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Experimental investigations on spray characteristics of non-edible oils using phase doppler particle analyser

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ABSTRACT

The study uses a phase Doppler particle analyzer to experimentally investigate the influence of minimum quantity lubrication (MQL) parameters on the spray characteristics of vegetable oils in the MQL system. Droplet velocity and diameter of the Azadirachta Indica, Ceiba Pentandra, Madhuca Longifolia, and Calophyllum Inophyllum are measured by varying pressure levels, flow rate, and nozzle diameter. MQL system, Spray chamber system, and PDPA unit are the major systems in the PDPA system. MQL system supplies the oil as a mist in the spray chamber through the nozzle. At the same time, the PDPA unit measures the spray characteristics of the disintegrated oil using the Doppler effect. The oil droplet's size decreased when the pressure increased, whereas it increased with the oil's viscosity. The nozzle of 2 mm diameter reduced the droplet size while it increased for the 2.5 mm nozzle. The effect of the oil flow rate on spray characteristics was found to be insignificant. The results showed that lower-viscosity oils, ideal for machining, offer less resistance to disintegration and generate smaller droplets in the spray. Among all, the disintegration of oils is highly encouraged by pressure and nozzle diameter. In addition, suitable MQL system parameters can be identified for sustainable machining.

Keywords: Biodegradable oils; Spray lubrication; Vegetable based cutting oils; Minimum quantity lubrication; Cutting fluids.

1. INTRODUCTION

The study "Experimental investigations on spray characteristics of non-edible oils using Phase Doppler Particle Analyser" aims to explore the behavior of non-edible vegetable oils under various conditions using advanced measurement techniques. The utilization of non-edible oils for industrial applications, particularly in the context of minimum quantity lubrication (MQL), is driven by the increasing need for sustainable and environmentally friendly alternatives to conventional lubricants. These oils, which include Azadirachta Indica (AI), Ceiba Pentandra (CP), Madhuca Longifolia (ML), and Calophyllum Inophyllum (CI), offer the potential for reduced environmental impact while maintaining or enhancing the performance of lubrication systems [1].

The background of this study lies in the broader context of reducing the environmental footprint of industrial processes. Traditional lubricants, often derived from petroleum, pose significant environmental risks due to their non-biodegradability and potential for contamination. In contrast, vegetable oils are biodegradable and renewable, making them attractive alternatives. However, the performance of these oils in MQL systems, particularly their spray characteristics, needs thorough investigation to ensure they meet the necessary industrial standards [2].

Literature on the subject indicates that vegetable oils have been studied extensively for their lubrication properties. However, a gap exists in understanding their behavior when used in spray form in MQL systems. Previous studies have primarily focused on the chemical and physical properties of these oils, such as viscosity,

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density, and surface tension, but less attention has been given to how these properties influence spray characteristics such as droplet size and velocity. The Phase Doppler Particle Analyzer (PDPA) provides a robust method for such investigations, offering simultaneous droplet size and velocity measurements, which are critical for optimizing MQL systems [3].

The significance of this research is multifaceted. Firstly, it addresses the need for sustainable machining processes by evaluating the effectiveness of non-edible oils in reducing environmental impact. Secondly, it provides detailed insights into the spray characteristics of these oils, which is crucial for their successful implementation in MQL systems. Understanding how pressure, flow rate, and nozzle diameter affect droplet size and velocity can help design more efficient lubrication systems that minimize oil consumption and maximize performance [4].

The primary objective of this study is to experimentally determine the influence of Minimum Quantity Lubrication (MQL) parameters on the spray characteristics of various non-edible vegetable oils using a Phase Doppler Particle Analyzer (PDPA) system. Specifically, the study aims to measure the droplet size and velocity of Azadirachta Indica (AI), Ceiba Pentandra (CP), Madhuca Longifolia (ML), and Calophyllum Inophyllum (CI) oils under different pressures, flow rates, and nozzle diameters. By analyzing how variations in these parameters affect the spray characteristics of each oil, the research seeks to identify optimal MQL system settings that produce the most desirable spray characteristics for sustainable machining. This detailed investigation is expected to provide valuable insights into the behavior of these oils in MQL systems, thereby contributing to the development of more efficient and environmentally friendly lubrication practices in industrial applications [5].

The experimental setup integrates an MQL system, a spray chamber, and a PDPA unit. The MQL system supplies the oil as a mist through the nozzle into the spray chamber, where the PDPA unit measures the characteristics of the disintegrated oil droplets using the Doppler effect. The study varies the pressure (0.7 to 2.8 bar), oil flow rate (30 to 90 ml/h), and nozzle diameter (1.5 to 2.5 mm) to assess their impact on droplet size and velocity [6].

Results from the experiments indicate that increasing pressure decreases droplet size while increasing droplet velocity, which is consistent across all oils tested. The study finds that lower-viscosity oils, such as AI, are more easily disintegrated, resulting in smaller droplets at higher velocities. Conversely, higher-viscosity oils like CI offer more resistance to disintegration, producing larger droplets at lower velocities. The nozzle diameter also plays a significant role, with a 2 mm nozzle found to be more effective in generating smaller droplets than the 1.5 mm and 2.5 mm nozzles [7].

The implications of these findings are significant for the machining industry. By optimizing MQL system parameters, manufacturers can achieve better lubrication with less oil, reducing costs and environmental impact. The study provides a comprehensive understanding of how non-edible vegetable oils behave in spray form, paving the way for their broader adoption in industrial applications [8].

In conclusion, this research contributes valuable knowledge to sustainable machining. By elucidating the spray characteristics of non-edible vegetable oils under various MQL conditions, the study offers practical insights for optimizing lubrication systems. The findings support the potential of these oils to serve as effective, environmentally friendly alternatives to conventional lubricants, aligning with the industry's growing emphasis on sustainability. The detailed analysis of droplet size and velocity as influenced by pressure, flow rate, and nozzle diameter provides a foundation for further research and development in this area.

