

SPRAY CHARACTERIZATION STUDY OF BIODIESEL MADE FROM DIFFERENT FREE FATTY ACID CONTENTS

Submitted in partial fulfilment of the requirements for the award of

Bachelor of Engineering degree in
Mechanical Engineering

By

NAGARAJU SUBBARAJU (Reg. No. 40150029)

PAMOTI SHANMUKH RAO (Reg. No. 40150033)



DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL ENGINEERING

SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with grade “A++” by NAAC

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI – 600119

APRIL 2024



SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited "A++" Grade by NAAC | 12B Status by UGC | Approved by AICTE

www.sathyabama.ac.in

DEPARTMENT OF MECHANICAL ENGINEERING

BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of NAGARAJU SUBBARAJU (Reg. No. 40150029) and PAMOTI SHANMUKH RAO (Reg. No. 40150033) who carried out the project entitled **"SPRAY CHARACTERIZATION STUDY OF BIODIESEL MADE FROM DIFFERENT FREE FATTY ACID CONTENTS"** under our supervision from December 2023 to April 2024.


Internal Guide 01/APRIL/2024.

Dr. NIVIN JOY., M.E., Ph.D.,

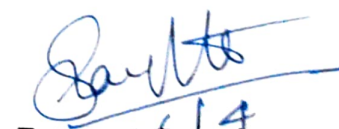

01/04/2024.

Head of the Department

Dr. S. GANESAN., M.E., Ph.D.

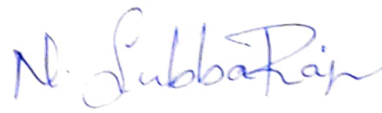
Submitted for Viva voce Examination held on 06/04/2024


06/04/2024.
Internal Examiner


6/4
External Examiner

DECLARATION

We NAGARAJU SUBBARAJU (Reg. No. 40150029) and PAMOTI SHANMUKH RAO (Reg. No. 40150033) hereby declare that the Project Report entitled "**SPRAY CHARACTERIZATION STUDY OF BIODIESEL MADE FROM DIFFERENT FREE FATTY ACID CONTENTS**" done by us under the guidance of Dr. NIVIN JOY., M.E., Ph.D., is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering degree in Mechanical Engineering.

1. 
2. 

DATE: 06/04/2024

PLACE: CHENNAI

SIGNATURE OF THE CANDIDATES

ACKNOWLEDGEMENT

I am pleased to acknowledge my sincere thanks to Board of Management of **SATHYABAMA** for their kind encouragement in doing this project and for completing it successfully. I am grateful to them.

I convey my sincere thanks to **Dr. S. GANESAN, M.E., Ph.D.**, Head of the Department, Department of Mechanical Engineering for providing me necessary support and details at the right time during the progressive reviews.

I would like to express my sincere and deep sense of gratitude to my Project Guide **Dr. NIVIN JOY., M.E., Ph.D.**, Associate Professor, Department of Mechanical Engineering for his valuable guidance, suggestions, and constant encouragement paved way for the successful completion of my project work.

I also express my thanks to all Teaching and Non-teaching staff members of the Department of Mechanical Engineering who were helpful in many ways for the completion of the project.

ABSTRACT

The study is about the spray characteristics of biodiesel made from high Free Fatty Contents (FFA) oils. Spray characterisation studies are important for several reasons when testing biodiesel generated from free fatty acid (FFA) concentrations. Spray behaviour is greatly influenced by the physical and chemical characteristics of biodiesel, such as density and viscosity, which are influenced by the amounts of FFA. Additionally, knowing the properties of the spray helps in improving engine efficiency, emissions control, and engine performance especially in diesel engines. The aim of conducting spray characteristics tests on biodiesel derived from FFA content is to assess its suitability for use in diesel engines. By analysing parameters such as spray penetration length, spray angle, and spray area helps to optimize engine performance, fuel efficiency, and emissions, ultimately facilitating the development of biodiesel fuels with enhanced combustion characteristics and environmental sustainability.

The spray characteristics test method used in the present study is Mei Scattering Technique. The biodiesel made from illupai oil and pongamia oil are tested in this study to find the spray characterization behaviour. A halogen white light is positioned on one side of the glass to illuminate the spray inside the cylinder's combustion chamber. On the opposite side, a high-resolution camera has been installed to capture the spray created by the end injector's double-hole nozzle at 50 frames per minute within the cylinder. After analysing each frame of the recorded video, the best image is selected and used for the analysis. The software called "ImageJ v1.47h" is used to analyse the image. Spray tip penetration length, spray angle, and spray area were calculated for both illupai oil and pongamia oil biodiesels by adjusting the threshold using the software. The results found that spray penetration and spray area of Biofuel made from illupai oil is more than biofuel made from pongamia oil. This is because the viscosity and density of the biodiesel made from illupai oil is less. It results in proper combustion, increased engine efficiency, reduced emissions. The spray angle of Biofuel made from illupai oil is more than biofuel made from pongamia oil. This is because the density and viscosity of the biofuel is less. Wider spray cone angle indicates that it leads to incomplete combustion, increased emissions, greater fuel consumption and decreases the engine efficiency.

TABLE OF CONTENTS

CHAPTER NO.	TITLE	Page NO.
	ABSTRACT	v
	LIST OF FIGURES	viii
	LIST OF TABLES	x
	LIST OF SYMBOLS AND ABBREVIATIONS	xi
1	INTRODUCTION	1
	1.1 Biodiesel	1
	1.2 Need of Using Biodiesel	1
	1.3 Free Fatty Acids	2
	1.3.1 Free Fatty Acid Content	3
	1.3.1.1 Low FFA Content	3
	1.3.1.2 Moderate FFA Content	3
	1.3.1.3 High FFA Content	3
	1.4 Optimizing Biodiesel Production from Free Fatty Acids	4
	1.5 Impact of FFA content on Biodiesel	4
	1.6 Spray Characteristics	6
	1.7 Importance of Studying Spray Characteristics	7
2	LITERATURE SURVEY	9
3	AIM & SCOPE	14
	3.1 Aim of the Project	14
	3.2 Scope of the Project	14
4	METHODOLOGY	16
	4.1 Oils Used	16
	4.1.1 Pongamia Oil (Pongamia Pinnata)	16
	4.1.2 Illupai Oil (Madhuca Longifolia)	16
	4.2 Preliminary Property Analysis of Oil Samples	17
	4.2.1 Free Fatty Acid Value	17
	4.2.1.1 Titration of FFA	18
	4.2.2 Density	19
	4.2.3 Kinematic Viscosity	19

	4.2.4 Moisture Content	20
	4.3 Biofuel Production from Pongamia oil & Illupai Oil	21
	4.3.1 Production of Biodiesel from Pongamia Oil (Pongamia Pinnata)	21
	4.3.2 Production of Biodiesel from Illupai Oil (Madhuca Longifolia)	25
	4.4 Spray Characterization Test	30
	4.4.1 Spray Characterization Test Equipment	31
	4.4.1.1 Fuel Injector	32
	4.4.1.2 Diesel Engine	33
	4.4.1.3 High Speed Camera	35
	4.4.1.4 Fuel Tank	36
	4.4.1.5 Quartz Glass	37
	4.4.2 Software's Used	38
	4.4.2.1 Image J software	38
5	RESULTS AND DISCUSSION	39
	5.1 Spray Characterization	39
	5.1.1 Spray Penetration Length	42
	5.1.2 Spray Angle	43
	5.1.3 Spray Area	44
	5.1.4 Understanding Spray Characteristics	45
	5.2 Spray Penetration Length Analysis	46
	5.3 Spray Angle Analysis	49
	5.4 Spray Area Analysis	51
6	SUMMARY AND CONCLUSION	62
	6.1 Summary	62
	6.2 Conclusion	63
	REFERENCES	64
	APPENDIX	72

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE NO.
1.1	Spray Characteristics	7
4.1	Pongamia Oil	21
4.2	Preheating of Pongamia Oil	22
4.3	Formation of 3 Layers at the Top of Pongamia Oil	23
4.4	Adding Catalyst to the Pongamia Oil	24
4.5	Biodiesel made from Pongamia Oil	25
4.6	Illupai Oil	26
4.7	Preheating of Illupai Oil	26
4.8	Formation of 3 layers at the Top of Illupai Oil	27
4.9	Adding Catalyst to the Illupai Oil	28
4.10	Biodiesel made from Pongamia Oil	29
4.11	Spray Characterization Test Equipment	31
4.12	Spray Characterization Experimental Setup	32
4.13	Fuel Injector	33
4.14	Diesel Engine	34
4.15	High Speed Camera	35
4.16	Fuel Tank	36
4.17	Quartz Glass	37
4.18	Image J Software Interface	38
5.1	Spray Image taken for Biodiesel made from Illupai Oil during the Experimentation	40
5.2	Spray Image taken for Biodiesel made from Pongamia Oil during the Experimentation	41
5.3	Spray Penetration Length	42
5.4	Spray Angle	43
5.5	Spray Area	44
5.6	Spray Penetration length Calculated from Image J Software for Illupai Oil	47
5.7	Spray Penetration length Calculated from Image J Software for Pongamia Oil	47

5.8	Time vs Spray Penetration Length Graph	48
5.9	Spray Angle calculated from Image J Software for Illupai Oil	49
5.10	Spray Angle calculated from Image J Software for Pongamia Oil	50
5.11	Time vs Spray Angle Graph	51
5.12	Spray Area calculated from Image J Software for Illupai Oil	52
5.13	Spray Area calculated from Image J Software for Pongamia Oil	52
5.14	Time vs Spray Area Graph	53
5.15	Photos taken while performing the Experiment	61

LIST OF TABLES

TABLE NO.	TITLE	PAGE NO.
4.1	Fuel Properties of Illupai Oil and Pongamia Oil	20
5.1	Variation of Spray Penetration Length with respect to Time	48
5.2	Variation of Spray Angle with respect to Time	50
5.3	Variation of Spray Area with respect to Time	53
5.4	Spray Characteristics of Biodiesel made from Illupai oil and Pongamia Oil	54
5.5	Spray Characteristics Parameters Comparison with other Biodiesels	55

LIST OF SYMBOLS AND ABBREVIATIONS

$^{\circ}\text{C}$	Degree Celsius (Temperature)
Θ	Spray Angle ($^{\circ}$)
ρ	Density (g/cc)
ν	Kinematic Viscosity (cSt)
M	Moisture content (%)
FFA	Free Fatty Acid
CO	Carbon Monoxide
HC	Hydrocarbons
PM	Particulate matter
NO _x	Nitrogen Oxide
ASTM	American Society for Testing and Materials
AV	Acid Value
RPM	Revolutions per Minute
LIF	Laser Induced Fluorescence
SI	Spark Ignition
CI	Combustion Ignition
PDA	Phase Doppler anemometry
CFD	Computational fluid dynamics
P_{inj}	Injection Pressure
P_{amb}	Ambient Pressure
T_{amb}	Ambient Temperature

CHAPTER 1

INTRODUCTION

1.1 BIODIESEL

Biodiesel, an environmentally friendly and sustainable alternative to standard diesel fuel, is produced from natural substances such as animal fats, vegetable oils and leftover cooking oils. Its production process typically comprises transesterification, in which triglycerides contained in these feedstocks react with alcohol (usually methanol or ethanol) in the presence of a catalyst to create biodiesel and glycerol as byproducts. Biodiesel provides several advantages over petroleum-based diesel, including decreased greenhouse gas emissions, a reduced reliance on finite fossil fuel supply, and major economic benefits in agricultural and waste management. Click or tap here to enter text. It is biodegradable, non-toxic, and can be used in existing diesel engines without modification, making it a viable choice for reducing carbon footprints and improving air quality. Furthermore, biodiesel production may promote rural development and job creation, leading in a more sustainable and resilient energy economy. As the world pursues greener and more sustainable energy sources, biodiesel looks to be a realistic option for satisfying transportation needs while minimizing environmental effect. (Tye et al., 2011)

1.2 NEED OF USING BIODIESEL

The need to utilize biodiesel arises from a mix of environmental, economic, and energy security concerns. For instance, biodiesel is a realistic option for reducing the negative environmental consequences of conventional fossil fuels. Its production and combustion emit far lower amounts of greenhouse gases, particulate matter, and other pollutants than conventional petroleum diesel. This reduction in emissions improves air quality while addressing climate change. (Milano et al., 2016)

Biodiesel production creates opportunities for rural development and economic regeneration. Communities may create employment, strengthen local economies, and reduce their dependency on imported fossil fuels by growing feedstock crops

and establishing biodiesel production facilities. The biodiesel production commonly employs agricultural byproducts and waste materials, offering an additional revenue stream for farmers and waste management organizations.

Biodiesel improves energy security by diversifying fuel sources and lowering dependence on imported oil. Biodiesel, being a renewable fuel generated domestically, is less vulnerable to global oil market supply interruptions and price volatility. This increases energy resilience and mitigates the geopolitical risks associated with oil dependence. The use of biodiesel is consistent with wider environmental aims, promoting a shift to a more sustainable and resilient energy system. By leveraging biodiesel's potential, society may achieve a variety of goals, including environmental preservation, economic growth, and energy security. Finally, the use of biodiesel provides a multidimensional solution to critical energy and environmental issues, with various advantages for society, the economy, and the planet.(Renzaho et al., 2017)

1.3 FREE FATTY ACIDS

Free fatty acids (FFAs) are organic compounds made up of a chain of carbon atoms bonded to hydrogen atoms with a carboxylic acid group (COOH) at one end. These chemicals are made from triglycerides, which are the main components of fats and oils. In triglycerides, three fatty acid molecules are esterified with a glycerol molecule, resulting in a molecule with a glycerol backbone and three fatty acid chains. When triglycerides are hydrolyzed, such as by exposure to water or enzymatic activity, the ester linkages between the fatty acids and glycerol are broken, releasing FFAs and glycerol. (Ahmad et al., 2017)

FFAs are essential in biodiesel production because they can reduce the effectiveness of the transesterification process. During transesterification, FFAs can react with alcohol and catalyst to form soap instead of biodiesel, reducing biodiesel yield and complicating the separation process. To ensure optimal conversion efficiency, the feedstock utilized for biodiesel synthesis should have the lowest FFA content achievable.(Atadashi et al., 2012a)

1.3.1 Free Fatty Acid Content

The FFA concentration is an important consideration in biodiesel synthesis since large amounts of FFAs might reduce the effectiveness of the transesterification process. (Kumar Tiwari et al., 2007)

1.3.1.1 Low FFA content (less than 0.5%):

Oils and fats with low FFA concentration are desirable for biodiesel synthesis since they need less pretreatment. These oils may be transesterified directly using an alcohol and a catalyst, yielding biodiesel and glycerol. This method is more efficient and cost-effective.

1.3.1.2 Moderate FFA Content (0.5% to 3.0%):

Oils having a modest FFA level may require pre-treatment prior to transesterification. Acid-catalyzed esterification is a popular pre-treatment process in which the FFAs react with an alcohol (methanol) in the presence of an acid catalyst to produce biodiesel and water. After esterification, the resultant mixture can be transesterified to yield biodiesel.

1.3.1.3 High FFA Content (Over 3%):

Oils or fats with a high FFA concentration are often subjected to substantial pre-treatment to lower FFA levels prior to transesterification. This pre-treatment may include many processes, such as acid-catalyzed esterification, neutralization, and washing, to eliminate contaminants and improve transesterification efficiency. Alternatively, these high-FFA feedstocks can be combined with feedstocks with lower FFA concentration to balance the total FFA level in the feedstock combination.

The feedstock's FFA concentration has a substantial effect on the biodiesel synthesis process. Low FFA concentration oils are preferable because they simplify the manufacturing process, whereas oils with moderate to high FFA level may necessitate additional pre-treatment processes to assure effective conversion into biodiesel. (Abomohra et al., 2020)

1.4 OPTIMIZING BIODIESEL PRODUCTION FROM FREE FATTY ACIDS

Biodiesel, a renewable alternative to standard diesel fuel, may be made from a variety of feedstocks, including vegetable oils, animal fats, and used cooking oils. The feedstock's FFA level is an important factor in determining biodiesel quality. FFAs can have a negative impact on the transesterification process, causing soap production and decreased biodiesel yield. Thus, understanding the effects of FFA levels on biodiesel properties is crucial for optimizing production techniques and ensuring fuel quality. Research on biodiesel produced with different FFA concentrations has revealed significant implications for fuel properties and performance, greater FFA concentrations in feedstocks frequently result in greater acidity, which can accelerate oxidative breakdown and degrade storage stability.(Kumar, 2017)

The greater FFA levels may influence biodiesel viscosity, cetane number, and combustion characteristics, resulting in variations in engine performance and emissions. Understanding these effects is crucial for generating solutions to FFA-related concerns in biodiesel production and use. Researchers have looked at new approaches to decreasing FFA levels in feedstocks, such as pre-treatment strategies and catalyst tuning during transesterification. By addressing FFA problems, researchers want to increase the overall efficiency, sustainability, and economic viability of biodiesel as a renewable fuel.

1.5 IMPACT OF FFA CONTENT ON BIODIESEL

Biodiesel, a renewable fuel generated from organic sources, has received a lot of interest as a potential replacement to conventional diesel fuel because of its environmental benefits and ability to lessen dependency on fossil fuels. The feedstock's FFA concentration is an important component that influences biodiesel synthesis. FFAs are molecules present in fats and oils that can react with the catalyst during the transesterification process, converting feedstock into biodiesel.(Ribeiro et al., n.d.)

