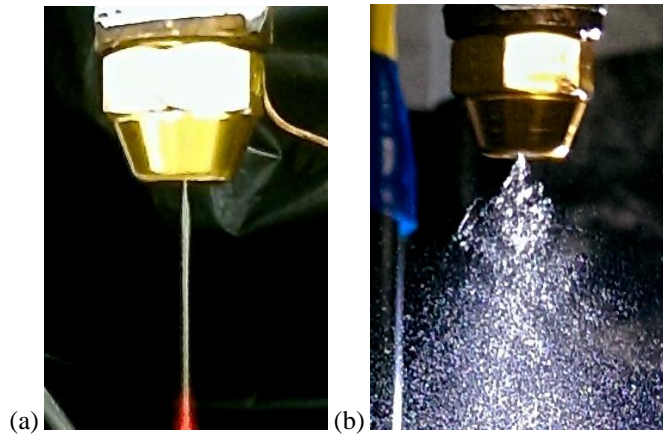


Image 6. Comparison of the atomization of 1% PS-Biodiesel (a) and 0.2% PS-Biodiesel (b) at 100 psi.

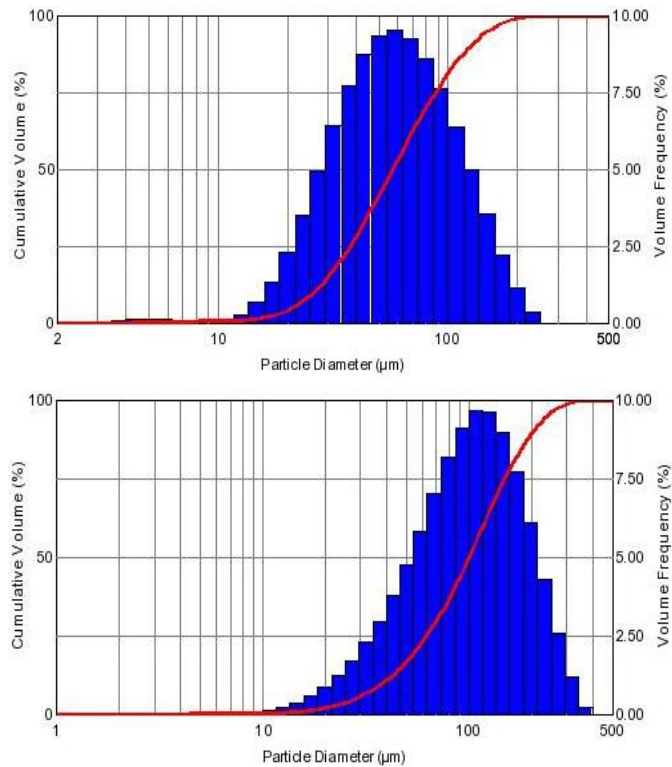


Figure 3. Comparison of the calculated average particle size droplet distributions of the atomization between 0% PS-Biodiesel (top) and 0.2% PS-Biodiesel.

	0% PS-Biodiesel	0.2% PS-Biodiesel
D[4,3]	68 μm	113 μm
D[3,2]	45 μm	69 μm

Table 1. Calculated Averages for the D[4,3] and D[3,2] of 0% PS-Biodiesel and 0.2% PS-Biodiesel

Combustion tests were then run at higher pressures of 400 psi using the DoF nozzle. Blend concentrations from 0.5% to 1% could combust at a relatively stable rate, compared to the 0.1% to 0.5% concentrations at 100 psi using the Danfoss nozzle. At PS-Biodiesel concentrations that create a stable combustion according to Oxygen levels, emissions vary slightly when compared to pure biodiesel, as depicted in Figures 2(c) and 2(d).

The quartz chamber tests comparing the combustion of biodiesel and a 0.5% PS-Biodiesel blend observed a significant increase in flame length and decrease in flame diameter, reaching the end of the chamber, with the addition of polystyrene, as seen in Image 7.



Image 7. Flame comparison in the quartz chamber between a 0% PS-Biodiesel (left) and a 0.5% PS-Biodiesel blend (right).

4. Discussion

As observed from the results, it was determined that the addition of polystyrene to biodiesel significantly reduces atomization and, therefore, combustibility of the solution. Originally, it was assumed 5% blends would be able to combust as previous experiments used these concentrations and higher. However, in those experiments, the use of diesel engines was used for combustion tests, as opposed to residential boilers⁷. This is a significant piece of information as diesel engines have system pressures varying from 500 psi up to 40,000 psi, compared to 100 psi in standard home boilers, indicating the importance of pressure in the combustion of polystyrene dissolved in biodiesel⁸. This factor of pressure is proven by the results of the combustion tests after raising the boiler/burner system pressure from 100 psi to 400 psi and reducing nozzle size from the 0.65 Danfoss to the 0.4 DoF. In initial combustion tests at 100 psi, PS-Biodiesel blends above 0.5% concentrations produced a drop in Oxygen percent levels, indicating an unstable flame. However, after the pressure increase, PS-Biodiesel concentrations up to 1% were able to burn with a relatively stable combustion.

It was discovered that the combustion failures of the blend concentrations at inadequate pressures was attributed to the long chain polymers of polystyrene molecules that lead to the reduction of fuel atomization. There was a significant increase in particle size of the 0.2% blend in comparison to 0% blend, with the concentration difference equivalent to the addition of approximately a single 4 fluid oz. Styrofoam cup in 500 mL of biodiesel. The larger droplet sizes lengthen the amount of time the fuel droplets require to be fully combusted, causing the visual flame differences in the quartz chamber tests. These observations have larger implications as they directly affect emissions. The larger droplet sizes that lead to longer combustion flames can extend beyond the boiler chamber walls, causing excess fuel to settle in the chamber. Polystyrene releases harmful emissions unless fully combusted at temperatures above 900°C⁹. Therefore, the excess fuel that is continually heated in the bottom of the chamber directly causes CO emissions to dramatically increase.

As a result of this preliminary study, it was determined that in order for PS-Biodiesel to be considered a viable fuel, the fuel's ability to atomize must be increased through changes in experimental factors, such as increased pressure, lower blend concentrations, or the additions of chemicals to change fluid properties. This should be a focal point of future studies, as well as exploring the combustion of PS-Biodiesel blends in high-pressure diesel engines or high-pressure air atomized commercial boilers. Once stable combustion is established for more varied blend concentrations, more detailed emission data set should be obtained.

5. Conclusion

This study investigated the feasibility of using dissolved polystyrene waste in biodiesel as a fuel source in combustion tests. The results show that the PS-Biodiesel blends decrease atomization, consequently increasing particle size and reducing flame stability. However, provided that the pressure was adequate enough to atomize the blend in the system, PS-Biodiesel combustion was achieved with minor changes in resulting emissions. The most practical route for future studies would explore the factor of pressure in various PS-Biodiesel concentrations and record more detailed emission measurements.

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