2. MATERIALS AND METHODS

Video cameras or laser lights are used to capture the behavior of the fluid in the spray. The critical parameter of the fluid in the spray is velocity and size, which can be measured using the reflection or refraction technique. Different measuring devices such as Optical Imaging Analyzer (OIA), Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV), and Phase Doppler Particle Analyzer (PDPA) are used to estimate the spray characteristics. The PDPA system determines the spray characteristics simultaneously. In contrast, other measuring devices can measure the velocity or size of the fluid in the spray. The spray characteristics of different vegetable oils were determined experimentally using the PDPA system. The vegetable oils are Azadirachta Indica (AI), Ceiba Pentandra (CP), Madhuca Longifolia (ML), and Calophyllum Inophyllum (CI).

The fluid properties of various oil are shown in Table 1. The density and surface tension are measured using a force tensiometer, and viscosity is measured using a Brookfield viscometer. Azadirachta Indica oil, which has a lower viscosity, disintegrates more readily under pressure, forming smaller droplets. This lower resistance to disintegration also allows the droplets to achieve higher velocities when sprayed. As a result, Azadirachta Indica produces smaller, faster-moving droplets, making it more efficient in applications that require fine misting and rapid distribution. On the other hand, Calophyllum Inophyllum oil, which has a higher viscosity, offers

Table 1: Fluid properties of various non-edible oils.

S. NO	NAME OF THE OIL UNIT	DENSITY (kg/m^3)	SURFACE TENSION (mN/m)	VISCOSITY@ 40°C (cP)
1	Azadirachta Indica	882.88	25.2	29.32
2	Ceiba Pentandra	905.11	27.52	35.60
3	Madhuca Longifolia	900.95	31.04	45.21
4	Calophyllum Inophyllum	919.50	21.90	47.16

more resistance to airflow, making it harder to disintegrate into smaller droplets. Consequently, the droplets formed are larger and travel at lower velocities. The higher viscosity of Calophyllum Inophyllum causes it to generate larger, slower-moving droplets, which might be less effective in applications requiring fine atomization but could be advantageous where a slower, more controlled distribution is needed. Azadirachta Indica is more prone to forming smaller, faster droplets, while Calophyllum Inophyllum tends to produce larger, slower droplets due to its higher viscosity.

Experiments are conducted by varying the air pressure (0.7 to 2.8 bar), oil flow rate (930 to 90 ml/h) and nozzle diameter (1.5 to 2.5 mm) to measure four non-edible oils' droplet velocity and diameter. The design of the experiment is given in Table 2. Nozzles used in all the experiments are designed by maintaining the length-to-diameter ratio (L/D_1) and angle (θ) constant. The design of the nozzle is shown in Figure 1. Nozzle diameter plays a crucial role in the formation of droplets in the Phase Doppler Particle Analyzer (PDPA) system, influencing droplet size and velocity. The nozzle diameter directly affects the size of the droplets formed, where a smaller nozzle diameter tends to produce finer droplets due to the higher velocity and more focused jet of oil exiting the nozzle. This focused jet facilitates better atomization, breaking the oil into smaller droplets [9].

Conversely, a larger nozzle diameter results in larger droplets because the oil jet is less focused, leading to less effective atomization. The nozzle diameter also impacts the velocity of the droplets. A smaller nozzle diameter creates a higher velocity jet, producing smaller droplets and propelling them at higher speeds. In contrast, a larger nozzle diameter reduces the jet's velocity, leading to slower-moving droplets. In the PDPA system, a nozzle diameter of 2 mm is particularly effective in generating smaller droplets with higher velocities compared to other nozzle sizes like 1.5 mm and 2.5 mm. This makes the selection of nozzle diameter a critical factor in optimizing spray characteristics for various applications [10].

2.1. Experimental system

The minimum Quantity Lubrication (MQL) system, spray chamber system, and PDPA system is integrated and developed into an experimental setup to measure the velocity and size of the fluid droplets. A schematic diagram and pictorial view of the experimental system are shown in Figure 2.

When the MQL system generates the droplets through a nozzle inside the spray chamber, the droplets reflect the laser light emitted from the laser transmitter in the PDPA system, and this reflected laser light is detected by the laser receiver and then is processed with the help of a signal processor. Later, the velocity and size of the liquid droplet are displayed on the computer.

2.2. MQL setup

MQL systems have grown faster in machining over the last two decades. MQL system supplies a small amount of liquid in the mist at the machining zone to enhance performance. MQL system comprises an MQL unit (oil reservoir, cyclic timer solenoid valve actuated pump, pressure regulators, connectors, and nozzle) and air compressor. MQL system was developed by arranging the elements, as shown in Figure 3. The compressed air from the compressor is branched into two directions by connector 1 [11]. One assists the pump to discharge, and another carries or disintegrates the dispensed fluid from the pump. Pressure regulators have been utilized to regulate airflow and induce spray formation. Air from the pressure regulator I actuate the piston placed inside the pump when the solenoid valve opens. The reservoir admits the liquid into the pump for every piston actuation. The compressed air, which pressure regulator II regulates, carries the discharged liquid at connector 2 and flows through the nozzle where the spray is generated.

2.3. Spray chamber system

The spray chamber system has been integrated with components such as the spray chamber, nozzle holder, straws, hose, and oil collecting tank. A schematic diagram and pictorial view of the spray chamber system are depicted in Figure 4.

Table 2: Experimental design for the determination of spray characteristics of the non-edible oil.