Feedstocks with a high FFA percentage, such as waste cooking oil or animal fats, provide issues in biodiesel manufacturing. Traditional transesterification techniques are unsuccessful for high-FFA feedstocks because FFAs react with the catalyst to generate soaps, limiting biodiesel output and complicating the separation process. To solve this problem, different procedures such as acid-catalyzed esterification and two-step transesterification processes are used. These techniques convert FFAs to biodiesel-compatible esters before transesterifying triglycerides, allowing for the effective conversion of high-FFA feedstocks into biodiesel.

The FFA concentration of the feedstock has a substantial impact on reaction kinetics and conversion efficiency during biodiesel manufacturing. Larger FFA content frequently necessitates longer reaction periods and larger catalyst concentrations to obtain appropriate conversion rates. The presence of FFAs might promote the development of undesired byproducts such as monoacylglycerols and diacylglycerols, affecting fuel quality and biodiesel stability.

The FFA concentration influences the qualities of the biodiesel produced. Biodiesel made from feedstocks with greater FFA concentration has more pollutants and impurities, reducing its purity and overall quality. Higher FFA level can also cause greater acidity in biodiesel, which can accelerate corrosion in engines and fuel systems if not adequately neutralized and purified.

The biodiesel produced from feedstocks with varied FFA level may differ in cold flow characteristics, oxidative stability, and cetane number, all of which are important factors influencing fuel performance and compatibility with current diesel engines. High-FFA biodiesel may have lower cold flow characteristics, resulting in filter blockage and fuel gelling in cooler temperatures. The inclusion of FFAs might reduce biodiesel's oxidative stability, making it more susceptible to breakdown and deposit formation during storage and engine running. (Jain & Sharma, 2010)

Despite the issues associated with high-FFA feedstocks, they have some advantages, including cheaper feedstock prices and the opportunity to use waste materials. Advances in processing methods and catalysts are improving the viability of turning high-FFA feedstocks into high-quality biodiesel. This research into

alternative feedstock sources and pretreatment methods attempts to reduce the effect of FFA levels on biodiesel output and quality.

The free fatty acid concentration of the feedstock is crucial in biodiesel synthesis, influencing reaction kinetics, conversion efficiency, fuel characteristics, and overall practicality. Understanding the effects of different FFA concentrations is crucial for improving biodiesel production processes, preserving fuel quality, and supporting the long-term use of renewable resources in the transportation sector.

1.6 SPRAY CHARACTERISTICS

Like any liquid fuel, the spray characteristics of biofuels are crucial to how they burn in internal combustion engines. These factors affect the effectiveness of combustion, emissions, and general engine performance. The following are some essential spray characteristics of biofuels: Spray Penetration length, Spray Angle, and Spray Area. Spray Penetration length, Spray Angle, and Spray Area are important parameters that affect how liquid fuels, including biofuels, perform and burn in internal combustion engines. Spray penetration measures the distance that the fuel spray covers before dispersing from the injector nozzle. By ensuring that fuel is delivered to the proper spot in the combustion chamber, proper spray penetration optimizes combustion and lowers emissions. (No, 2014)

The process of atomization involves separating liquid fuel into tiny droplets. A finer spray with smaller droplets is produced by efficient atomization, increasing the surface area available for combustion, and enhancing combustion efficiency. The diameter and direction of the fuel spray cone are referred to as the spray angle. Even fuel distribution inside the combustion chamber is ensured by a carefully managed spray angle, which promotes effective combustion and lowers emissions. The fuel spray's range of droplet sizes is described by this parameter. Although very small droplets can result in increased NO_x emissions due to higher flame temperatures, smaller droplets tend to burn more thoroughly. (Nizami & Cernansky, n.d.)

To maintain a balance between combustion efficiency and emissions reduction, proper droplet size distribution is crucial. Whether using traditional or alternative fuels like biofuels, these characteristics are crucial for optimizing the combustion process in internal combustion engines. To achieve efficient and environmentally friendly combustion, minimize emissions, and improve engine performance when using biofuels or other liquid fuels, it is essential to comprehend and manage these properties.

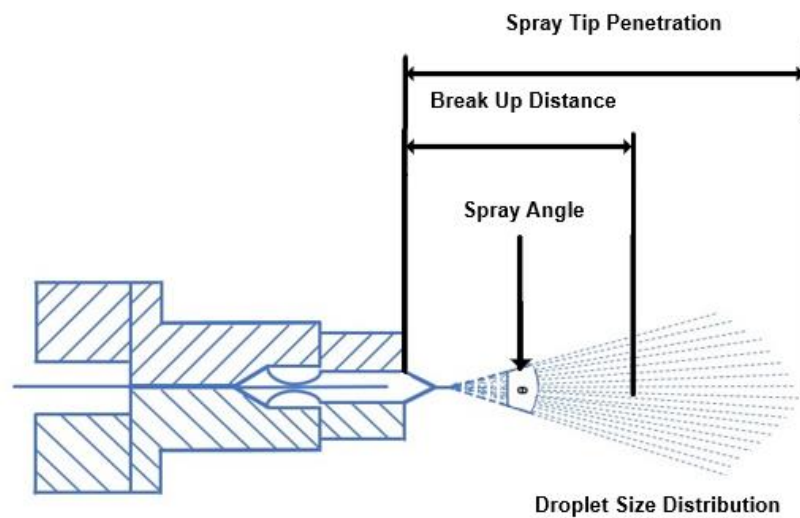


Fig.1.1: Spray Characteristics

1.7 IMPORTANCE OF STUDYING SPRAY CHARACTERISTICS

In the field of environmentally friendly energy and transportation, research on the spray properties of biofuels is of utmost relevance. Because they have a smaller impact on the environment than traditional fossil fuels, biofuels made from sustainable sources including plants, algae, and garbage have gained popularity as potential replacements. It is crucial to comprehend and improve the spray properties of biofuels for several reasons. Initial spray characteristics have a significant impact on combustion efficiency. The energy stored in biofuels is successfully tapped through efficient combustion, which enhances engine efficiency and fuel efficiency. A full and even burning is promoted by proper atomization of biofuel into small droplets, as well as an ideal spray angle and penetration, which lowers the emissions of dangerous pollutants.(Jedelský et al., 2021)

And by examining spray characteristics, biofuel attributes can be tailored to meet the needs of combustion systems. For optimum performance, different engines and applications may call for specific spray characteristics. Researchers and engineers can increase the compatibility and efficiency of biofuel-powered engines by modifying the qualities of the fuel to conform to these specifications. Furthermore, spray qualities significantly affect the emissions profile of biofuel-powered engines. Reduced emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) from correctly atomized biofuels help to clean the air and have a lower environmental impact.

Assessing the atomization process is an important part of researching spray properties. Atomization is the process of breaking up liquid fuel into microscopic droplets during fuel injection. The spray pattern, droplet size distribution, and spray penetration depth all have a direct influence on fuel-air mixing, combustion stability, and emissions production in the engine cylinder. Biodiesel's greater viscosity and surface tension than diesel might alter atomization, potentially compromising spray quality and combustion processes.

The spray properties of biodiesel also influence fuel-air mixing in the combustion chamber. Proper fuel-air mixing is crucial for efficient combustion and low emissions. Variations in spray pattern and droplet size distribution can impact the homogeneity of the air-fuel combination, reducing combustion efficiency and emissions performance.

The effects of biodiesel spray characteristics on engine components, such as fuel injectors and combustion chambers, must be addressed. The variable chemical composition and lubricity qualities of biodiesel may impact injector dynamics, resulting in variations in fuel delivery and spray production. Understanding these consequences is critical to ensure engine dependability, durability, and performance while utilizing biodiesel fuel. Understanding the spray properties of biodiesel in engines is critical for improving combustion processes, emissions performance, and engine dependability. Researchers and engineers can improve the efficiency and environmental sustainability of biodiesel-powered engines by better understanding atomization, evaporation, and fuel-air mixing behavior.(Yoon et al., 2009)

CHAPTER 2

LITERATURE SURVEY

Mehra et al., (2023) Spray penetration measures the distance that the fuel spray covers before dispersing from the injector nozzle. By ensuring that fuel is delivered to the proper spot in the combustion chamber, proper spray penetration optimizes combustion and lowers emissions. The process of atomization involves separating liquid fuel into tiny droplets. A finer spray with smaller droplets is produced by efficient atomization, increasing the surface area available for combustion, and enhancing combustion efficiency.

Payri et al., (2005) In the field of environmentally friendly energy and transportation, research on the spray properties of biofuels is of utmost relevance. Because they have a smaller impact on the environment than traditional fossil fuels, biofuels made from sustainable sources including plants, algae, and garbage have gained popularity as potential replacements. It is crucial to comprehend and improve the spray properties of biofuels for several reasons. Initial spray characteristics have a significant impact on combustion efficiency. The energy stored in biofuels is successfully tapped through efficient combustion, which enhances engine efficiency and fuel efficiency. A full and even burning is promoted by proper atomization of biofuel into small droplets, as well as an ideal spray angle and penetration, which lowers the emissions of dangerous pollutants. Secondly, by examining spray characteristics, biofuel attributes can be tailored to meet the needs of combustion systems.

Agarwal & Chaudhury, (2012) Understanding the spray properties of biofuels in both spark ignition (SI) and compression ignition (CI) engines requires a fundamental understanding of spray characterization. It entails a thorough examination of how biofuels atomize and spread when injected into an engine's combustion chamber. Because it directly affects emissions, combustion efficiency, and overall engine performance, this process is crucial. Researchers may evaluate the fuel's characteristics throughout the intake and compression strokes of SI engines, where

biofuels like ethanol or methanol are often employed. The effectiveness of air-fuel mixing is influenced by variables such as spray penetration, cone angle, droplet size distribution, and spray atomization. To maximize combustion and achieve high thermal efficiency, a well-mixed air-fuel combination must be achieved. Spray characterization helps to spot possible problems like insufficient vaporization or inadequate atomization, which can result in misfires or higher emissions.

Battistoni & Grimaldi, (2012) Spray characterization is also important in CI engines, which frequently employ biofuels like biodiesel or algae-based fuels. These biofuels' characteristics, such as viscosity and chemical makeup, are different from those of conventional diesel fuel. For the injection system to be optimized, it is crucial to comprehend how these biofuels spray. The spray properties have a direct impact on the air-fuel mixing, ignition, and combustion processes in CI engines. For instance, the performance of the combustion stability and emissions might be impacted by the spray's penetration depth. The droplet size distribution and spray tip velocity also have a big impact on how effectively fuel burns. Researchers frequently use cutting-edge diagnostic tools and procedures to carry out spray characterization investigations.

Zandie et al., (2022) Biodiesel is a prospective biofuel for researching spray properties in both spark ignition (SI) and compression ignition (CI) engines since it is made from renewable sources, such as vegetable oils or animal fats. It is a flexible contender due to its usage as a mix in SI engines and as a replacement for regular diesel fuel in CI engines. The unique qualities of biodiesel, such as its greater viscosity and different chemical make-up from diesel, can have a big influence on spray characteristics. Analyzing the spray properties of biodiesel is essential for maximizing engine efficiency and emissions while utilizing this sustainable fuel. Efficiency and emissions are impacted by the combustion characteristics of biodiesel in CI engines, which are determined by its spray pattern. Understanding its spray characteristics is crucial for studying its combustion characteristics in SI engines because of its function as an octane enhancer.

(Chaudhari et al., 2021) Like any liquid fuel, the spray characteristics of biofuels are crucial to how they burn in internal combustion engines. These factors affect the effectiveness of combustion, emissions, and general engine performance. The following are some essential spray characteristics of biofuels: Spray Penetration, Atomization, Spray Angle, and Droplet Size Distribution. Spray penetration, atomization, spray angle, and droplet size distribution are important parameters that affect how liquid fuels, including biofuels, perform and burn in internal combustion engines.

(Douvartzides et al., 2019) Researchers can create precise models of the combustion process thanks to computational fluid dynamics (CFD) simulations, which are made possible by the data gathered during spray characterization studies. For increased efficiency and lower emissions, these models enhance in improving fuel injection, combustion control, and engine design. The analysis of the spray characteristics of biofuels in SI and CI engines begins with the spray characterization. Researchers can adjust engine settings, improve combustion efficiency, and create more sustainable and ecologically friendly engine technologies by having a thorough grasp of how these biofuels spray. The spray characteristics include spray penetration length, spray angle, droplet size distribution, spray atomization, spray tip velocity, cone shape.

(Agathou & Kyritsis, 2012) The spray morphology, droplet size distribution, and atomization behavior are research priorities. It will also be critical to look at how different biofuel qualities, such viscosity and surface tension, affect spray effectiveness. Concerns of stability, pollution, and combustion efficiency must be addressed if biofuels are to be successfully incorporated into conventional engines. It is also envisaged that collaborations with industry and politicians to create standards and guidelines for biofuel spray features will assist their wider implementation in the sustainable energy and transportation sectors.

(Canakci & Van Gerpen, n.d.) Most biodiesel produced today is produced with soybean oil, methanol, and an alkaline catalyst. The high value of soybean oil as a food commodity makes producing a cost-effective fuel extremely difficult. However, many low-cost oils and fats, such as restaurant trash and animal fats, might be

transformed into biodiesel. The issue with processing these low-cost oils and fats is that they frequently include high levels of free fatty acids (FFA), which cannot be converted to biodiesel using an alkaline catalyst. This paper describes a strategy for reducing the free fatty acid content of these feedstocks by employing an acid catalysed pretreatment to esterify the free fatty acids before transesterifying the triglycerides using an alkaline catalyst to finish the process. The initial process development was carried out utilizing synthetic mixes containing 20% and 40% free fatty acids produced using palmitic acid.

(Ashraful et al., 2014) The higher the viscosity, the more gums are formed in the biodiesel, affecting its performance. The study also examines the influence of Pongamia oil and its biodiesel on engine performance and exhaust emissions. The findings are also compared to *Jatropha curcas* biodiesel and waste cooking biodiesel. According to the research, no modifications are required up to B20. The test results show that using biodiesel reduces particulate emissions, CO emissions, and power loss while increasing fuel consumption and NO_x emissions on conventional diesel engines with no or few modifications.

(Bobade SN & Khyade VB, 2012) The primary fatty acids found in *Pongamia pinnata* crude oil included palmitic acid, stearic acid, linoleic acid, and eicosanoic acid. The oil extracts have good physical and chemical qualities and may be employed as a biodiesel feedstock and in industrial applications. Using less expensive fatty acid-containing feedstock can help reduce biodiesel manufacturing expenses. Non-edible oils include waste vegetable oils, animal fats, and oil refinery wastes. With no competing food applications, these characteristics draw attention to *Pongamia pinnata*, which thrives in tropical and subtropical temperatures all over the world.

(Ghadge & Raheman, 2005) A technology for producing biodiesel from mahua oil (*Madhuca indica*) with a high free fatty acid content (19% FFA) has been developed. The high FFA content of mahua oil was decreased to less than 1% using a two-step pretreatment procedure. Each stage was performed with a methanol-to-oil ratio of 0.30-0.35 v/v in the presence of 1% v/v H₂SO₄ as an acid catalyst in a 1-hour reaction at 60^o C. After the reaction, the liquid was allowed to settle for an hour,

and the methanol-water mixture that had separated on top was removed. The second step product at the bottom was transesterified using 0.25 v/v methanol and 0.7% w/v KOH as an alkaline catalyst to generate biodiesel. The fuel properties of mahua biodiesel were found to be comparable to those of diesel and conforming to both the American and European standards.

(Muthukumaran et al., 2020) Mahua biofuels were produced using catalytic cracking with coal ash as a catalyst, and their fuel properties were investigated. An experimental examination was conducted on a single-cylinder, four-stroke, water-cooled diesel engine. Biofuel made from Mahua oil meets ASTM standards and may thus be used as an alternative to diesel fuel.

(Algayyim & Wandel, 2021) The greater viscosity and surface tension of biodiesel reduced the injection velocity and Weber number. This resulted in a bigger droplet size and poor atomization properties. Alcohol addition increased the atomization efficiency of biodiesel and mineral fuel because alcohol has a low kinematic viscosity and surface tension, allowing for a more active contact with the surrounding gas. Surface tension, density, and viscosity are all important fuel parameters that influence spray characteristics. As a result, before using surrogate fuels as a substitute to traditional fuels, it is critical to understand the link between spray characteristics and physical qualities of the fuel itself.

CHAPTER 3

AIM AND SCOPE

3.1 AIM OF THE PROJECT

The global energy environment is changing dramatically because of concerns about climate change, energy security, and the depletion of fossil fuel reserves. As a result, there is a growing interest in alternative and sustainable energy sources, with biofuels emerging as a promising candidate. The aim of this project is the spray characterization study of biodiesel made from different free fatty acid (FFA) contents i.e., to investigate how variations in FFA levels affect the atomization and combustion characteristics of biodiesel spray.

The two biodiesels used for the study are pongamia oil (*Pongamia pinnata*) and illupai oil (*Maduca Langifolia*). The biodiesel is made from the two oils and then tested in spray characteristics test equipment. The purpose of the experiment was to see how biodiesel produced from pongamia and illupai oils sprayed into a diesel engine. By analyzing parameters such as spray angle, spray area and spray penetration we can find the how the combustion efficiency and emissions are affecting. This knowledge helps optimize biodiesel production processes and engine performance, contributing to the development of more efficient and environmentally sustainable biodiesel fuels for use in combustion engines.

3.2 SCOPE OF THE PROJECT

The study of spray properties of biodiesel generated from free fatty acids (FFAs) has a wide range of consequences for engine performance, emissions, and fuel consumption. Understanding these spray properties is critical for optimizing combustion processes, increasing fuel economy, and reducing the environmental consequences of biodiesel use. The atomization behavior of biodiesel derived from FFAs must be investigated further. Atomization is the process of breaking down liquid fuel into microscopic droplets during fuel injection. The spray pattern, droplet size distribution, and spray penetration depth have a direct impact on fuel-air mixing, combustion efficiency, and emissions production within the engine cylinders.

Atomization properties can influence combustion stability, ignition delay, and pollutant emissions such as particulate matter and nitrogen oxides (NO_x).

It is crucial to study the evaporation properties of biodiesel droplets. Biodiesel generated from FFAs often has different evaporation rates and vaporization characteristics than normal diesel fuel. Variations in droplet evaporation can affect combustion timing, fuel-air mixing, and overall combustion efficiency. Understanding these features is critical for improving engine performance and implementing emission control techniques. The effects of biodiesel spray properties on engine components should be examined. Spray characteristics may influence injector dynamics, fuel delivery, and combustion chamber design. Addressing these consequences is critical to ensure engine dependability, durability, and performance while utilizing biodiesel fuels made from FFA.

The scope of spray characteristic investigations includes the development of techniques for lowering FFA levels in biodiesel feedstock. This involves looking at pre-treatment procedures, catalyst optimization, and feedstock selection to reduce FFA-related issues and increase fuel quality. The study of spray properties of biodiesel produced from FFAs has enormous potential for improving engine efficiency, lowering emissions, and increasing biodiesel's sustainability as a renewable fuel source. Researchers want to realize biodiesel's full potential as a viable alternative to conventional diesel fuel by thoroughly understanding and tackling the challenges involved with FFA-derived biodiesel sprays.

CHAPTER 4

METHODOLOGY

4.1 OILS USED

4.1.1 *Pongamia oil (Pongamia Pinnata)*

Pongamia oil, derived from the seeds of the *Pongamia pinnata* tree, is a viable alternative for biodiesel production due to its high triglyceride content. The transesterification process, which converts triglycerides to biodiesel, is an important stage in manufacturing. However, differences in Pongamia oil's free fatty acid (FFA) composition can have an influence on process efficiency. High FFA levels can produce soap, limiting biodiesel output and complicating purification. Before manufacture, it is critical to determine FFA concentration using procedures such as acid-base titration or chromatography. Evaluating biodiesel qualities such as viscosity, density, and oxidative stability, as well as engine performance, sheds light on its suitability as fuel. By understanding these factors, researchers strive to optimize Pongamia oil-derived biodiesel production, contributing to sustainable energy solutions and environmental conservation efforts. (Atadashi et al., 2011)

4.1.2 *Illupai oil (Madhuca longifolia)*

Illupai oil, obtained from the seeds of the *Madhuca longifolia* tree, is a viable feedstock for biodiesel synthesis due to its abundance and high oil concentration. This oil includes different quantities of free fatty acids (FFAs), which have a substantial influence on biodiesel synthesis and performance. It is critical to investigate the performance of biodiesel made from Illupai oil with varying FFA percentages to maximize its use. Higher FFA levels can cause higher acidity and viscosity, impacting biodiesel quality and engine efficiency. Biodiesel made from Illupai oil with different FFA levels is being studied for its physicochemical qualities, combustion characteristics, emissions, and engine performance factors. Understanding how differing FFA levels affect biodiesel characteristics and performance allows for the development of efficient production procedures and

assures the best use of Illupai oil as a sustainable alternative fuel source. (Ramasubramanian et al., 2022)

4.2 PRELIMINARY PROPERTY ANALYSIS OF OIL SAMPLES

The initial characteristics of the gathered oil samples, such as the density, kinematic viscosity, free fatty acid (FFA) percentages and moisture content, were evaluated in a laboratory setting in accordance with the relevant ASTM (American society for testing and materials) standards.

A wide range of materials and chemicals were used in the study to precisely quantify the various characteristics of the biodiesel samples. To assess density, a precision measurement equipment called a Pycnometer was used in combination with a weighing machine to correctly weigh the sample. Kinematic viscosity, another key attribute, was evaluated with a specialized instrument known as a Kinematic Viscometer, which is developed to examine fluid flow properties. Several chemicals and equipment were used to determine the proportion of free fatty acids (FFA), including 0.1 normal sodium hydroxide, a thermometer, isopropyl alcohol, a 250 mL conical flask, and phenolphthalein indicator. These materials and chemicals were carefully chosen to assure the precision and dependability of the FFA measurement method. Finally, moisture content was determined using a crucible and a hot air oven. This technique guarantees that the moisture content of biodiesel samples is reliably measured, which is critical for quality control. Overall, the utilization of these materials and chemicals in the analysis process indicates a thorough method to determining the essential features of biodiesel samples, allowing for more informed decision-making and quality assurance in biodiesel production. (Monteiro et al., 2008)

4.2.1 Free fatty acid value

Biodiesel production from various feedstocks has gained popularity as a renewable and ecological alternative to traditional diesel fuels. The proportion of free fatty acids (FFA) in feedstock oils influences the efficiency and quality of biodiesel synthesis. This study seeks to give a full review of the function of FFA concentration in biodiesel production, including its impact on process efficiency, product quality, and solutions for avoiding adverse impacts. (Atadashi et al., 2012b)

The free fatty acid (FFA) concentration in oils is a measure of the oil's acidity and is commonly used as an indicator of oil quality. To assess an oil's FFA content, utilize the acid value (AV) determination process, which comprises titration with a standard solution of sodium hydroxide (NaOH). For this titration procedure, a burette solution of sodium hydroxide with a normality of 0.1 N must first be prepared. A 5 grams sample of oil is weighed inside a conical flask. In addition, 25 mL of isopropyl alcohol is added to a conical flask containing the sample oil.

The mixture is subsequently treated with four drops of the 0.1 normality NaOH solution in the burette. The mixture is then heated to a temperature of 60⁰ C. It is then allowed to cool until the sample has reached room temperature. Once the solution has warmed to room temperature, the phenolphthalein indicator is added. The solution's titration results are then documented by noting and calculating the reading in the burette.

4.2.1.1 Titration of FFA

The process of titration for Free Fatty Acid (FFA) analysis consists of numerous precisely conducted phases that assure the precision and dependability of the results. Initially, a precise amount of 5 grams of oil, usually obtained from waste cooking oil samples, is meticulously metered out. This oil sample is then mixed with 25 millilitres of isopropyl alcohol and a precise amount of 0.1 normality NaOH solution, which is used as the titrant. The mixture is then gently heated at 60⁰ C to facilitate the interaction between the FFA in the oil sample and the NaOH solution. Once the heating procedure is completed, the sample is allowed to cool to room temperature, ensuring that the titration takes place under controlled circumstances. Following the cooling phase, 2 drops of phenolphthalein indicator are added to the solution, which causes a colour shift when the titration reaches its endpoint.

Finally, the titration is performed by progressively adding the NaOH solution until a definite pink hue appears, indicating that the reaction between the FFA and the titrant is complete.

This precisely organized set of processes guarantees that the FFA concentration of the oil sample is accurately determined, offering useful insights for quality control and process optimization in biodiesel manufacturing.

FFA (%) = Normality [0.1] x Volume of NaOH(ml) x 28.2/sample of weight (g)

Calculation: Pongamia oil: FFA = $(28.2 \times 0.1 \times 0.1) \div 5 = 5.6$

Illupai oil: FFA = $(28.5 \times 0.1 \times 0.1) \div 5 = 11.5$

After the biodiesel is produced i.e., before blending with diesel, again the free fatty acid value is calculated. It is found that the pongamia oil has 3.1 % and illupai oil has 2.2 % FFA content.

4.2.2 Density(ρ)

A pycnometer can be used to determine the density of an oil sample. Pycnometers are glass containers with stoppers that hold known volumes. The pycnometer's empty weight is initially measured using a weighing machine. The oil sample is then placed in the pycnometer, and the weighing machine is used to calculate the weight of the pycnometer and oil sample together. The density was estimated by dividing the mass by the pycnometer volume. The pycnometer has a capacity of 25ml. The density is then calculated using the method below, which is based on the basic density equation of mass divided by volume. The unit of density is g/cm³.

Calculation: Pongamia oil, density, $\rho = (46.64 - 23.08) \div 25 = 0.9424$ g/cc

Illupai oil, density $\rho = (46.12 - 23.09) \div 25 = 0.9212$ g /cc

4.2.3 Kinematic viscosity(ν)

This is a normal test for determining the kinematic viscosity of both transparent and opaque liquids. To complete the test, a predetermined volume of oil sample must be run through a capillary tube at a temperature of 40⁰ C while keeping the heat constant. The kinematic viscosity is then computed using the time length and capillary tube diameter. The kinematic viscosity of the oil is important in determining the biofuel's properties since it affects how it burns. Kinematic viscosity is a fluid's (liquid or gas) resistance to changes in shape or movement of adjacent components relative to one another.

Viscosity is an indication of flow resistance. The kinematic viscometer bath machine is used to measure kinematic viscosity. Oil is placed into a glass flask tube and

heated at 40°C. The oil is inflated using a sucker and then allowed to settle. The time it takes for the oil to settle is then measured and used to compute kinematic viscosity.

Viscosity, ν = Time taken (in seconds) $\times$ 0.014

Calculation: Pongamia oil: T = 40 °C, Viscosity, ν = 47.05 $\times$ 0.014 = 39 .55 cSt

Illupai oil: T = 40°C, Viscosity, ν = 44.10 $\times$ 0.014 = 36 .96 cSt

4.2.4 Moisture content

Initially, the complete weight of the crucible and the weight of the 5gm oil sample were measured and recorded on a weighing machine. The sample was then placed in a hot air oven set to 110⁰ C and baked for three hours. The sample is then withdrawn from the oven and allowed to cool until it is at room temperature. The total sample weight was then calculated. The variance in weight estimation of the sample's moisture content can be determined.

Moisture content = [(Initial weight of sample - dry weight of sample) $\div$ dry weight sample] $\times$ 100

Calculation: pongamia oil: M = [(74.75 – 12.05) $\div$ 12.05] $\times$ 100 = 0.0751%

illupai oil: M = [(27.19 -27.10) $\div$ 27.10] $\times$ 100 = 0.332 %

Table 4.1: Fuel Properties of Illupai oil and Pongamia Oil

Fuel Properties	Illupai Oil	Pongamia Oil
Free Fatty Acid Content	2.2	3.1
Moisture Content (%)	0.332	0.0751
Viscosity (cSt) at 40 ⁰ C	36.96	39.55
Density (g/cc)	0.9212	0.9424

4.3 BIOFUEL PRODUCTION FROM PONGAMIA OIL AND ILLUPAI OIL

Pongamia oil and Illupai oil are both effective feedstocks for biofuel production. Pongamia oil, obtained from Pongamia pinnata seeds, contains a high concentration of triglycerides that are appropriate for biodiesel synthesis by transesterification. Similarly, Illupai oil, derived from the Illupai tree (Mahua), is high in triglycerides and may be used to produce biodiesel. Both oils are viable alternatives to traditional fossil fuels, contributing to renewable energy and sustainable development efforts. To maximize biofuel yields from these plentiful and renewable feedstocks, researchers are continuing to investigate effective extraction methods and manufacturing procedures. (Mathiyazhagan et al., 2011)

4.3.1 Production of Biodiesel from Pongamia Oil (Pongamia Pinnata)

There are various stages involved in turning pongamia oil into biodiesel, such as extraction, transesterification, and purification. Because of its high fatty acid content, pongamia oil is a good feedstock. Oil from pongamia seeds is usually extracted, transesterification is used to turn the oil into biodiesel, and the biodiesel is then purified to get rid of contaminants. Compared to conventional fossil fuels, it is a more environmentally friendly fuel. (Naik et al., 2008)

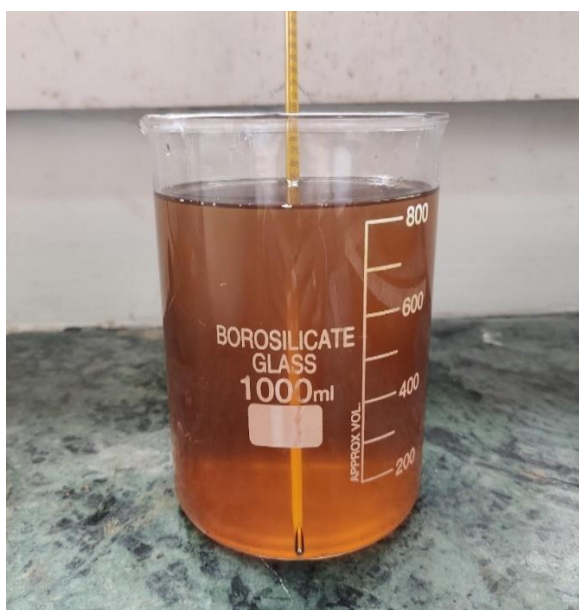


Fig. 4.1: Pongamia Oil

Step 1: Preheating Process

To lower viscosity and improve the effectiveness of future processes like neutralization or degumming, the crude oil is normally heated to a specific temperature range (generally between 60 and 70°C) during the preheating process for Free Fatty Acids (FFA) in the manufacturing of all sample oil. This preheating process enhances the oil's overall quality by removing contaminants.

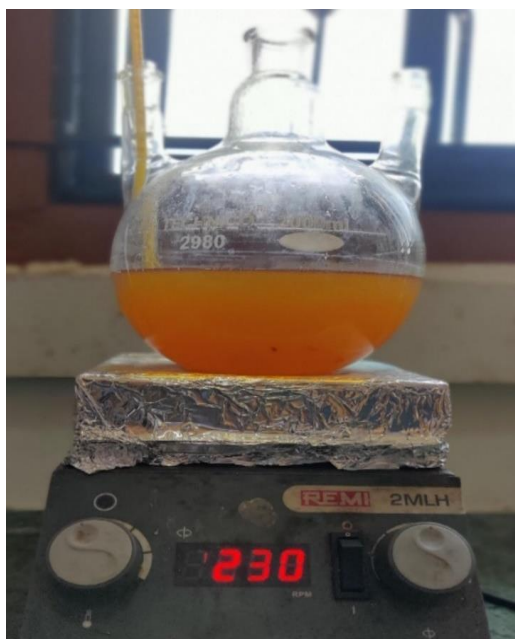


Fig. 4.2: Preheating of Pongamia Oil

You seem to be talking about the procedure where large concentrations of free fatty acids (FFA) are encountered when making biodiesel from all sample oil. Because high FFA level might induce soap formation and other problems during the transesterification process, it can complicate the synthesis of biodiesel.

To remedy this, you might need to use extra pre-treatment procedures to lower the FFA content before turning the oil into biodiesel, such as acid esterification or alkaline esterification.



Fig. 4.3: Formation of 3 layers at the top of Illupai oil

Step 2: Transesterification of the Oil

Pongamia oil is typically transesterified into biodiesel by reacting it with an alcohol, such as methanol or ethanol, in the presence of a catalyst, most often potassium or sodium hydroxide. This method produces glycerol as a byproduct and converts the oil's triglycerides into fatty acid methyl or ethyl esters, which are the key components in biodiesel. The specific parameters and circumstances of the transesterification reaction may vary depending on factors such as oil composition, catalyst concentration, reaction temperature, and reaction time.

Step 3: Catalyst preparation

To evaluate the Free Fatty Acid (FFA) content in extracted oil, acid-base titration or enzymatic procedures are used. Excessive FFA levels demand acid pretreatment, which is often accomplished by acid-catalysed esterification with sulfuric or methane sulfonic acids. Esterification involves heating and stirring the oil with an acid catalyst and a suitable alcohol (usually methanol) to speed up the process. After esterification, neutralization is used to eliminate any remaining acid catalyst. This entails adding a basic, such as potassium or sodium hydroxide, to the liquid, which causes the glycerol and biodiesel layers to separate when it settles. The glycerol

layer is then removed. These methods enable the identification and decrease of FFA concentration in extracted oil, which is critical for quality control in biodiesel manufacturing.



Fig. 4.4: Adding catalyst to the oil

Step 4: Crude oil for FFA in Bio diesel of production

Crude oil, sometimes called cruise oil, is made from pig oil and has a variable amount of free fatty acids (FFA) depending on how it is extracted and refined. Usually, the goal for making biodiesel from all sample oil is to lower the FFA content by neutralization or esterification before turning the oil into biodiesel. Both the finished product's quality and the biodiesel conversion process are impacted by the FFA.

Step 5: Water wash for bio diesel of production in FFA

Water washing is an important step in biodiesel manufacturing for removing free fatty acids (FFA) and impurities. Following transesterification with alcohol and a catalyst, the mixture separates into glycerol and biodiesel. Washing the biodiesel with water eliminates contaminants and reduces FFA concentrations. Water forms a separate phase in which contaminants dissolve, facilitating their removal. After settling, the water and contaminants separate from the biodiesel, which is

subsequently dried to eliminate any leftover water with heat or desiccants. Quality testing, including moisture content and FFA levels, guarantees that the biodiesel satisfies specifications. This rigorous technique improves biodiesel quality, making it appropriate for a variety of applications by lowering FFA concentration and impurities.



Fig. 4.5: Biodiesel made from Pongamia Oil

Finally, an additional step known as acid esterification is typically necessary to decrease the Free Fatty Acid (FFA) level prior to transesterification in the synthesis of biodiesel from any sample oils having a high FFA concentration. This technique improves both the output and quality of biodiesel.