INDEPENDENT VARIABLES				DEPENDENT VARIABLES
PRESSURE (bar)	MASS FLOW RATE (ml/h)	NOZZLE OF DIAMETER (mm)	NON-EDIBLE OIL	OUTPUT FROM PDPA
0.7	30	1.5	Azadirachta Indica	Droplet diameter and velocity
1.4	45	2.0	Ceiba Pentandra	
2.1	65	2.5	Madhuca Longifolia	
2.8	90	-	Calophyllum Inophyllum	

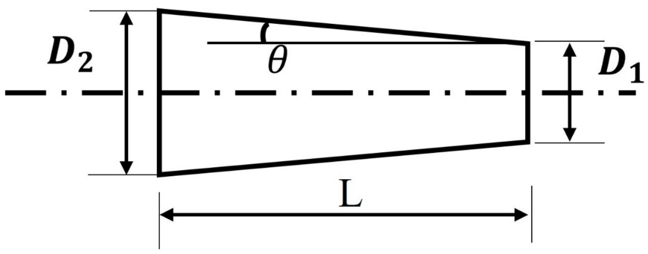

Figure 1: Schematic view of the nozzle design.

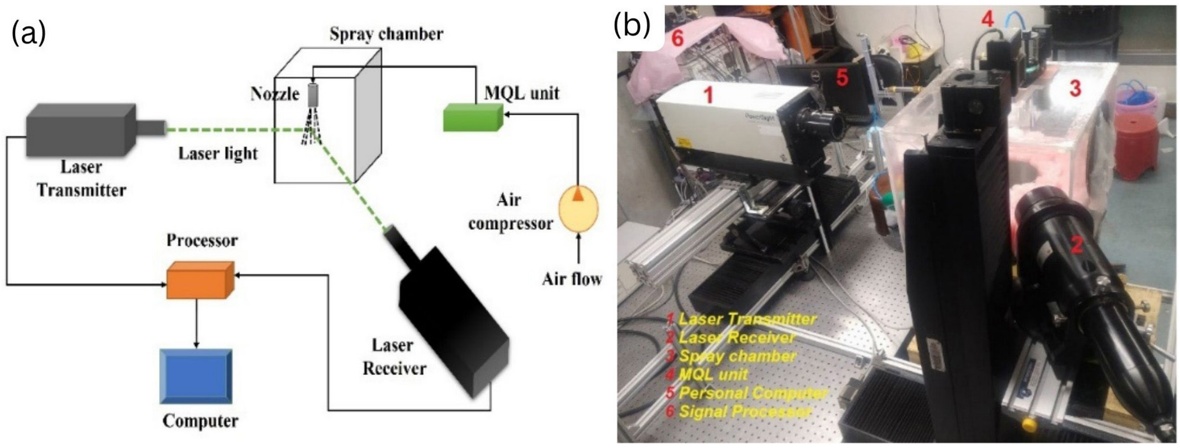

Figure 2: Experimental setup (a) schematic diagram (b) pictorial view.

Figure 4 (a) shows that the spray chamber system is fabricated and placed on the table. The spray chamber comprises acrylic glass material thickness of 6 mm with dimensions of 400 × 400 × 500 mm. It is a boundary between the workspace and liquid spray and maintains the work floor clean from liquid spillage. The nozzle holder is mounted at the center of the top lid of the spray chamber to hold the nozzle rigidly [12]. A bunch of straws is placed inside the chamber to minimize the recirculation of spray mist. A leakproof spray chamber could be damaged when compressed air is supplied continuously with a liquid spray. Two holes are made in the spray chamber to connect hoses and are admitted into the atmosphere. The discharged liquid inside the chamber is collected using a collection tank at the bottom of the table.

2.4. PDPA system

The spray characteristics of fluid were studied using a Phase Doppler Particle Analyser (PDPA). The PDPA measures the velocity and size of the liquid droplets based on the Doppler effect. It evolved from the LDV. PDPA can determine the particle's velocity and size, whereas LDV can measure only the particle's velocity. PDPA follows the Eulerian approach that tracks the particle in space at a specific point. The components of the PDPA system include a laser transmitter and receiver, traverse, signal processor, and computer arranged as shown in Figure 5. The rear and front pictorial view of the PDPA system is shown in Figure 5 (a) and (b), respectively. Monochromatic laser light has been used in the PDPA transmitter for data measurement [13]. Optical components in the transmitter emit two laser beams, which later intersect at a point known as probe volume. Successive regions of

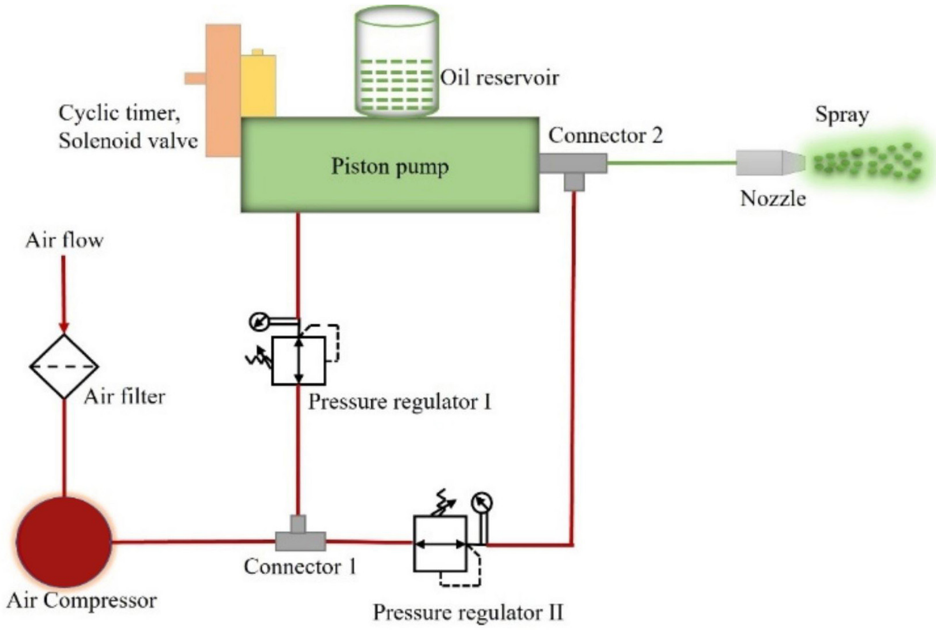

Figure 3: Schematic view of MQL system.

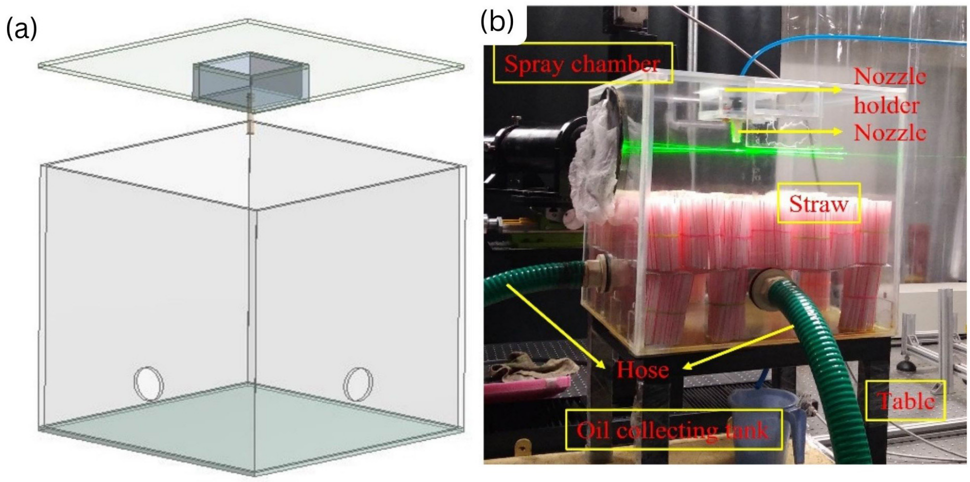

Figure 4: Spray chamber system (a) schematic diagram (exploded view) (b) pictorial view.

dark and light lines in the probe volume are known as the fringe pattern, and the same is shown in Figure 5 (c). PDPA receiver is usually positioned to probe volume to detect the frequency of reflected lights when the particle moves through the fringe pattern. The light signal from the reflected light is processed and converted into a digital signal by a signal processor. Finally, the data, such as the velocity and size of the particle, are displayed on the computer. The transmitter and receiver can be positioned at any place with the help of a traverse.

The gap between light or dark fringe is known during the calibration process. PDPA system calculates the time taken for any particle that passes through fringes by detecting the pulse of light reflections. This known distance and time determine the velocity of the particle. The droplet passing through the fringe pattern is depicted in Figure 5 (c). Unlike particle velocity determination, the method of determination of droplet size is carried out differently [14]. The particle size measurement is illustrated in Figure 6. The droplet size could be determined based on the phase angle of the reflected light signal. Three photomultiplier face plates are positioned in the laser receiver to detect the refracted lights when the droplet moves through the probe volume. The droplet size measurement is that the larger droplet has shallow curvature that lessens the incident rays. In contrast, the smaller droplet has sharp curvature that deviates more. The face plate detects the degree of phase angle that indicates how small or large a droplet is.

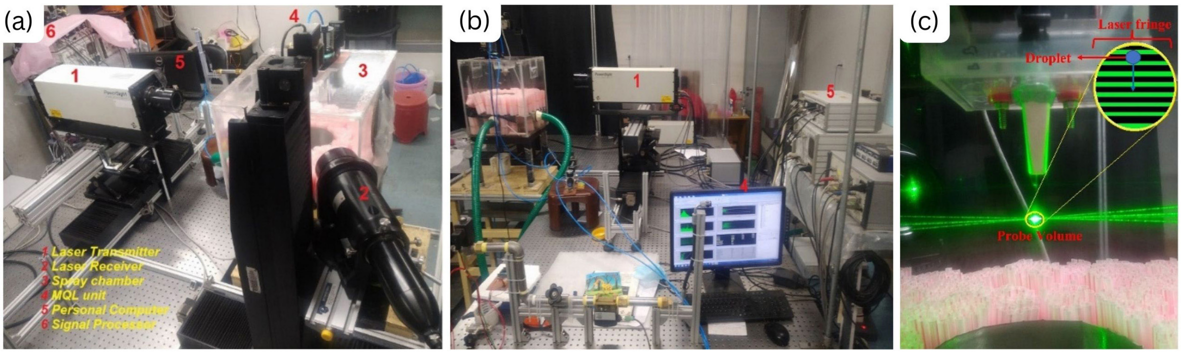

Figure 5: Pictorial view of PDPA system (a) rear view (b) front view (c) velocity measurement.

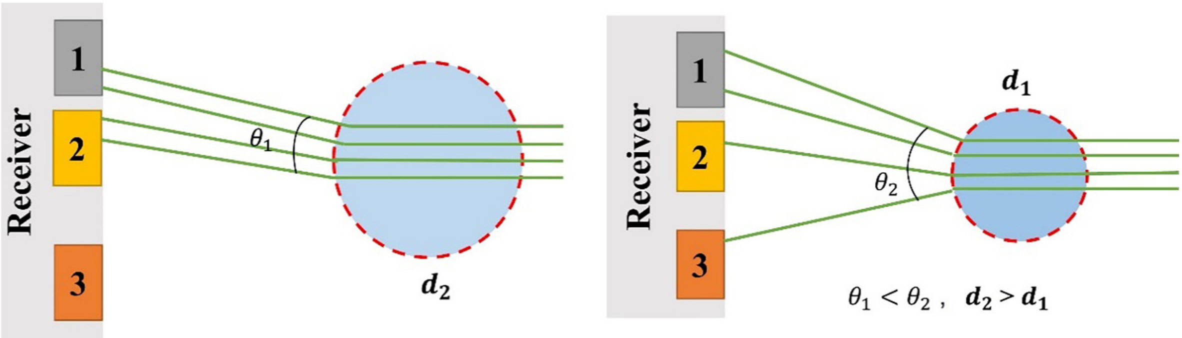

Figure 6: Schematic view of the measurement of particle size.