4.3.2 Production of Biodiesel from Illupai Oil (*Madhuca Longifolia*):

Madhuca longifolia oil, sometimes referred to as illupai oil, is a possible feedstock for the manufacturing of biodiesel. It is taken out of the seeds of the native Indian Illupai tree. Illupai seeds have a 50% oil content, which makes them perfect for producing biodiesel. Before employing Illupai oil for large-scale biodiesel synthesis, however, issues like availability, extraction efficiency, and economic viability need to be considered, just like with any other feedstock. Aspects of social and environmental sustainability should also be considered. (Sudalai et al., 2023)



Fig. 4.6: Illupai Oil

Step 1: Preheating Process

To lower viscosity and improve the effectiveness of future processes like neutralization or degumming, the crude oil is normally heated to a specific temperature range (generally between 60 and 70°C) during the preheating process for Free Fatty Acids (FFA) in the manufacturing of all sample oil. This preheating process enhances the oil's overall quality by removing contaminants.

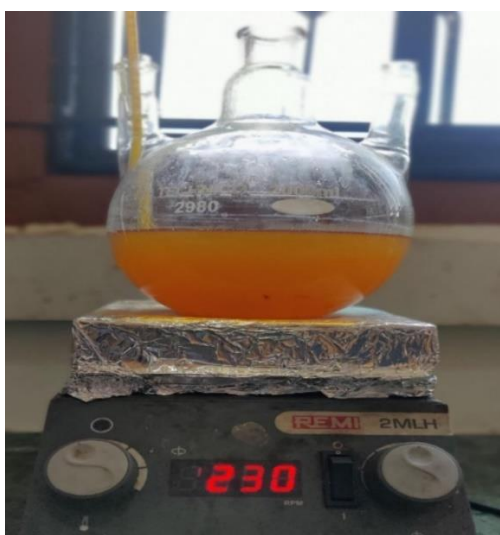


Fig. 4.7: Preheating of the Illupai Oil

You seem to be talking about the procedure where large concentrations of free fatty acids (FFA) are encountered when making biodiesel from all sample oil. Because high FFA level might induce soap formation and other problems during the transesterification process, it can complicate the synthesis of biodiesel. To remedy this, you might need to use extra pre-treatment procedures to lower the FFA content before turning the oil into biodiesel, such as acid esterification or alkaline esterification.



Fig. 4.8: Formation of 3 layers at the top of Illupai oil

Step 2: Transesterification of the Oil

Madhuca oil is in fact utilized as a feedstock for the transesterification process, which produces biodiesel. Transesterification is the process of combining oil with an alcohol, usually methanol or ethanol, in the presence of a catalyst to create glycerol as a byproduct and biodiesel (methyl or ethyl esters). Madhuca oil's high oil content and advantageous fatty acid composition make it appealing for the generation of biodiesel. However, while using any feedstock for the manufacturing of biodiesel, it is imperative to maintain sustainability and take environmental factors into consideration.

Step 3: Catalyst preparation

To evaluate the Free Fatty Acid (FFA) content in extracted oil, acid-base titration or enzymatic procedures are used. Excessive FFA levels demand acid pretreatment, which is often accomplished by acid-catalysed esterification with sulfuric or methane sulfonic acids. Esterification involves heating and stirring the oil with an acid catalyst and a suitable alcohol (usually methanol) to speed up the process. After esterification, neutralization is used to eliminate any remaining acid catalyst. This entails adding a basic, such as potassium or sodium hydroxide, to the liquid, which causes the glycerol and biodiesel layers to separate when it settles. The glycerol layer is then removed. These methods enable the identification and decrease of FFA concentration in extracted oil, which is critical for quality control in biodiesel manufacturing.



Fig. 4.9: Adding catalyst to the Illupai oil

Step 4: Crude oil for FFA in Bio diesel of production

Crude oil, sometimes called cruise oil, is made from pig oil and has a variable amount of free fatty acids (FFA) depending on how it is extracted and refined. Usually, the goal for making biodiesel from all sample oil is to lower the FFA content by neutralization or esterification before turning the oil into biodiesel. Both the finished product's quality and the biodiesel conversion process are impacted by the FFA.

Step 5: Water wash for bio diesel of production in FFA

Water washing is a common method for eliminating free fatty acids (FFA) from oil samples during the biodiesel synthesis process. Initially, the oil is transesterified using an alcohol (usually methanol or ethanol) and a catalyst (usually sodium or potassium hydroxide) to produce biodiesel and glycerol. Following the procedure, the fluid separates into two layers: glycerol on the bottom and biodiesel on top. The biodiesel layer is then washed with water to remove contaminants such as soap and residual catalyst, as well as to lower the FFA concentration.

Water produces a distinct phase in which pollutants dissolve, facilitating their removal. After settling again, the water and impurities separate from the biodiesel, providing cleaner biodiesel after the water phase is removed. Following washing, the biodiesel is dried to remove any residual water. Heating and the use of desiccants can help in this process. Finally, before it is used or sold, the biodiesel is quality tested, which includes testing for moisture content, FFA levels, and overall purity. This thorough method produces high-quality biodiesel suited for a variety of uses. This water wash procedure lowers the biodiesel's FFA content and contaminants, improving its quality and suitability for fuel use.



Fig. 4.10: Biodiesel made from Illupai Oil

Finally, an additional step known as acid esterification is typically necessary to decrease the Free Fatty Acid (FFA) level prior to transesterification in the synthesis of biodiesel from any sample oils having a high FFA concentration. This technique improves both the output and quality of biodiesel.

4.4 SPRAY CHARACTERIZATION TEST

Spray characterisation testing for biodiesel involves identifying the physical characteristics and behaviour of the biodiesel spray, which is critical for understanding its combustion performance in diesel engines. This test is designed to assess factors such as spray penetration length, spray angle, and spray area.

A biodiesel spray is manufactured under regulated conditions utilizing specialized equipment such as a spray chamber or injector system. To get precise information regarding spray shape and dynamics, high-speed imaging methods, laser diffraction, or phase Doppler anemometry can be used. (Mancaruso et al., 2011)

Researchers can discover more about how biodiesel fuel atomizes, disperses, and interacts with air in a diesel engine's combustion chamber by evaluating the spray characteristics. This information is crucial for improving engine architecture, fuel injection systems, and combustion processes to increase fuel efficiency, lower emissions, and improve overall engine performance.

Furthermore, spray characterisation testing offers useful information for verifying computational fluid dynamics (CFD) models that replicate gasoline spray behaviour in engine simulations. Engineers may develop and validate their models by comparing experimental and computational data, resulting in more accurate engine performance and emissions projections.

Overall, spray characterisation testing plays an important role in the development and optimization of biodiesel fuels for use in diesel engines, contributing to advances in sustainable transportation technology.(Patel et al., 2016)

4.4.1 Spray Characterization Test Equipment

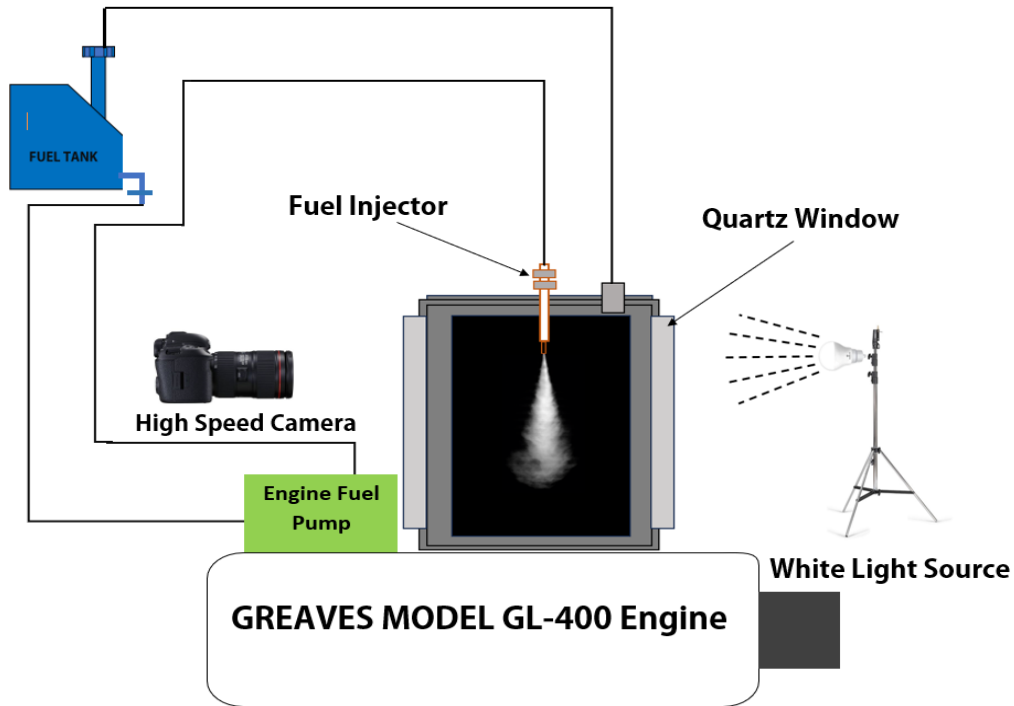


Fig. 4.11: Spray Characterization Test Equipment

The injector in this engine features a double-hole nozzle. The cylindrical walls have two windows on each side. Quartz glass, used in the windows, can withstand temperatures of up to 1500°C and pressures of up to 1000 bar. The actual experimental setup was shown in Fig. 4.12.

A halogen white light is positioned on one side of the glass to illuminate the spray inside the cylinder's combustion chamber. On the opposite side, a high-resolution camera has been installed to capture the spray created by the end injector's double-hole nozzle at 50 frames per minute within the cylinder. After analyzing each frame of the recorded video, the best image is selected and used for the analysis.

The software called "ImageJ v1.47h" is used to analyze the image. Spray tip penetration length, spray angle, and spray area were calculated for both illupai oil and pongamia oil biodiesels by adjusting the threshold using the software.

In the biodiesel spray characteristics test, the GREAVES MODEL GL-400 engine powers the test equipment, allowing for accurate control and measurement of fuel injection parameters. Its dependable performance assures consistent operation throughout the test, allowing researchers to examine the spray pattern, atomization,

and combustion parameters of biodiesel under a variety of operating situations. The engine's ability to maintain constant RPMs while delivering accurate fuel supply makes it easier to evaluate biodiesel's performance and applicability for different applications.



Fig. 4.12: Spray Characterization Experimental Setup

Main components in this equipment are fuel tank, fuel injector, diesel engine, quartz window, high speed camera. The fuel tank contains the biodiesel fuel that will be injected. Fuel Injector helps in the process of atomizing the liquid fuel into a fine spray under high pressure. Quartz Window is a translucent window allows researchers to see the spray pattern of biodiesel entering the injector nozzle. The white light source highlights the spray pattern, allowing the high-speed camera to see it more clearly. High speed camera captures the photographs of the spray at extremely small-time intervals, allowing researchers to monitor the formation and spread of the spray plume.

4.4.1.1 Fuel Injector

In the spray characterisation of biodiesel in engines, the fuel injector is crucial in determining spray characteristics and combustion performance. Fuel injectors oversee properly atomizing liquid fuel into small droplets to ensure proper mixing with air in the combustion chamber. Biodiesel qualities, such as viscosity and

surface tension, differ from regular diesel fuel, which might affect injector dynamics and fuel distribution.

Variations in spray parameters, such as droplet size distribution and spray pattern, have a direct influence on fuel-air mixing, combustion efficiency, and emissions. Understanding the relationship between biodiesel spray characteristics and injector design is critical for maximizing engine efficiency, assuring consistent fuel delivery, and avoiding possible issues related with biodiesel use in engines. The fuel injector used here is a two-hole fuel injector and the hole diameter is 0.23 mm.



Fig. 4.13: Fuel Injector

4.4.1.2 Diesel Engine

Understanding the engine's combustion process is critical for improving fuel injection techniques and attaining efficient combustion when spraying biodiesel into diesel engines. Biodiesel, which is sourced from renewable sources such as vegetable oils or animal fats, has different spray properties than traditional diesel fuel due to differences in viscosity, density, and surface tension.

These variations affect atomization, spray dispersion, and fuel-air mixing in the combustion chamber. Spray attributes like as droplet size distribution and penetration have a direct influence on combustion efficiency, emissions

performance, and engine durability. As a result, understanding biodiesel spray characteristics in diesel engines is critical for determining optimal operating conditions, improving fuel economy, and lowering environmental consequences related with combustion processes in transportation and industrial applications.



Fig. 4.14: Diesel Engine

Table 4.2: Specifications of Diesel Engine used for the experimentation

Engine Model	GREAVES MODEL GL-400
Type of Engine	Diesel Engine
No. of Cylinders	Single Cylinder
No. of Strokes	4
Type of Cooling System	Air Cooled
Speed	1500 RPM
Power	7.5 hp
Bore Diameter	85 mm
Stroke Length	127 mm

4.4.1.3 High Speed Camera

High-speed cameras are essential for spray characterisation of biodiesel in engine combustion processes. These cameras record quick events with great temporal resolution, allowing researchers to see and evaluate biodiesel spray dynamics in real time. For best results in spray characterisation tests, there are parameters that must be followed when using a Canon camera to capture spray particles. Start with a Canon EOS 5D Mark IV or another high-resolution camera. Go for a medium aperture setting (around f/8 to f/11) to achieve a balance between sharpness and depth of field. Pick a quick shutter speed—1/1000s or faster—to stop the spray particles' mobility. Adjust the frame rate to 50 frames per second. Lower the ISO (100–400) to reduce noise. Moreover, activate the continuous shooting mode to quickly take several frames.

High-speed cameras provide information on fuel-air mixing, combustion stability, and emissions formation within the engine cylinder by recording the atomization process, spray pattern, and droplet size distribution at high frame rates. This precise information helps to understand the effect of biodiesel characteristics on spray behaviour and combustion efficiency. Furthermore, high-speed camera video allows researchers to evaluate computer models, enhance fuel injection tactics, and create innovative combustion technologies targeted at increasing engine efficiency and lowering environmental pollutants related with biodiesel combustion.



Fig. 4.15: High Speed Camera

4.4.1.4 Fuel Tank

While the fuel tank is not directly engaged in biodiesel spray characterisation in the engine, it does play an important role in providing biodiesel to the engine for testing and analysis. The fuel tank holds the biodiesel fuel, guaranteeing a stable supply throughout testing. Proper fuel tank design and management are critical for maintaining fuel quality and preventing contamination, which can impact spray characteristics and engine performance. Furthermore, the fuel tank's location relative to the engine and fuel delivery system can affect fuel pressure and flow rates, influencing spray behaviour during injection. Overall, the fuel tank provides the major supply of biodiesel for engine testing, allowing for precise and consistent spray characterisation studies, which are critical for improving combustion processes and fuel consumption.



Fig. 4.16: Fuel Tank

4.4.1.5 Quartz Glass

Quartz glass, recognized for its exceptional optical clarity and resilience to heat and chemical damage, is used to characterize biodiesel sprays in engine research. In example, quartz glass is frequently used to create clear windows or optical access ports within experimental combustion chambers. These windows enable researchers to directly examine biodiesel spray dynamics, combustion processes, and flame behaviour within the engine cylinder using modern optical diagnostics such as laser-induced fluorescence (LIF) or high-speed imaging. Quartz glass allows for real-time observation and study of biodiesel spray properties, giving a better knowledge of fuel-air mixing, combustion efficiency, and emission production in biodiesel-powered engines.



Fig. 4.17 Quartz Glass

4.4.2 Software's Used

4.4.2.1 Image J Software

The software used in determining the spray length, spray angle, and spray area is Image J software. ImageJ is an open-source image processing tool created by the National Institutes of Health. It is commonly used in scientific research and includes a complete set of tools for analysing, manipulating, and quantifying digital pictures. ImageJ supports a wide range of image formats and offers significant image modification features, including as filtering, segmentation, and morphological operations. It also includes advanced quantitative analysis tools such as intensity profiling, particle analysis, and picture registration.

ImageJ's user-friendly interface, broad plugin library, and scripting features make it an adaptable tool for a variety of applications in biology, medicine, materials science, and engineering. Furthermore, the software's open-source nature promotes cooperation and modification, allowing users to modify it to their own research requirements.(Achebe et al., 2020)

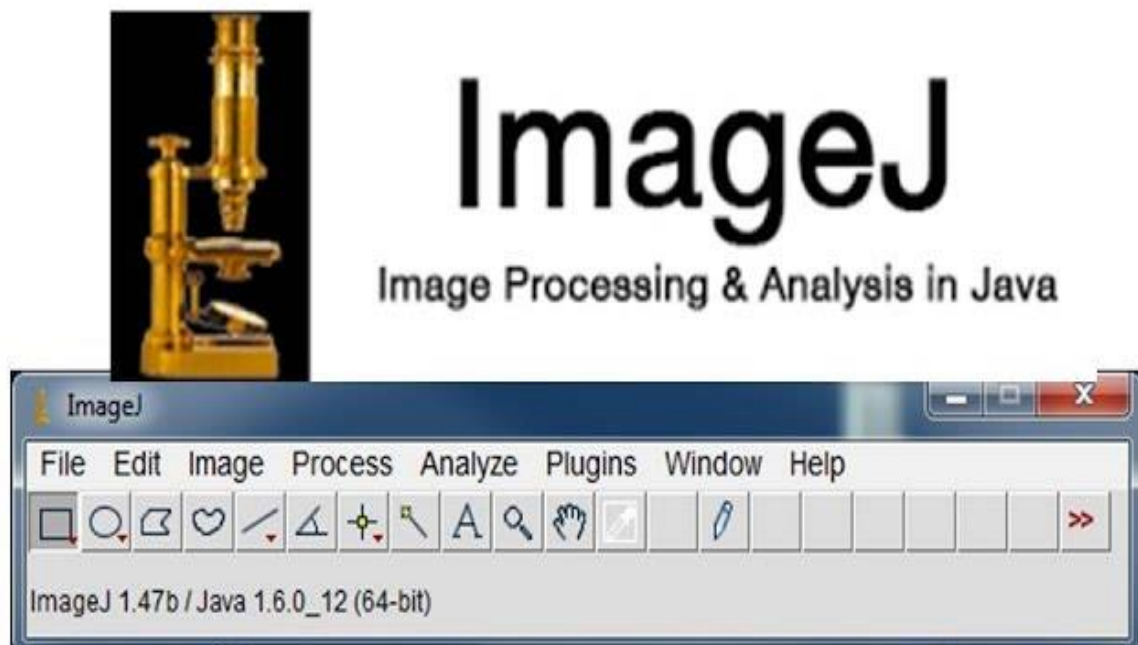


Fig. 4.18: Image J Software Interface

CHAPTER 5

RESULTS AND DISCUSSION

5.1 SPRAY CHARACTERISTICS ANALYSIS

Understanding the spray properties of biofuels in both spark ignition (SI) and compression ignition (CI) engines requires a fundamental understanding of spray characterization. It entails a thorough examination of how biofuels atomize and spread when injected into an engine's combustion chamber. Because it directly affects emissions, combustion efficiency, and overall engine performance, this process is crucial.

Researchers may evaluate the fuel's characteristics throughout the intake and compression strokes of SI engines, where biofuels like ethanol or methanol are often employed. The effectiveness of air-fuel mixing is influenced by variables such as spray penetration, cone angle, droplet size distribution, and spray atomization. To maximize combustion and achieve high thermal efficiency, a well-mixed air-fuel combination must be achieved.

Spray characterization helps to spot possible problems like insufficient vaporization or inadequate atomization, which can result in misfires or higher emissions. Spray characterization is also important in CI engines, which frequently employ biofuels like biodiesel or algae-based fuels.

These biofuels' properties, such as viscosity and chemical composition, differ from those of traditional diesel fuel. To enhance the injection mechanism, we must first understand how these biofuels spray. The spray qualities directly affect the air-fuel mixing, ignition, and combustion processes in CI engines. (Mahmudul et al., 2017)

For instance, the performance of the combustion stability and emissions might be impacted by the spray's penetration depth. The droplet size distribution and spray tip velocity also have a big impact on how effectively fuel burns. Researchers frequently use cutting-edge diagnostic tools and procedures to carry out spray characterization investigations. Laser-induced fluorescence (LIF) or shadowgraph

are examples of high-speed imaging technologies that may record the temporal and spatial properties of the spray.

To assess droplet size distribution, phase-Doppler anemometry (PDA) or laser diffraction methods can also be utilized. Researchers can create precise models of the combustion process thanks to computational fluid dynamics (CFD) simulations, which are made possible by the data gathered during spray characterization studies. For increased efficiency and lower emissions, these models enhance in improving fuel injection, combustion control, and engine design. The analysis of the spray characteristics of biofuels in SI and CI engines begins with the spray characterization.

Researchers can adjust engine settings, improve combustion efficiency, and create more sustainable and ecologically friendly engine technologies by having a thorough grasp of how these biofuels spray. The spray characteristics are as spray penetration, spray cone angle, spray Area.

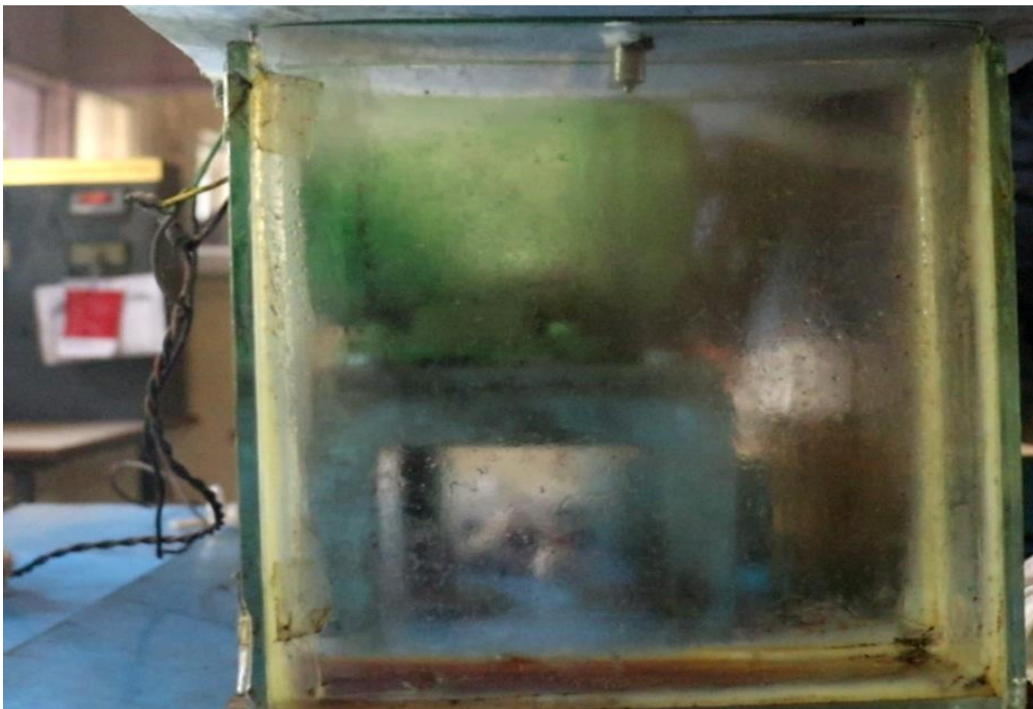


Fig. 5.1: Spray Image taken for Biodiesel made from Illupai Oil during the experimentation



Fig. 5.2: Spray Image taken for Biodiesel made from Pongamia Oil during the experimentation

The above two pictures are the sample images taken for the analysis of the spray characterization like spray penetration length, spray angle and spray area. A sample of 6 to 8 images are taken for the analysis of the spray characteristics.

Biodiesel spray properties are investigated by selecting biodiesel samples, modelling engine conditions, and changing injection settings in experimental setups. High-speed photography records spray dynamics, allowing for the investigation of characteristics such as spray angle and droplet dispersion. The findings assist to understand biodiesel's behaviour in comparison to diesel, as well as its interaction with engine combustion.

The analysis of acquired data highlights patterns and obstacles, which guide the development of specialized engine designs and combustion techniques for biodiesel fuels, therefore promoting sustainable transportation technology.

5.1.1 Spray Penetration Length

It describes the distance that the fuel spray makes after being injected into the combustion chamber. Optimized spray penetration in CI engines is essential for improving air-fuel mixing and combustion efficiency. To ensure that all fuel droplets have enough time to mix with the air and ignite, a longer penetration enables better fuel distribution throughout the chamber.

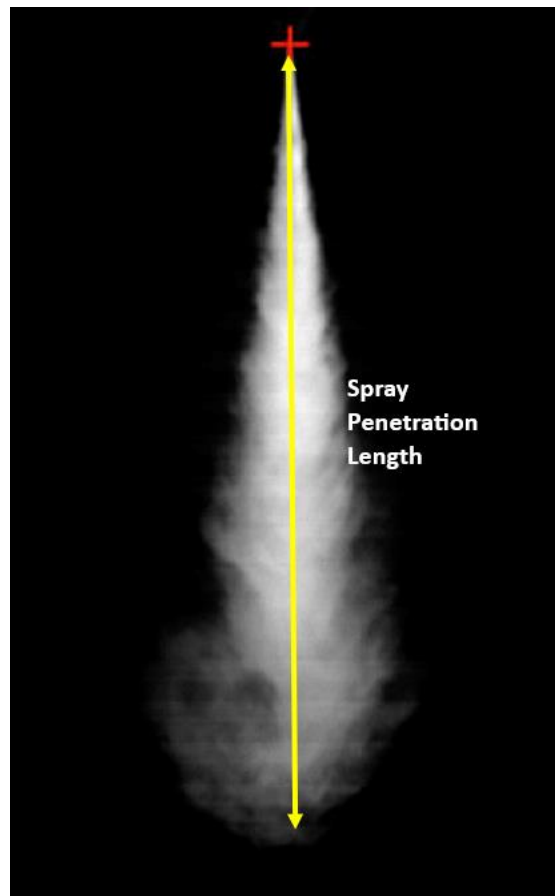


Fig. 5.3: Spray Penetration Length

Controlling the spray penetration in SI engines will help to guarantee that the fuel gets to the proper places for effective combustion. It is crucial to research and refine spray penetration for biofuels with specific qualities that might affect this parameter. Researchers can increase engine performance, emissions, and fuel efficiency while utilizing sustainable biofuels by comprehending and managing spray penetration. This will help the transportation industry become cleaner and more environmentally friendly. (Soid & Zainal, 2011a)

5.1.2 Spray angle

The angle at which the fuel spray fanned out as it leaves the injector nozzle is what it symbolizes. The distribution and coverage of the fuel within the combustion chamber are strongly impacted by the spray cone angle. Achieving the ideal spray cone angle in CI engines is crucial for facilitating efficient air-fuel mixing. The fuel is dispersed uniformly and may be burned completely with the help of a precisely specified and regulated cone angle.

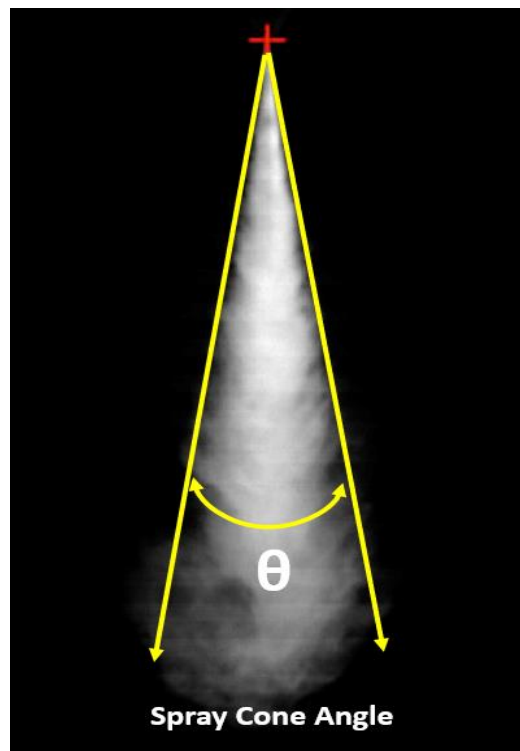


Fig. 5.4: Spray Angle

When utilizing biofuels like biodiesel, where optimum mixing is essential for lowering emissions and increasing combustion efficiency, this value is very crucial. To ensure that the fuel spray is directed to the appropriate locations for effective combustion in SI engines, the spray cone angle should be tailored to the engine's unique requirements. For biofuels like ethanol or methanol, properly defining and managing the spray cone angle is essential for getting the best engine performance and emissions reduction, advancing environmentally friendly transportation solutions. (Bergthorson & Thomson, 2015)

5.1.3 Spray Area

In spray characteristics testing, the spray area is the geographical distribution of the sprayed substance. It refers to the coverage and dispersion of the spray pattern, which is critical for a variety of applications ranging from agricultural to industrial coating. A thorough analysis of the spray region entails assessing variables such as spray angle, droplet size distribution, and spray pattern consistency. The spray angle defines the breadth of the spray pattern, which is critical for determining coverage efficiency. The measurement is taken from the nozzle's centre axis to the spray's outer margins.

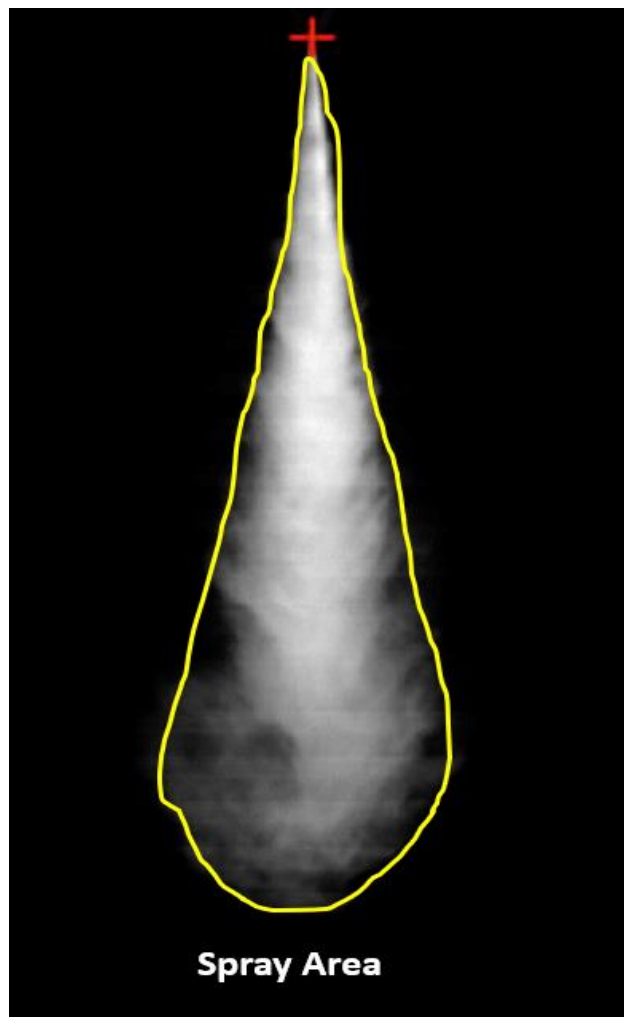


Fig. 5.5: Spray Area

Droplet size distribution measures the range of droplet sizes generated by the nozzle, which influences aspects such as drift potential and target penetration. A regular spray pattern offers continuous coverage over the desired area, reducing waste and increasing efficacy.(Dayal et al., 2004)

Visual examination, image analysis, and specialist equipment like laser diffraction systems are common testing methods. These approaches give quantitative information on spray area parameters, which aids in nozzle selection, calibration, and optimization for specific applications. Understanding the spray area in detail enables accurate control and modification of spraying systems, resulting in improved performance and less environmental impact.

5.1.4 Understanding Spray Characteristics

Spray length indicates how far the spray extends from the site of injection, which is important for determining its reach within the combustion chamber or target region. The spray angle indicates the dispersion or spread of the spray. A broader spray angle suggests higher dispersion, which may influence fuel-air mixing and combustion efficiency.

In contrast, a narrower spray angle indicates a more concentrated spray, which may affect fuel distribution within the combustion chamber. Finally, the spray area refers to the entire surface area covered by the spray pattern. This metric provides information on the spray's total coverage and density, which is useful for evaluating its efficacy in attaining ideal combustion conditions. (Qin et al., 2015)

Researchers can better comprehend the physical distribution, dispersion, and coverage of the spray pattern by combining analyses of spray length, spray angle, and spray area. This information is critical for improving fuel injection techniques, combustion processes, and engine performance in a variety of applications, including automobile engines, industrial burners, and sprayer systems.

5.2 SPRAY PENETRATION LENGTH ANALYSIS

Spray tip penetration refers to the length obtained by the spray tip after injection.(Agarwal & Chaudhury, 2012b)The spray penetration length is critical in engine research since it directly effects combustion efficiency and emissions. Proper penetration ensures that fuel combines efficiently with air, which improves ignition and combustion processes. Understanding and managing this characteristic helps to develop engines with higher performance, better fuel economy, and lower environmental impact.