3. RESULTS

3.1. Effect of MQL system parameters on droplet diameter of various non-edible oils

The experiments used a PDPA system to study various non-edible oils' spray characteristics. The droplet velocity and diameter were determined for four different oils by varying the pressure, oil flow rate, and nozzle diameter. Figure 7 shows the variation in droplet diameter by MQL system parameters. The effect of pressure on the mean droplet diameter of four different oil at the flow rate of 30 ml/h and nozzle diameter of 1.5 mm is depicted in Figure 7 (a). It is seen that the mean droplet diameter of each oil is decreased as the pressure from 0.7 bar to 2.8 bar. The disintegration of oil is possible when the resistance offered by the oil against the airflow is lower [15, 16]. The airflow velocity is increased when the pressure increases so that oil is disintegrated and forms into droplets.

Increasing pressure significantly impacts the droplet size and velocity of non-edible oils in spray applications. As pressure increases, the droplet size tends to decrease because the higher pressure enhances the disintegration of the oil, breaking it into smaller droplets due to the increased airflow velocity. This effect is consistent across various non-edible oils such as Azadirachta Indica, Ceiba Pentandra, Madhuca Longifolia, and Calophyllum Inophyllum. Concurrently, the droplet velocity increases with higher pressure. This is particularly evident in oils with lower viscosity, like Azadirachta Indica, which disintegrate more easily, resulting in smaller droplets that travel at higher velocities. Conversely, more viscous oils, like Calophyllum Inophyllum, resist disintegration, producing larger droplets that move at slower velocities. Thus, pressure is a crucial parameter in optimizing the spray characteristics of non-edible oils, especially in systems like minimum quantity lubrication, where controlling droplet size and velocity is vital for efficient operation.

Oil viscosity significantly influences the spray characteristics and droplet size in Minimum Quantity Lubrication (MQL) systems. Viscosity, which measures a fluid's resistance to flow, directly affects the disintegration process of oil into droplets during spraying. Higher viscosity oils, such as Calophyllum Inophyllum, offer more resistance to airflow, making them harder to disintegrate into smaller droplets. As a result, these oils tend to produce larger droplets because the increased viscosity inhibits the breakup of the oil stream into finer particles. The higher resistance also means that these droplets move at lower velocities, as the oil's thickness dampens the kinetic energy imparted by the spray system [17]. Conversely, lower-viscosity oils, like Azadirachta Indica, are more easily disintegrated by the airflow. These oils produce smaller droplets

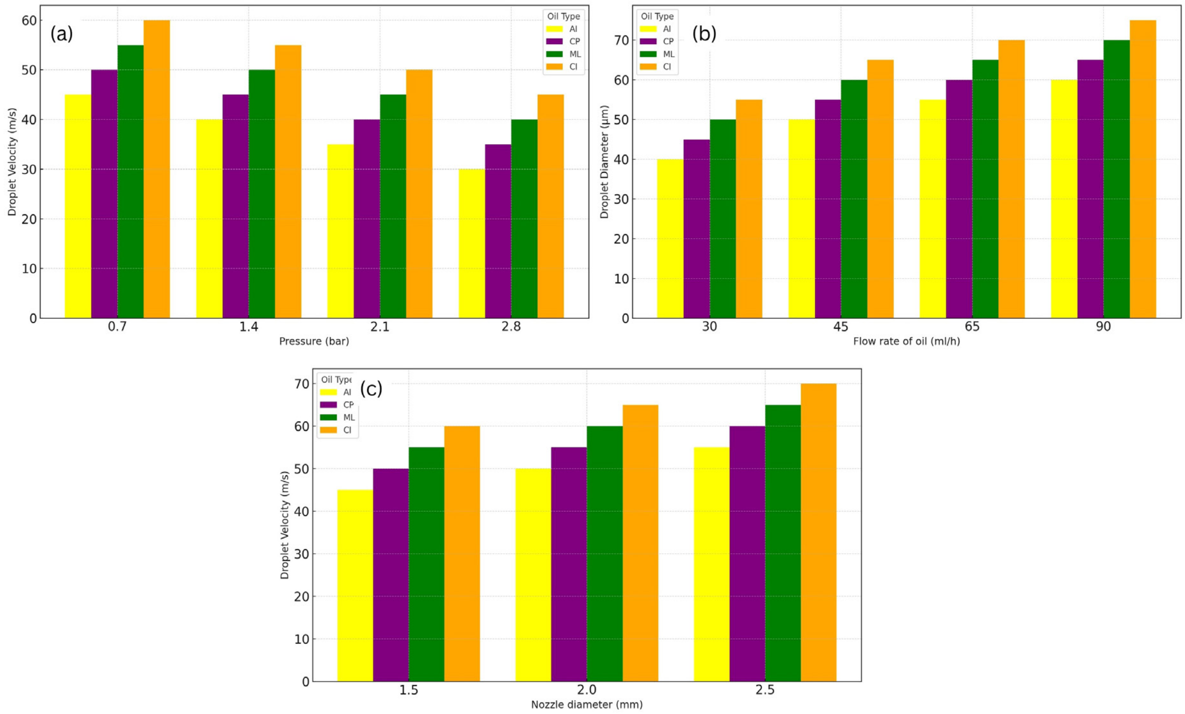

Figure 7: Effect of MQL system parameters on droplet diameter of various non-edible oils.

because their lower resistance allows the spray system to break the oil into finer particles more efficiently. The reduced viscosity also enables these droplets to travel at higher velocities, as the oil flows more freely and is more easily propelled by the spray mechanism. Higher viscosity oils generate larger, slower-moving droplets, while lower viscosity oils produce smaller, faster-moving droplets in MQL systems. This makes viscosity a critical factor in determining the effectiveness of lubrication and spray coverage in various industrial applications.