In engine studies, spray penetration length is essential for improving fuel-air mixing, combustion efficiency, and emissions management. It allows engineers to customize injection techniques, piston shape, and combustion chamber design for improved performance, fuel efficiency, and pollutant reduction, resulting in better engine operation and environmental sustainability. (Soid & Zainal, 2011b)

Spray tip penetration length was tested for biofuels made from illupai and Pongamia oils. The results revealed significant differences in penetration lengths between the two biodiesels. The average spray penetration length taken from best images i.e., Fig.5.6 and Fig 5.7, of illupai oil-based biofuel was found to be 48.35 mm, whereas that of Pongamia oil-based biofuel was 33.41 mm. The spray penetration of Biofuel made from illupai oil is more than biofuel made from pongamia oil. This is because the viscosity and density of the biodiesel made from illupai oil is less. If the spray penetration length of the biodiesel is more it enhances air fuel mixing, improves combustion efficiency and reduced emissions. The findings imply that biofuels derived from various feedstocks may have variable spray properties, which might affect combustion efficiency and emissions. (Agarwal & Chaudhury, 2012c)

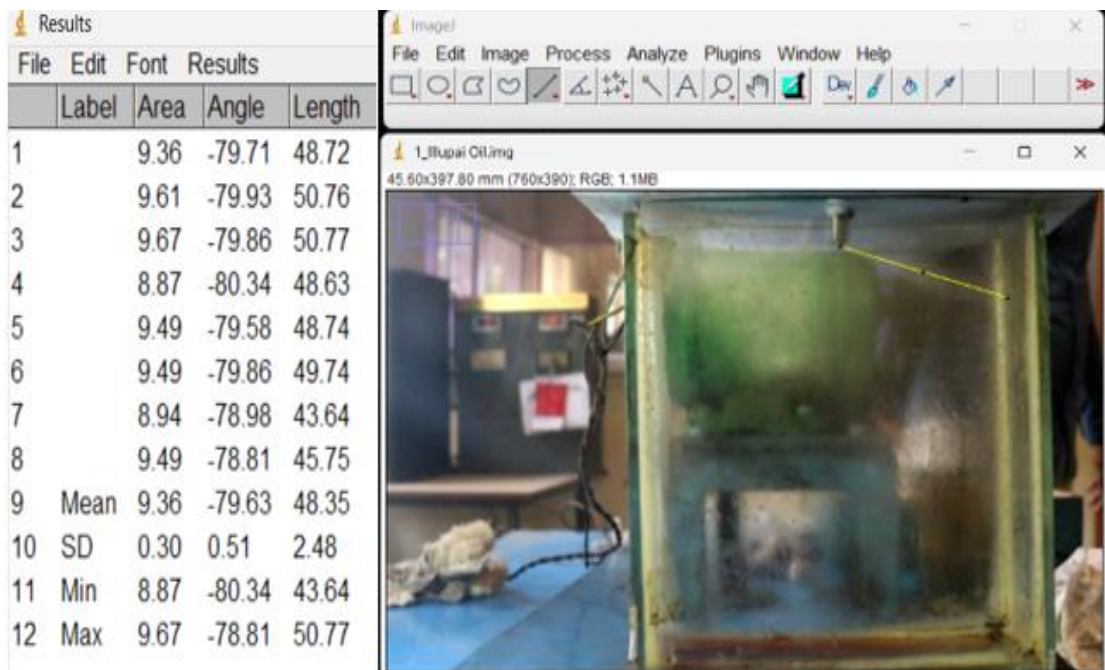


Fig. 5.6: Spray Penetration length calculated from Image J Software for Illupai Oil

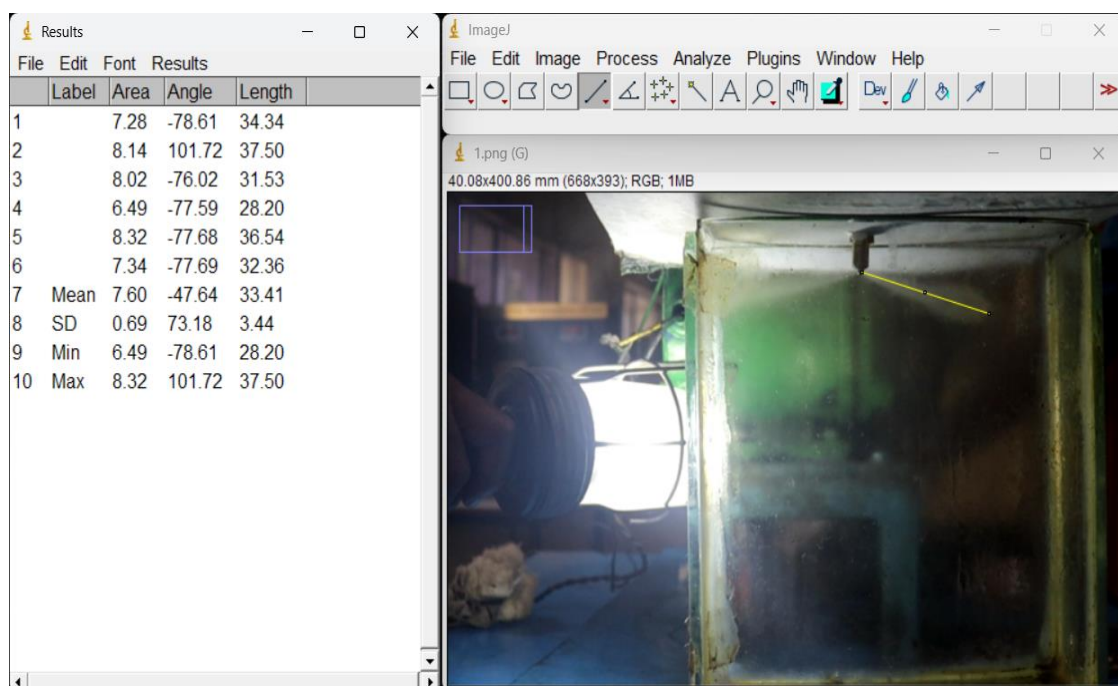


Fig.5.7: Spray Penetration length calculated from Image J Software for Pongamia Oil

Table 5.1: Variation of Spray Penetration Length with respect to time

Time (ms)	Spray Penetration Length (mm)	
	Illupai Oil	Pongamia Oil
10	11.35	8.42
20	19.24	12.34
30	28.31	19.89
40	37.79	26.21
50	48.35	33.41

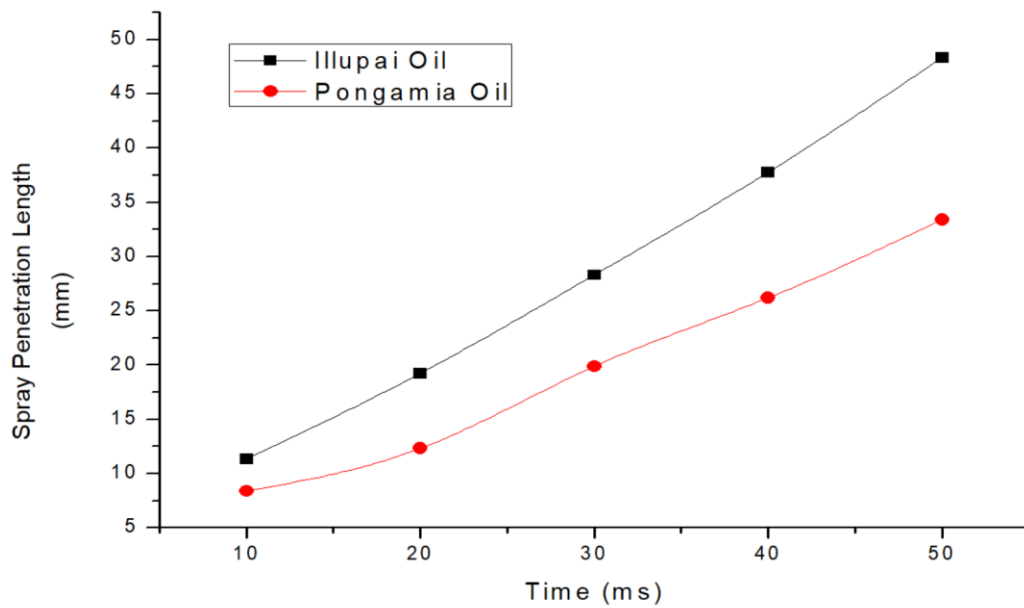


Fig.5.8: Time vs Spray Penetration Length Graph

5.3 SPRAY ANGLE ANALYSIS

The spray angle refers to the angle formed by straight lines from the nozzle tip to the spray boundary. (Wang et al., 2010) The spray angle plays a major role in engine research because it controls fuel dispersion, vaporization, and mixing with air. The spray angle improves combustion efficiency, power output, and emission control. Understanding and managing this characteristic helps to develop engines with greater performance, fuel economy, and environmental effect. (Ma et al., 2015)

The spray angle in engine research is critical for effective fuel distribution, combustion, and emissions management. It has a direct impact on air/fuel mixing, combustion stability, and heat release rates. Optimizing spray angle improves engine performance, fuel economy, and pollution reduction, which is critical for satisfying rigorous environmental laws and improving overall engine functioning. (Shu et al., 2019)

The average spray angle taken from the best images i.e., Fig.5.9 and Fig 5.10, during the experimentation of illupai oil-based biofuel was found to be 20.94° , whereas that of Pongamia oil-based biofuel was 19.17° . The spray angle of Biofuel made from illupai oil is more than biofuel made from pongamia oil. This is because the density and viscosity of the biofuel is less. Wider spray cone angle indicates that it leads to incomplete combustion, increased emissions, greater fuel consumption and decreases the engine efficiency. (Shu et al., 2019)

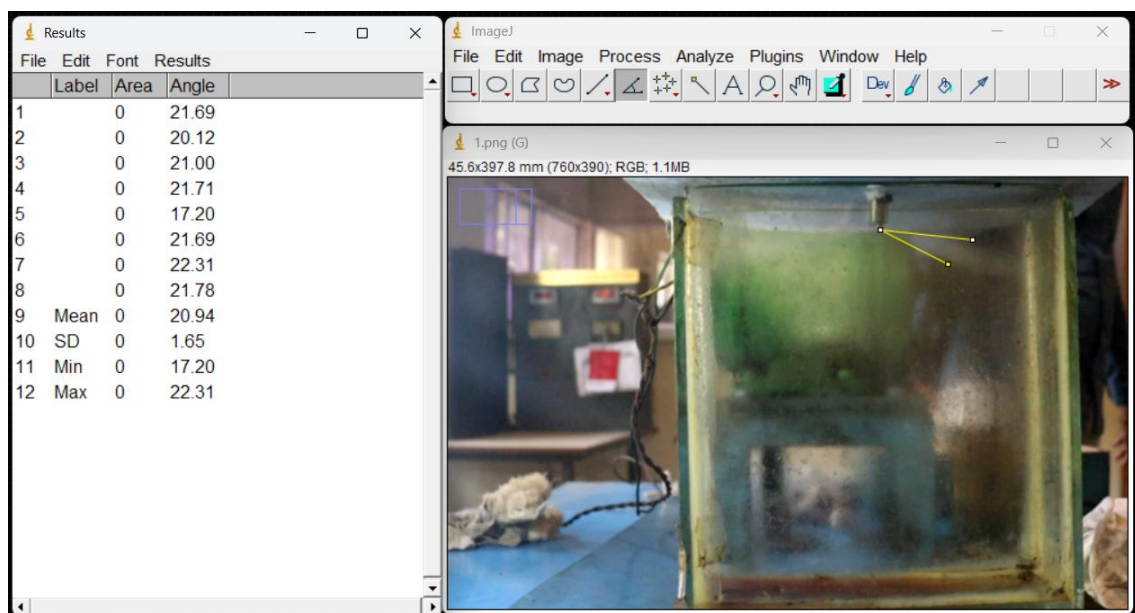


Fig.5.9: Spray Angle calculated from Image J Software for Illupai Oil

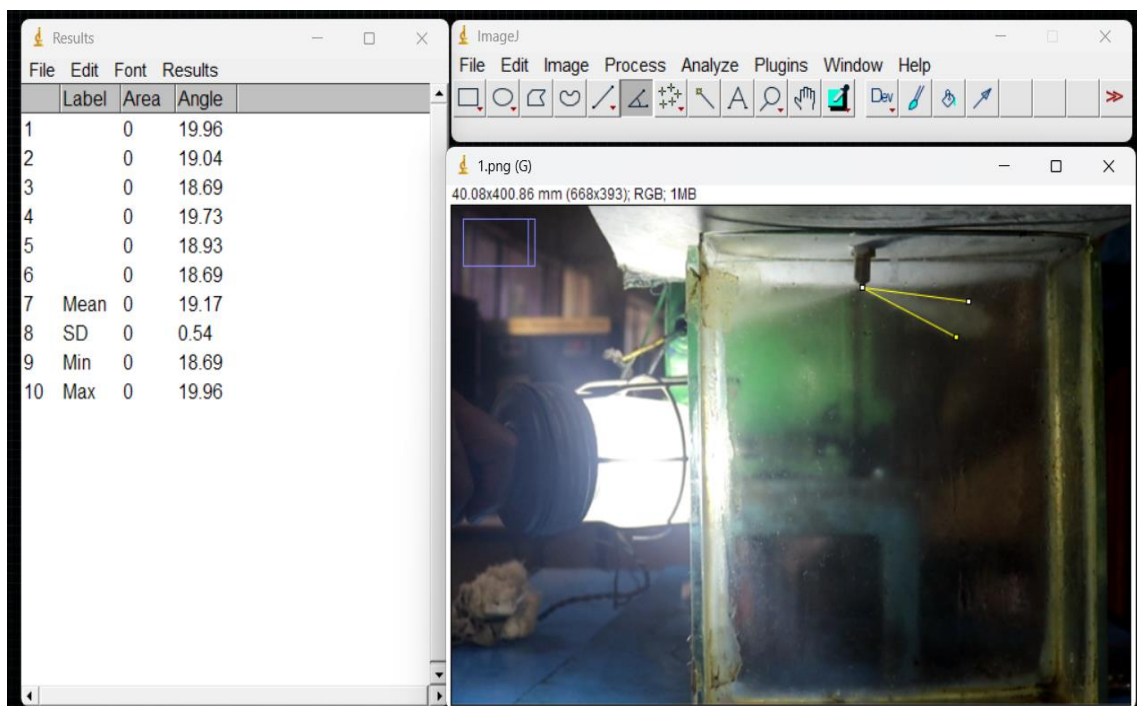


Fig.5.10: Spray Angle calculated from Image J Software for Pongamia Oil

Table 5.2: Variation of Spray Angle with respect to time

Time (ms)	Spray Angle (in degrees)	
	Illupai Oil	Pongamia Oil
10	19.75	18.59
20	19.91	18.73
30	20.02	18.92
40	20.43	19.01
50	20.94	19.17

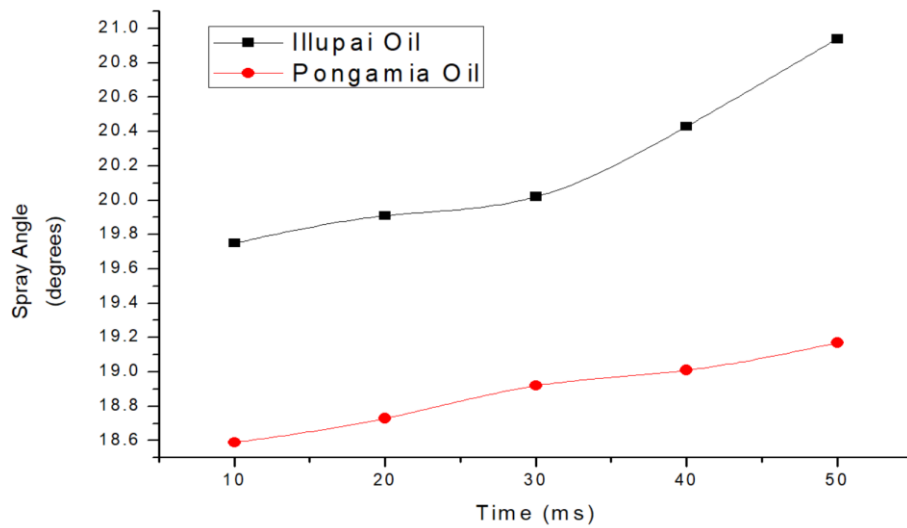


Fig.5.11: Time vs Spray Angle Graph

5.4 SPRAY AREA ANALYSIS

Spray area is the entire surface covering of droplets distributed by a spray. (Park et al., 2011) The spray area in engine studies is important because it influences fuel-air mixing, combustion efficiency, and emissions. Understanding and managing the spray area improves engine performance, fuel efficiency, and emissions management measures. It helps to build engines with higher efficiency, lower emissions, and better overall combustion characteristics.

Measuring spray area in engine studies is critical for optimizing fuel distribution, combustion efficiency, and emission control. It gives critical insights into the efficacy of fuel injection systems and aids in the design of engines with increased performance, better fuel economy, and lower environmental impact, assuring efficient and sustainable operation. (Yu et al., 2009a)

The spray area analysis revealed distinct characteristics between biofuels derived from Illupai and Pongamia oils. The average spray angle taken from the best images i.e., Fig.5.12 and Fig 5.13, Illupai oil-based biofuel exhibited a spray area of 161.16 mm², while Pongamia oil-based biofuel showed a spray area of 131.41 mm². Illupai oil-based biofuel has a larger spray area than Pongamia oil-based biofuel, this is

because the illupai oil-based biodiesel had less density and viscosity. When the spray area is higher it results in proper combustion, increased engine efficiency, reduced emissions.(Yu et al., 2009b)

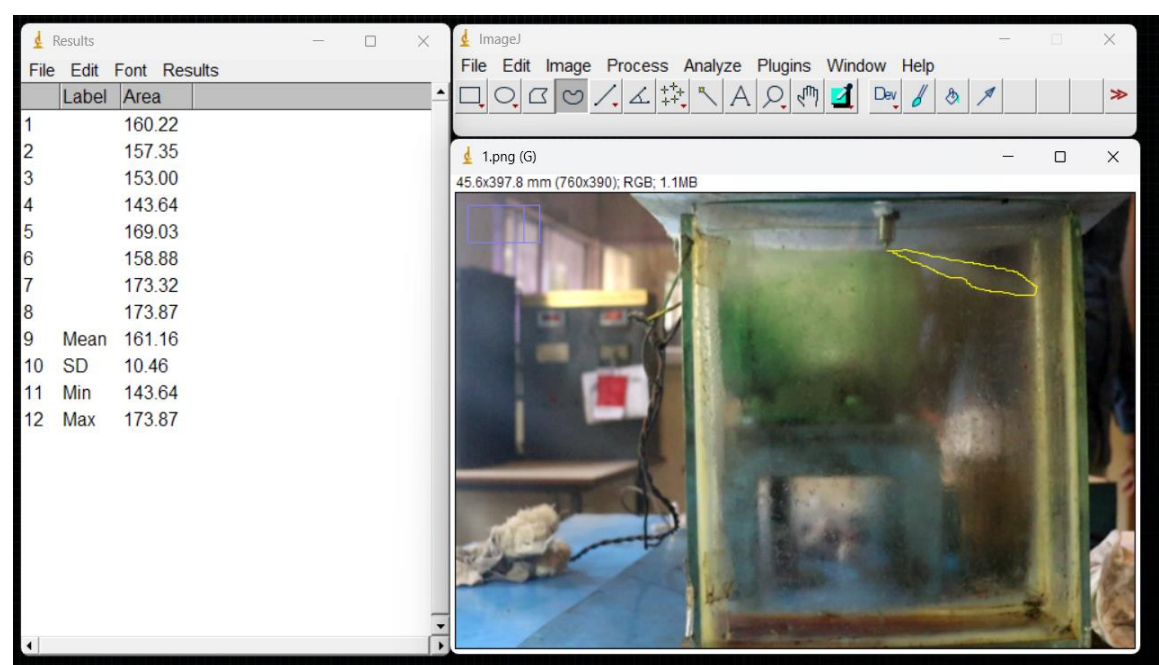


Fig.5.12: Spray Area calculated from Image J Software for Illupai Oil

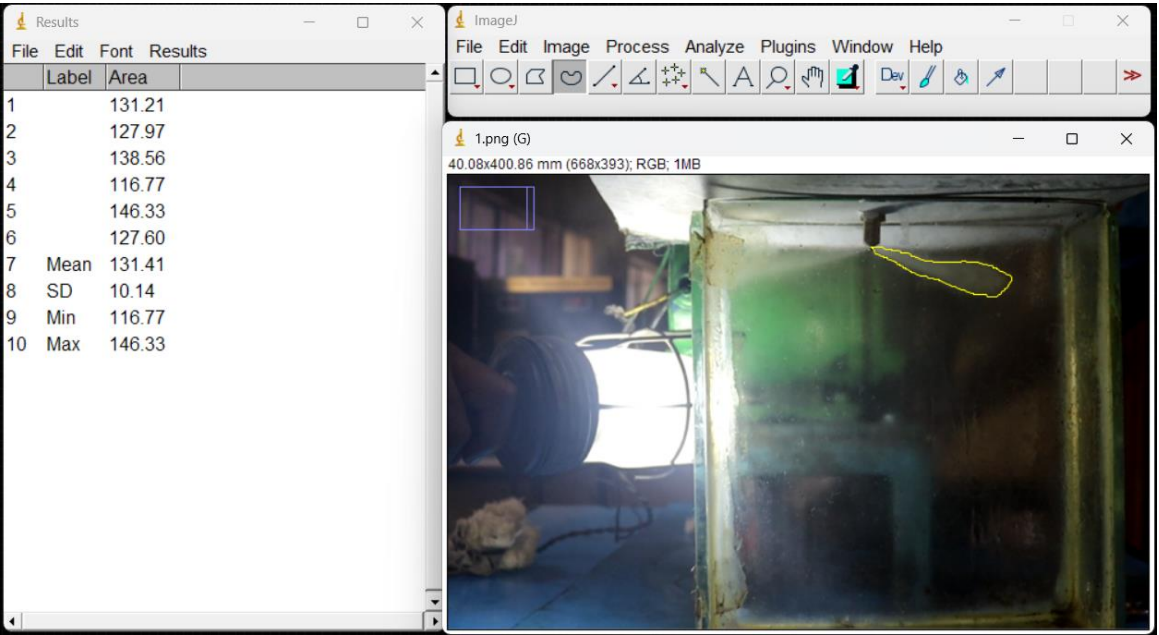


Fig.5.13: Spray Area calculated from Image J Software for Pongamia Oil

Table 5.3: Variation of Spray Area with respect to time

Time (ms)	Spray Area (mm ²)	
	Illupai Oil	Pongamia Oil
10	29.38	29.34
20	68.73	48.49
30	105.36	71.16
40	121.91	113.71
50	161.16	131.41

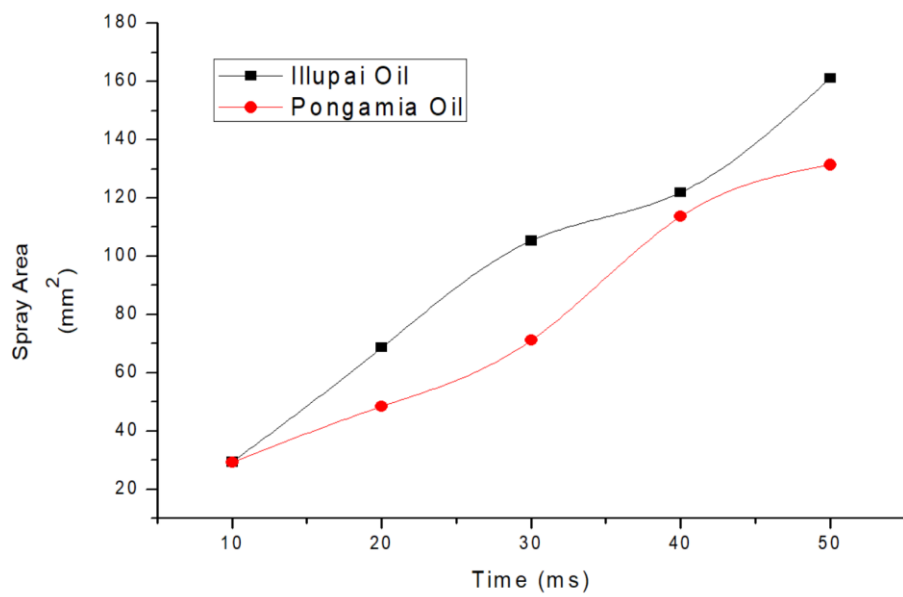


Fig.5.14: Time vs Spray Area Graph

**Table 5.4: Spray Characteristics of biodiesels made from
illupai oil and pongamia oil**

Spray Characteristics	Illupai Oil based Biodiesel	Pongamia Oil based Biodiesel
Spray Penetration Length	48.35 mm	43.41 mm
Spray Angle	20.94 ⁰	19.17 ⁰
Spray Area	161.16 mm ²	131.41 mm ²

Finally, it is observed that the spray penetration length is more for the illupai oil-based biodiesel than pongamia oil-based biodiesel. When the spray penetration length is more, we can say that it enhances air fuel mixing, improves combustion efficiency and reduced emissions. The viscosity and density of the biodiesel made from illupai oil is less so it has the more penetration length.

It is observed that the spray angle is more for the illupai oil-based biodiesel than pongamia oil-based biodiesel. When the spray angle is more, we can say that it leads to incomplete combustion, increased emissions, greater fuel consumption and decreases the engine efficiency. The density and viscosity of the biofuel is less so that the spray angle is more. If the viscosity and density is less it may result in narrower cone angle.

It is observed that the spray area is more for the illupai oil-based biodiesel than pongamia oil-based biodiesel. When the spray area is more, we can say that it exhibits proper combustion, increased engine efficiency, reduced emissions. The viscosity and density of the biodiesel is less so the spray area is more.

Table 5.5: Spray Characteristics Parameters comparison with other biodiesels

Fuel Type	Blend Ratios	Conditions	Spray Penetration Length (mm)	Spray Angle (in degrees)	Spray Area (mm²)	References
Jatropha Oil	B5	P _{inj} =200 bar	78.51	13.67 ⁰	-	(Gao et al., 2009)
	B10		79.80	15.91 ⁰	-	(Gao et al., 2009)
	B20		81.75	14.4 ⁰	-	(Gao et al., 2009)
	B50		83.01	14.38 ⁰	-	(Gao et al., 2009)
Used Fried Oil	B5	P _{inj} =200 bar	81.27	14.23 ⁰	-	(Gao et al., 2009)
	B10		82.70	13.78 ⁰	-	(Gao et al., 2009)
	B20		84.01	15.23 ⁰	-	(Gao et al., 2009)
	B50		85.6	15.12 ⁰	-	(Gao et al., 2009)
Palm Oil	B5	P _{inj} =200 bar	81.06	13.53 ⁰	-	(Gao et al., 2009)
	B10		81.96	14.98 ⁰	-	(Gao et al., 2009)
	B20		83.74	14.01 ⁰	-	(Gao et al., 2009)

	B50		85.12	14.16 ⁰	-	(Gao et al., 2009)
Palm Oil Methyl Ester	B100	P _{inj} = 230 bar	32.69 ⁰	15.72 ⁰	-	(P. R. Raghu et al., 2013)
Waste Cooking Oil	B20	P _{inj} =600 bar, P _{Amb} =30 bar	51.79	17.81 ⁰	-	(Mohan et al., 2014)
		P _{inj} =1000 bar, P _{Amb} =30 bar	57.71	18.5 ⁰	-	(Mohan et al., 2014)
	B100	P _{inj} =600 bar, P _{Amb} =30 bar	55.65	16.75 ⁰	-	(Mohan et al., 2014)
		P _{inj} =1000 bar, P _{Amb} =30 bar	59.81	17.6 ⁰	-	(Mohan et al., 2014)
Karanja Oil Methyl Ester	B100	P _{inj} = 180 bar	54.81	18.63 ⁰	-	(Prakash et al., 2015)
		P _{inj} = 220 bar	57.72	13.33	69.6	(P. Raghu et al., 2015)
		P _{inj} = 240 bar	57.98	17.88	-	(Prakash et al., 2015)
Jatropha Oil Methyl Ester	B100	P _{inj} = 220 bar	56.06	11.89	67.2	(P. Raghu et al., 2015)
Emulsified Castor Biodiesel	B100	P _{inj} = 196 bar	48.95	17.25 ⁰	-	(Lin & Lin, 2011)

Castor Biodiesel	B100	$P_{inj} = 196$ bar	40.73	17.30^0	-	(Lin & Lin, 2011)
Fatty acid methyl ester	B100	$P_{inj} = 700$ bar, $P_{Amb} = 20$ bar	68.86	14.75	637.51	(Fu et al., 2023)
		$P_{inj} = 700$ bar, $P_{Amb} = 28$ bar	57.89	15.02	543.69	(Fu et al., 2023)
		$P_{inj} = 15$ bar, $T_{Amb} = 550K$	61.23	-	-	(Otchere et al., 2020)
		$P_{inj} = 25$ bar, $T_{Amb} = 550K$	54.78	-	-	(Otchere et al., 2020)
	B15	$P_{inj} = 700$ bar, $P_{Amb} = 14$ bar	66.32	-	-	(Fu et al., 2020)
		$P_{inj} = 900$ bar, $P_{Amb} = 28$ bar	63.56	-	-	(Fu et al., 2020)
	B30	$P_{inj} = 700$ bar, $P_{Amb} = 14$ bar	58.79	-	-	(Fu et al., 2020)
Biodiesel made from Illupai Oil	B20	$P_{inj} = 230$ bar	48.35	20.94^0	161.16	Present Study
Biodiesel made from Pongamia Oil	B20	$P_{inj} = 230$ bar	43.41	19.17^0	131.41	Present Study

When compared to Jatropha oil, the spray characteristic characteristics of biodiesel derived from Illupai and Pongamia oil show noticeable differences. Biodiesel made from illupai oil has a somewhat lower spray penetration length (48.35 mm) than biodiesel made from jatropha oil (78.51 mm to 85.6 mm depending on the mix ratio). On the other hand, biodiesel derived from pongamia oil has a larger spray penetration length (43.41 mm), while it is still within the Jatropha oil's range. When compared to Jatropha oil, the biodiesels from Illupai and Pongamia oil exhibit bigger spray areas (161.16 mm² and 131.41 mm², respectively), suggesting a possibly wider spray dispersion.

Significant variations may be seen when comparing the spray characteristic parameters of biodiesel made from illupai and pongamia oils with used fried oil. The spray penetration length of biodiesel derived from Illupai oil is 48.35 mm, whereas that of used fried oil varies from 81.27 mm to 85.6 mm at various mix ratios. On the other hand, the biodiesel derived from pomelo oil has a larger spray penetration length (43.41 mm), while it is still within the Used Fried Oil's range. In comparison to Used Fried Oil, both Illupai and Pongamia oil biodiesels exhibit bigger spray areas (161.16 mm² and 131.41 mm², respectively). These changes indicate that the biodiesels made from various feedstock oils and utilized fried oil may differ in terms of atomization efficiency, combustion characteristics, and emissions performance.

There are a few differences in the spray characteristic characteristics of biodiesel made from illupai and pongamia oils and palm oil. The spray penetration length of biodiesel derived from Illupai oil is 48.35 mm, whereas that of palm oil varies between 81.06 mm and 85.12 mm at various mix ratios. In contrast, the biodiesel derived from pongamia oil exhibits a spray penetration length of 43.41 mm when compared to palm oil. When compared to palm oil, the spray areas of Illupai and Pongamia oil biodiesels are likewise greater (161.16 mm² and 131.41 mm², respectively). These discrepancies might indicate that the biodiesels made from illupai, pongamia, and palm oils differ in terms of atomization efficiency, combustion behavior, and emissions characteristics, which could affect how suitable they are for usage in diesel engines.

Several noteworthy distinctions may be seen when comparing the spray characteristic characteristics of biodiesel made from illupai and pongamia oils with Palm Oil Methyl Ester (POME). In comparison to POME, which varies in spray penetration length from 32.690 mm to 57.98 mm at various injection pressures, biodiesel derived from Illupai oil has a shorter spray penetration length of 48.35 mm. On the other hand, POME and Pongamia oil-based biodiesel exhibit different spray penetration lengths (43.41 mm). Furthermore, as compared to POME, the spray areas of Illupai and Pongamia oil biodiesels are bigger (161.16 mm² and 131.41 mm², respectively). These differences point to possible differences in atomization efficiency, combustion properties, and emissions performance between the biodiesels made from pongamia oil, palm oil methyl ester, and illupai oil, which might affect how suitable they are for use in diesel engines.

A few distinctions may be seen when comparing the spray characteristic characteristics of biodiesel made from illupai and pongamia oils with Waste Cooking Oil (WCO). The spray penetration length of biodiesel derived from Illupai oil is 48.35 mm, whereas that of WCO varies between 51.79 mm and 59.81 mm at varying injection pressures. In contrast, the biodiesel derived from pongamia oil exhibits a spray penetration length of 43.41 mm, which is comparable to that of WCO. Furthermore, as compared to WCO, the spray areas of Illupai and Pongamia oil biodiesels are bigger (161.16 mm² and 131.41 mm², respectively). These variances raise the possibility that the biodiesels made from waste cooking oil, illupai oil, and pongamia oil differ in terms of atomization efficiency, combustion behavior, and emissions characteristics, which might have an impact on how well they function in diesel engines.

There are noticeable variations when comparing the spray characteristic characteristics of biodiesel made from illupai and pongamia oils with Karanja Oil Methyl Ester (KOME). In comparison to KOME, which varies in spray penetration length between 54.81 and 57.98 mm at varying injection pressures, biodiesel derived from Illupai oil has a shorter length of 48.35 mm. On the other hand, Pongamia oil-based biodiesel exhibits a spray penetration length (43.41 mm) that is comparable to that of KOME. Furthermore, as compared to KOME, the spray areas

of Illupai and Pongamia oil biodiesels are bigger (161.16 mm² and 131.41 mm², respectively). These changes may point to discrepancies in the biodiesels made from illupai oil, pongamia oil, and karanja oil methyl ester that affect their appropriateness for use in diesel engines in terms of atomization efficiency, combustion characteristics, and emissions performance.

There are several noticeable variations when comparing the spray characteristic characteristics of biodiesel made from illupai and pongamia oils with Jatropha Oil Methyl Ester (JOME). The spray penetration length of biodiesel derived from Illupai oil is 48.35 mm, whereas that of JOME varies between 56.06 mm and 83.01 mm at varying injection pressures. On the other hand, Pongamia oil-based biodiesel exhibits a spray penetration length (43.41 mm) that is comparable to that of JOME. Furthermore, as compared to JOME, the spray areas of Illupai and Pongamia oil biodiesels are bigger (161.16 mm² and 131.41 mm², respectively). These variances imply that the biodiesels made from illupai oil, pongamia oil, and jatropha oil methyl ester may differ in terms of atomization efficiency, combustion behaviors, and emissions characteristics, which might affect how well they function in diesel engines.

There are notable distinctions and parallels between the spray characteristic characteristics of biodiesel made from illupai and pongamia oils and those of emulsified castor biodiesel (ECB), castor biodiesel (CB), and fatty acid methyl ester (FAME). In comparison to ECB and CB, which normally have spray penetration lengths ranging from 40.73 mm to 48.95 mm, illupai oil-based biodiesel has a somewhat lower spray penetration length (48.35 mm). The spray penetration length of pongamia oil-based biodiesel (43.41 mm) is comparable to that of ECB and CB.

Comparing Illupai and Pongamia oil biodiesels to ECB and CB, the latter two exhibit smaller spray areas (161.16 mm² and 131.41 mm², respectively), suggesting a possible wider spray dispersion. Meanwhile, FAME exhibits variable spray characteristics between 543.69 mm² and 637.51 mm², with spray penetration lengths ranging from 32.69 mm to 68.86 mm, contingent upon injection pressure and environmental circumstances. These variances point to possible discrepancies in the atomization efficiency, combustion behaviour, and emissions characteristics

of the biodiesels made from FAME, ECB, CB, and Illupai oil. Spray properties are largely dependent on variables including fuel mix, injection pressure, and environmental factors. All things considered, these comparisons provide light on the variety of biodiesel fuels and whether they are suitable for use in diesel engines in terms of spray performance.