On the other hand, the droplet diameter is increased in the order of oils AI, CP, ML, and CI when the pressure at each step is increased by 0.7 bar. The maximum percentage of decrement in the mean droplet diameter of AI, CP, ML, and CI oils is 35.26, 34.14, 29.10, and 24.5, respectively, between the pressure of 0.7 and 2.8 bar. It is seen that the CI oil offers more resistance to airflow and is challenging to disintegrate into tiny droplets [18, 19]. The maximum percentage of increment in the droplet diameter between AI and CI is 35.60, 38.68, 51.73, and 58.12 at each step of increase in pressure from 0.7 bar to 2.8 bar. The mean droplet diameter is reduced when the pressure is from 0.7 to 2.8 bar. The result shows that the ease of oil disintegration follows in the order of CI, ML, CP, and AI when operating the pressure is between 0.7 and 2.8 bar. The same trend is observed when varying the oil flow rate from 45 to 90 ml/h and nozzle diameter from 2 to 2.5 mm when operating; the pressure is from 1.4 to 2.8 bar with a step size of 0.7 bar [20].

Figure 7 (b) illustrates the effect of the flow rate of oils on the mean droplet diameter at the pressure of 0.7 bar and nozzle diameter of 1.5 mm. It is observed from Figure 7 (b) that each oil's mean droplet diameter is increased when the flow rate is increased from 30 to 90 ml/h. The maximum percentage of increment in the droplet diameter is noted for each oil operating between the flow rate of 30 and 90 ml/h, and it is observed that the maximum percentage of increment in the droplet diameter of each oil lies between 5 and 12. This means there is not much difference in the variation in mean droplet diameter, and the effect seems to be negligibly small in the droplet size when the oil flow rate is varying [21]. The maximum increment percentage in the droplet diameter is observed between AI and CI. It is noticed that the maximum percentage of increment in the droplet diameter is reduced from 35.60 to 28.64 when increasing the flow rate of oil from 30 to 90 ml/h. The result shows that the oil flow rate (30–90 ml/h) less influences variation in mean droplet diameter. Among different oils, the flow rate of CI oil has more influence on variation in mean droplet diameter.

The effect of nozzle diameter on droplet diameter of various oils at the pressure of 0.7 bar and flow rate of oil of 30 ml/h is depicted in Figure 7 (c). It is noticed from Figure 7 (c) that the droplet size is increased in the order of AI, CP, ML, and CI for all the nozzle sizes (1.5, 2, and 2.5 mm). The droplet diameter of AI is observed as 50.45, 33.12, and 47.13 when changing the nozzle diameter from 1.5 to 2.5 mm. The droplet diameter value has decreased and then increased for 2 and 2.5 mm nozzles, respectively [22]. The same trend was observed for all the oil, varying the pressure from 1.4 to 2.8 bar and flow rate from 45 to 90 ml/h. The maximum increment percentage in droplet diameter between AI and CI is 35.60, 59.41, and 37.44 for the nozzle diameter of 1.5, 2, and 2.5 mm, respectively. This means that the 2 mm nozzle can disintegrate the oil into tiny droplets compared to the other two nozzles. It is concluded that the nozzle diameter of 2 mm greatly influences droplet diameter compared to other nozzles [23].

3.2. Effect of MQL system parameters on droplet velocity of various non-edible oils

The influence of MQL system parameters, such as pressure, the flow rate of oil, and nozzle diameter on the mean droplet velocity of the various oils are shown in Figure 8. Figure 8 (a) shows the effect of pressure on the mean droplet velocity of oils at a constant flow rate of 30 ml/h and nozzle diameter of 1.5 mm [24]. The mean droplet velocity of oil is increased with increasing the pressure from 0.7 bar to 2.8 bar in intervals of 0.7 bar. The droplet velocity of various oils is decreased in the order of AI, CP, ML, and CI at the pressure of 0.7 bar, and the same trend was observed when increasing the pressure from 1.4 to 2.8 bar. The maximum percentage of increment in the droplet velocity of AI, CP, ML, and CI oil is 96.64, 83.59, 79.44, and 52.10, respectively, when operating the pressure from 0.7 to 2.8 bar. The maximum percentage of decrement in the droplet velocity between AI and CI is 8.54 at 0.7 bar and increased to 29.22 at 2.8 bar. The same trend was obtained when increasing the flow rate from 45 to 90 ml/h and the nozzle diameter from 2 to 2.5 mm. This means that a larger droplet offers more resistance to airflow, whereas a smaller droplet does not.

Figure 8 (b) illustrates the effect of the flow rate of oils on the mean droplet velocity of various oils at the pressure of 0.7 bar and nozzle diameter of 1.5 mm. It is seen from Figure 8 (b) that the mean droplet velocity of the oil is reduced without any significance for any oil flow rate. The maximum percentage of decrease in droplet velocity between AI and CI is observed and ranges between 8.54 and 16.82 [25]. Also, each oil's maximum percentage of increment in droplet velocity falls within 3%. The same trend was obtained when varying the pressure from 1.4 to 2.8 bar and the nozzle diameter from 2 to 2.5 mm. It is concluded that the flow rate of the oil has no significant influence on the variation in droplet velocity [26]. The effect of nozzle diameter on droplet velocity of the various oils at the pressure of 0.7 bar and flow rate of oil of 50 ml/h is shown in Figure 8 (c). The droplet velocity of oil is decreased in the order of AI, CP, ML, and CI for each nozzle size. The maximum percentage decrease in the droplet velocity between AI and CI is 8.54, 11.2, and 7.02 for the nozzle of 1.5, 2, and 2.5 mm, respectively. Similarly, the droplet velocity of the oil AI is obtained as 67.65, 137.20, and 101.31 m/s for the nozzle of 1.5, 2, and 2.5 mm. The same trend was noticed when varying the pressure from 1.4 to 2.8 bar and the flow rate from 45 to 90 ml/h. It is concluded that the nozzle diameter of 2 mm has increased the droplet velocity significantly.