Fig. 5.15: Photos taken while performing the Experiment

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 SUMMARY

The spray properties of biodiesel generated from free fatty acids were examined in this study to better understand its potential as an alternative fuel. Biodiesel made from free fatty acids is a viable source of sustainable energy due to its renewable nature and ability to minimize greenhouse gas emissions. However, knowing its spray properties is critical for determining its combustion efficiency and emissions disposition. The experimental investigation involves the use of a cutting-edge spray chamber device to imitate real-world situations. Spray angle, spray area, and spray penetration were precisely monitored and studied. The study used two biodiesels made from pongamia oil and illupai oil to assess the effect of biodiesel content on spray characteristics.

The results showed that biodiesel generated from free fatty acids had unique spray properties compared to regular diesel. Our study found that spray penetration changed as the viscosity and density of the fuel is changed. Biodiesel with low density had the longer penetration durations. The spray penetration length of Biofuel made from illupai oil is more than biofuel made from pongamia oil. This is because the viscosity and density of the biodiesel made from illupai oil is less. If the spray penetration length of the biodiesel is more it enhances air fuel mixing, improves combustion efficiency and reduced emissions. The findings imply that biofuels derived from various feedstocks may have variable spray properties, which might affect combustion efficiency and emissions.

The average spray angle illupai oil-based biofuel was found to be 20.94° , whereas that of Pongamia oil-based biofuel was 19.17° . The spray angle of Biofuel made from illupai oil is more than biofuel made from pongamia oil. This is because the density and viscosity of the biofuel is less. Wider spray cone angle indicates that it leads to incomplete combustion, increased emissions, greater fuel consumption and decreases the engine efficiency.

The spray area analysis revealed distinct characteristics between biofuels derived from Illupai and Pongamia oils. Illupai oil-based biofuel exhibited a spray area of 161.16 mm^2 , while Pongamia oil-based biofuel showed a spray area of 131.41 mm^2 . Illupai oil-based biofuel has a larger spray area than Pongamia oil-based biofuel, this is because the illupai oil-based biodiesel had less density and viscosity. This results proper combustion, increased engine efficiency, reduced emissions. Understanding these variations is crucial for improving engine performance and emissions control measures when using biodiesel made from free fatty acids.

The spray characteristics investigation sheds light on the possible usage of biodiesel derived from free fatty acids as a viable alternative fuel. The observed variations in spray behaviour compared to standard diesel underscore the significance of customized combustion techniques and engine modifications for peak performance. Overall, this work adds to the expanding body of information about alternative fuels and their potential applications in addressing environmental problems and energy sustainability. This study advances renewable energy technology by understanding the spray properties of biodiesel generated from free fatty acids.

6.2 CONCLUSION

The current experimental investigations are being carried out in DI Diesel engines employing high-definition video cameras and image processing approaches. Important spray properties such as spray tip penetration, spray angle, and spray area were explored. Illupai oil has a lower density and viscosity than pongamia oil.

It was concluded that spray penetration length is more for biofuel made from illupai oil than biofuel made from pongamia oil. This means that the higher spray penetration length indicates it enhances air fuel mixing, improves combustion efficiency and reduced emissions. The spray cone angle for illupai oil is more than pongamia oil. This means that larger spray cone angle leads to incomplete combustion, increased emissions, greater fuel consumption and decreases the engine efficiency. And the spray area of illupai oil is more than the pongamia oil. This means that higher spray area results proper combustion, increased engine efficiency, reduced emissions.

REFERENCES

1. Abomohra, A. E. F., Elsayed, M., Esakkimuthu, S., El-Sheekh, M., & Hanelt, D. (2020). Potential of fat, oil and grease (FOG) for biodiesel production: A critical review on the recent progress and future perspectives. In *Progress in Energy and Combustion Science* (Vol. 81). Elsevier Ltd.
2. Achebe, C. H., Ogunedo, B. M. O., Chukwuneke, J. L., & Anosike, N. B. (2020). Analysis of diesel engine injector nozzle spray characteristics fueled with residual fuel oil. *Heliyon*, 6(8).
3. Agarwal, A. K., & Chaudhury, V. H. (2012a). Spray characteristics of biodiesel/blends in a high pressure constant volume spray chamber. *Experimental Thermal and Fluid Science*, 42, 212–218.
4. Agathou, M. S., & Kyritsis, D. C. (2012). Fuel composition effect on the electrostatically-driven atomization of bio-butanol containing engine fuel blends. *Energy Conversion and Management*, 60, 28–35.
5. Ahmad, M. U., Ali, S. M., Ahmad, A., Sheikh, S., & Ahmad, I. (2017). Carbocyclic Fatty Acids: Chemistry and Biological Properties. In *Fatty Acids: Chemistry, Synthesis, and Applications* (pp. 147–185). Elsevier.
6. Algayyim, S. J. M., & Wandel, A. P. (2021). Macroscopic and microscopic characteristics of biofuel spray (biodiesel and alcohols) in CI engines: A review. *Fuel*, 292, 120303.
7. Ashraful, A. M., Masjuki, H. H., Kalam, M. A., Rizwanul Fattah, I. M., Imtenan, S., Shahir, S. A., & Mobarak, H. M. (2014). Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: A review. *Energy Conversion and Management*, 80, 202–228.

8. Atadashi, I. M., Aroua, M. K., Abdul Aziz, A. R., & Sulaiman, N. M. N. (2012a). Production of biodiesel using high free fatty acid feedstocks. In *Renewable and Sustainable Energy Reviews* (Vol. 16, Issue 5, pp. 3275–3285).
9. Atadashi, I. M., Aroua, M. K., & Aziz, A. A. (2011). Biodiesel separation and purification: A review. In *Renewable Energy* (Vol. 36, Issue 2, pp. 437–443).
10. Battistoni, M., & Grimaldi, C. N. (2012). Numerical analysis of injector flow and spray characteristics from diesel injectors using fossil and biodiesel fuels. *Applied Energy*, 97, 656–666.
11. Bergthorson, J. M., & Thomson, M. J. (2015). A review of the combustion and emissions properties of advanced transportation biofuels and their impact on existing and future engines. In *Renewable and Sustainable Energy Reviews* (Vol. 42, pp. 1393–1417). Elsevier Ltd.
12. Bobade SN, & Khyade VB. (2012). Detail study on the Properties of Pongamia Pinnata (Karanja) for the Production of Biofuel. In *Research Journal of Chemical Sciences* (Vol. 2, Issue 7).
13. Canakci, M., & Van Gerpen, J. (n.d.). BIODIESEL PRODUCTION FROM OILS AND FATS WITH HIGH FREE FATTY ACIDS. *Transactions of the ASAE*, 44(6), 1429–1436.
14. Chaudhari, V. D., Kulkarni, A., & Deshmukh, D. (2021). Spray characteristics of biofuels for advance combustion engines. *Cleaner Engineering and Technology*, 5, 100265.
15. Dayal, P., Shaik, M. S., & Singh, M. (2004). Evaluation of different parameters that affect droplet-size distribution from nasal sprays using the Malvern Spraytec®. *Journal of Pharmaceutical Sciences*, 93(7), 1725–1742.
16. Douvartzides, S. L., Charisiou, N. D., Papageridis, K. N., & Goula, M. A. (2019). Green diesel: Biomass feedstocks, production technologies, catalytic

- research, fuel properties and performance in compression ignition internal combustion engines. In *Energies* (Vol. 12, Issue 5). MDPI AG.
17. Dwivedi, G., Jain, S., & Sharma, M. P. (2011). Impact analysis of biodiesel on engine performance - A review. In *Renewable and Sustainable Energy Reviews* (Vol. 15, Issue 9, pp. 4633–4641).
 18. Fu, W., Li, F., Liu, Y., Meng, K., & Lin, Q. (2023). Effect of in-cylinder environment on spray characteristics of diesel and biodiesel. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, 45(2), 3464–3474.
 19. Fu, W., Li, F., Meng, K., Liu, Y., & Lin, Q. (2020). Experimental and Analysis of Macroscopic Spray Characteristics of Biodiesel Blended with Di-n-butyl Ether Under Inert Conditions. *Waste and Biomass Valorization*, 11(7), 3501–3511.
 20. Gao, Y., Deng, J., Li, C., Dang, F., Liao, Z., Wu, Z., & Li, L. (2009). Experimental study of the spray characteristics of biodiesel based on inedible oil. *Biotechnology Advances*, 27(5), 616–624.
 21. Ghadge, S. V., & Raheman, H. (2005). Biodiesel production from mahua (*Madhuca indica*) oil having high free fatty acids. *Biomass and Bioenergy*, 28(6), 601–605.
 22. Jain, S., & Sharma, M. P. (2010). Stability of biodiesel and its blends: A review. In *Renewable and Sustainable Energy Reviews* (Vol. 14, Issue 2, pp. 667–678).
 23. Jedelský, J., Malý, M., Jícha, M., Sláma, J., & Wigley, G. (2021). Importance of geometrical factors on spray characteristics of spill-return atomizers. *Journal of Propulsion and Power*, 37(3), 408–418.

24. Kumar, N. (2017). Oxidative stability of biodiesel: Causes, effects and prevention. In *Fuel* (Vol. 190, pp. 328–350). Elsevier Ltd.
25. Kumar Tiwari, A., Kumar, A., & Raheman, H. (2007). Biodiesel production from jatropha oil (*Jatropha curcas*) with high free fatty acids: An optimized process. *Biomass and Bioenergy*, 31(8), 569–575.
26. Lin, Y. S., & Lin, H. P. (2011). Spray characteristics of emulsified castor biodiesel on engine emissions and deposit formation. *Renewable Energy*, 36(12), 3507–3516.
27. Ma, R., Dong, B., Yu, Z., Zhang, T., Wang, Y., & Li, W. (2015). An experimental study on the spray characteristics of the air-blast atomizer. *Applied Thermal Engineering*, 88, 149–156.
28. Mahmudul, H. M., Hagos, F. Y., Mamat, R., Adam, A. A., Ishak, W. F. W., & Alenezi, R. (2017). Production, characterization and performance of biodiesel as an alternative fuel in diesel engines – A review. In *Renewable and Sustainable Energy Reviews* (Vol. 72, pp. 497–509). Elsevier Ltd.
29. Mancaruso, E., Sequino, L., & Vaglieco, B. M. (2011). First and second generation biodiesels spray characterization in a diesel engine. *Fuel*, 90(9), 2870–2883.
30. Mathiyazhagan, M., Ganapathi, A., Jaganath, B., Renganayaki, N., & Sasireka, N. (2011). Production of Biodiesel from Non-edible plant oils having high FFA content. In *International Journal of Chemical and Environmental Engineering* (Vol. 2, Issue 2).
31. Mehra, K. S., Pal, J., & Goel, V. (2023). A comprehensive review on the atomization and spray characteristics of renewable biofuels. *Sustainable Energy Technologies and Assessments*, 56, 103106.

32. Milano, J., Ong, H. C., Masjuki, H. H., Chong, W. T., Lam, M. K., Loh, P. K., & Vellayan, V. (2016). Microalgae biofuels as an alternative to fossil fuel for power generation. In *Renewable and Sustainable Energy Reviews* (Vol. 58, pp. 180–197). Elsevier Ltd.
33. Mohan, B., Yang, W., Tay, K. L., & Yu, W. (2014). Experimental study of spray characteristics of biodiesel derived from waste cooking oil. *Energy Conversion and Management*, 88, 622–632.
34. Monteiro, M. R., Ambrozin, A. R. P., Lião, L. M., & Ferreira, A. G. (2008). Critical review on analytical methods for biodiesel characterization. In *Talanta* (Vol. 77, Issue 2, pp. 593–605). Elsevier.
35. Muthukumaran, N., Prasanna Raj Yadav, S., Saravanan, C. G., & Sekar, T. (2020). Synthesis of cracked Mahua oil using coal ash catalyst for diesel engine application. *International Journal of Ambient Energy*, 41(3), 241–256.
36. Naik, M., Meher, L. C., Naik, S. N., & Das, L. M. (2008). Production of biodiesel from high free fatty acid Karanja (*Pongamia pinnata*) oil. *Biomass and Bioenergy*, 32(4), 354–357.
37. Nizami, A. A., & Cernansky, N. P. (n.d.). *NO_x FORMATION IN MONODISPERSE FUEL SPRAY COMBUSTION*.
38. No, S.-Y. (2014). A Review on Spray Characteristics of Bioethanol and Its Blended Fuels in CI Engines. *Journal of ILASS-Korea*, 19(4), 155–166.
39. Otchere, P., Pan, J., Fan, B., Chen, W., Lu, Y., & Jianxing, L. (2020). Biodiesel Spray Characteristics and a CFD Simulation Study of Injection Timing Effects on the Combustion Process in a Biodiesel-Fueled, Direct-Injection Rotary Engine. *Journal of Energy Engineering*, 146(5).

40. Park, S. H., Yoon, S. H., & Lee, C. S. (2011). Effects of multiple-injection strategies on overall spray behavior, combustion, and emissions reduction characteristics of biodiesel fuel. *Applied Energy*, 88(1), 88–98.
41. Patel, C., Lee, S., Tiwari, N., Agarwal, A. K., Lee, C. S., & Park, S. (2016). Spray characterization, combustion, noise and vibrations investigations of Jatropha biodiesel fuelled genset engine. *Fuel*, 185, 410–420.
42. Payri, R., García, J. M., Salvador, F. J., & Gimeno, J. (2005). Using spray momentum flux measurements to understand the influence of diesel nozzle geometry on spray characteristics. *Fuel*, 84(5), 551–561.
43. Prakash, V., Ramanujam, B. P., Nivedan, C. S., Nallusamy, N., & Raghu, P. (2015). Effect of Various Injection Pressures on Spray Characteristics of Karanja Oil Methyl Ester (KOME) and Diesel in a DI Diesel Engine. *Applied Mechanics and Materials*, 787, 815–819.
44. Qin, W., Hung, D. L. S., & Xu, M. (2015). Investigation of the temporal evolution and spatial variation of in-cylinder engine fuel spray characteristics. *Energy Conversion and Management*, 98, 430–439.
45. Raghu, P., Nallusamy, N., & Kasivisvanathan, P. (2015). Spray Characteristics of Diesel and Biodiesel Fuels for Various Injection Timings under Non Evaporating Conditions. *Applied Mechanics and Materials*, 787, 682–686.
46. Raghu, P. R., Thilagan, K. T., Thirumoorthy, M. T., Lokachari, S., & Nallusamy, N. (2013). Spray characteristics of diesel and biodiesel in direct injection diesel engine. *Advanced Materials Research*, 768, 173–179.
47. Ramasubramanian, S., Shai Sundram, V. S., Karikalan, L., Baskar, S., Kumar Sahu, S., Borkar, D. S., & Kumar, P. (2022). Experimental analysis of nano additive blended in Mahua oil biodiesel on engine characteristics. *Materials Today: Proceedings*, 63, 535–541.

48. Renzaho, A. M. N., Kamara, J. K., & Toole, M. (2017). Biofuel production and its impact on food security in low and middle income countries: Implications for the post-2015 sustainable development goals. In *Renewable and Sustainable Energy Reviews* (Vol. 78, pp. 503–516). Elsevier Ltd.
49. Ribeiro, A., Castro, F., & Carvalho, J. (n.d.). *INFLUENCE OF FREE FATTY ACID CONTENT IN BIODIESEL PRODUCTION ON NON-EDIBLE OILS*.
50. Shu, J., Fu, J., Liu, J., Ma, Y., Wang, S., Deng, B., & Zeng, D. (2019). Effects of injector spray angle on combustion and emissions characteristics of a natural gas (NG)-diesel dual fuel engine based on CFD coupled with reduced chemical kinetic model. *Applied Energy*, 233–234, 182–195.
51. Soid, S. N., & Zainal, Z. A. (2011a). Spray and combustion characterization for internal combustion engines using optical measuring techniques - A review. In *Energy* (Vol. 36, Issue 2, pp. 724–741). Elsevier Ltd.
52. Sudalai, S., Rupesh, K. J., Devanesan, M. G., & Arumugam, A. (2023). A critical review of Madhuca indica as an efficient biodiesel producer: Towards sustainability. *Renewable and Sustainable Energy Reviews*, 188, 113811.
53. Tye, Y. Y., Lee, K. T., Wan Abdullah, W. N., & Leh, C. P. (2011). Second-generation bioethanol as a sustainable energy source in Malaysia transportation sector: Status, potential and future prospects. In *Renewable and Sustainable Energy Reviews* (Vol. 15, Issue 9, pp. 4521–4536).
54. Wang, X., Huang, Z., Kutti, O. A., Zhang, W., & Nishida, K. (2010). Experimental and analytical study on biodiesel and diesel spray characteristics under ultra-high injection pressure. *International Journal of Heat and Fluid Flow*, 31(4), 659–666.
55. Yoon, S. H., Suh, H. K., & Lee, C. S. (2009). Effect of spray and EGR rate on the combustion and emission characteristics of biodiesel fuel in a compression ignition engine. *Energy and Fuels*, 23(3), 1486–1493.

56. Yu, Y., Zhu, H., Frantz, J. M., Reding, M. E., Chan, K. C., & Ozkan, H. E. (2009a). Evaporation and coverage area of pesticide droplets on hairy and waxy leaves. *Biosystems Engineering*, 104(3), 324–334.
57. Zandie, M., Ng, H. K., Gan, S., Muhamad Said, M. F., & Cheng, X. (2022). A comprehensive CFD study of the spray combustion, soot formation and emissions of ternary mixtures of diesel, biodiesel and gasoline under compression ignition engine-relevant conditions. *Energy*, 260, 125191.

APPENDIX



Images taken during spray experimentation without quartz glass



Tip of 2-hole nozzle (fuel injector)



Photos taken with the technical staff after the completion of the experimentation work