4. DISCUSSIONS

The spray characteristics of various non-edible oils were studied for different MQL system parameters and their effect on droplet diameter and velocity. The droplet diameter is reduced by increasing the pressure from 0.7 to 2.8 bar and increasing velocity. The disintegration of liquid is possible when the pressure force overcomes the resistance offered by fluid. This resistance force may be the viscous force or, surface tension force, or density. The highest droplet diameter and lowest droplet velocity were observed for the oil CI, and vice versa was obtained for AI. The oil CI's higher viscosity offers more airflow resistance and lowers the disintegration, resulting in the formation of a larger droplet diameter at a lower velocity. Unlike CI, the disintegration of AI is more due to its lower viscosity and produces smaller droplets at higher velocities [27]. It is evident from the result that higher viscous oil can generate a larger diameter with low velocity in the spray mist. Droplet diameter and velocity increased when the flow rate increased from 30 to 90 ml/h, but variations in the spray characteristics were negligible. The effect of the flow rate of oils on droplet diameter and velocity is observed to be insignificant. A nozzle diameter of 2 mm generated droplets much smaller than the droplets generated by the nozzle of 1.5 mm and 2.5 mm. A nozzle of 1.5 mm has more pressure drop. This leads to less disintegration of oil and generates larger droplets at lower velocities. On the other hand, a nozzle of 2.5 mm supplies a higher air flow rate, causing less disintegration and generating larger droplets at lower velocities.

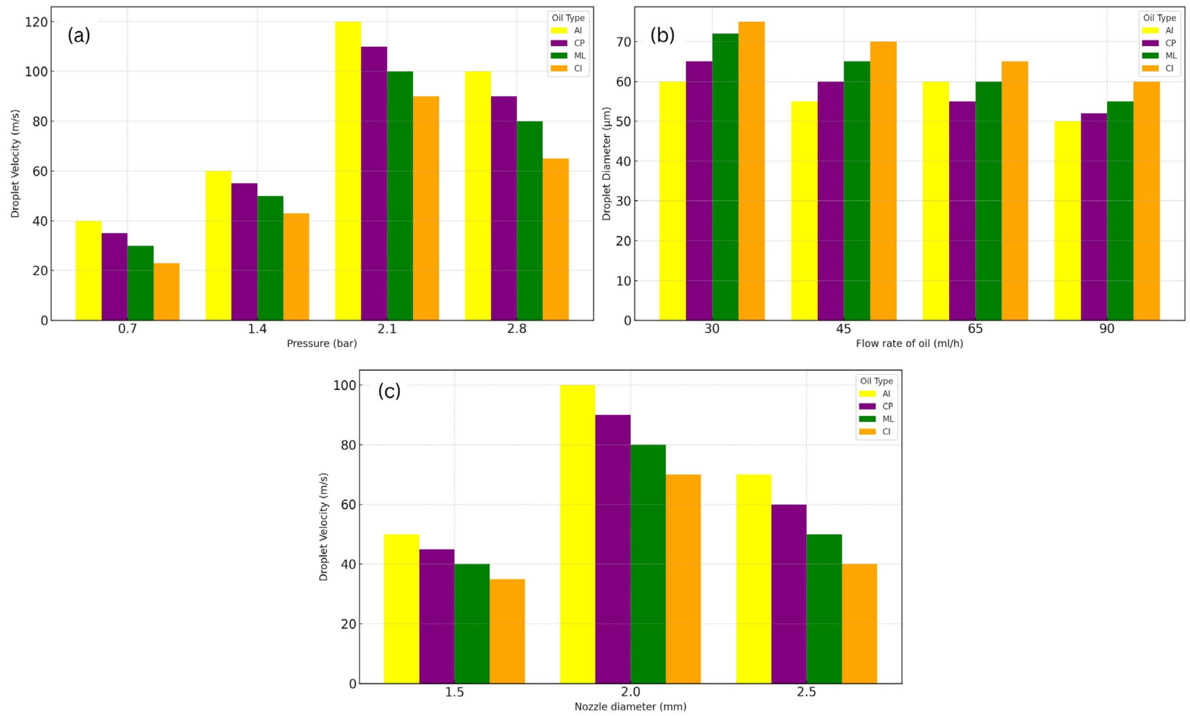

Figure 8: Effect of MQL system parameters on droplet velocity of various non-edible oils.

4.1. Response surface methodology (RSM) analysis

The Response Surface Methodology (RSM) was employed to optimize the spray characteristics of non-edible oils in a Minimum Quantity Lubrication (MQL) system. RSM is a collection of mathematical and statistical techniques for developing, improving, and optimizing processes. It also helps evaluate the relative significance of several affecting factors, even in complex interactions.

The central composite design (CCD), a common experimental design for RSM, was used to systematically vary the levels of input factors (pressure, oil flow rate, and nozzle diameter) and study their effects on the response variables (droplet diameter and velocity). The CCD included factorial, axial, and center points, comprehensively assessing the factor space. The experimental setup involved using a Phase Doppler Particle Analyzer (PDPA) to measure the droplet size and velocity of four different non-edible oils: Azadirachta Indica (AI), Ceiba Pentandra (CP), Madhuca Longifolia (ML), and Calophyllum Inophyllum (CI). The factors and their levels are summarized in Table 1.

The independent variables considered in this study were Pressure (P): 0.7 to 2.8 bar, Oil Flow Rate (F): 30 to 90 ml/h, and Nozzle Diameter (D): 1.5 to 2.5 mm. The response variables were Droplet Diameter (DD) and Droplet Velocity (DV). The second-order polynomial model used for RSM is given by Equation (1):

$$[Y = \hat{a}_0 + \sum_{i=1}^{k} \hat{a}_i X_i + \sum_{i=1}^{k} \hat{a}_{ii} X_i^2 + \sum_{i<j}^{k} \hat{a}_{ij} X_i X_j + \in] \quad (1)$$

where (Y) is the response variable, ($\hat{a}_0$) is the intercept term, ($\hat{a}_i$) represents the linear effect of (X_i), ($\hat{a}_{ii}$) represents the quadratic effect of (X_i), ($\hat{a}_{ii}$) represents the interaction effect between (X_i) and (X_j), and (ϵ) is the random error. The experimental data were fitted to this model using regression analysis. Analysis of variance (ANOVA) was conducted to determine the significance of each term in the model.

The regression analysis provided the following fitted equations for droplet diameter and velocity:

For droplet diameter (DD) (Equation 2)

$$[DD = \hat{a}_0 + \hat{a}_1 P + \hat{a}_2 F + \hat{a}_3 D + \hat{a}_{11} P^2 + \hat{a}_{22} F^2 + \hat{a}_{33} D^2 + \hat{a}_{12} PF + \hat{a}_{13} PD + \hat{a}_{23} FD] \quad (2)$$

For droplet velocity (DV) (Equation 3)

$$[DV = \hat{a}_0 + \hat{a}_1P + \hat{a}_2F + \hat{a}_3D + \hat{a}_{11}P^2 + \hat{a}_{22}F^2 + \hat{a}_{33}D^2 + \hat{a}_{12}PF + \hat{a}_{13}PD + \hat{a}_{23}FD] \tag{3}$$

The coefficients ((â)) were estimated using least squares regression. The significance of each coefficient was tested using ANOVA, with p-values less than 0.05 indicating significant effects.

The RSM analysis revealed significant interactions between the MQL system parameters and the spray characteristics of the oils. Key findings include that pressure significantly influences both droplet diameter and velocity. Higher pressure leads to smaller droplet diameters and higher velocities. Nozzle diameter plays a crucial role in determining the droplet size and velocity. Smaller nozzle diameters produce finer droplets and higher velocities. The oil flow rate has a less pronounced effect than pressure and nozzle diameter but can still fine-tune the spray characteristics.

Figure 9 shows the effect of pressure and oil flow rate on droplet diameter. The surface plot on the left illustrates how increasing pressure from 0.7 to 2.8 bar significantly reduces droplet diameter. Conversely, the flow rate, ranging from 30 to 90 ml/h, shows a less pronounced effect on droplet diameter. The contour plot on the right reinforces these observations, indicating that higher pressures consistently produce finer droplets. At the highest pressure of 2.8 bar, the droplet diameter decreases to approximately 800 µm. Meanwhile, flow rate variations lead to minor droplet size fluctuations, which remain between 3200 µm and 9200 µm. The atomization efficiency improves with higher pressure due to increased energy for breaking the oil into smaller droplets. The flow rate's minimal effect is because the primary atomization force is pressure, while flow rate adjustments fine-tune the droplet size distribution.

Figure 10 illustrates the influence of pressure and nozzle diameter on droplet diameter. The surface plot on the left shows that increasing pressure significantly reduces droplet diameter. The smallest nozzle diameter of 1.5 mm leads to the finest droplets, while larger diameters like 2.5 mm result in larger droplets. The contour plot on the right confirms these trends, showing that high pressure and small nozzle diameters are optimal for producing the smallest droplet diameters.

At a pressure of 2.8 bar and a nozzle diameter of 1.5 mm, the droplet diameter is reduced to approximately 800 µm. In contrast, at a nozzle diameter of 2.5 mm, the droplet diameter increases up to 9200 µm under the same pressure conditions. Higher pressures provide more energy to disintegrate the oil, resulting in finer

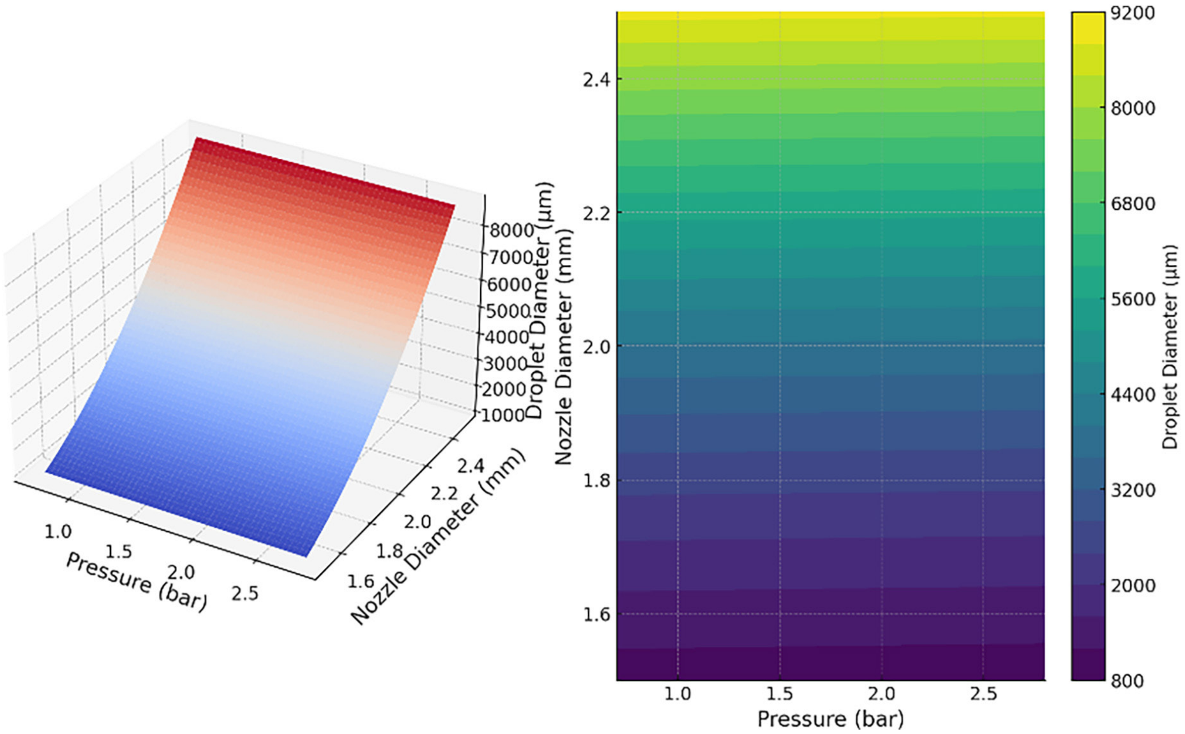

Figure 9: Surface plot and contour plot for droplet diameter vs. pressure and flow rate.

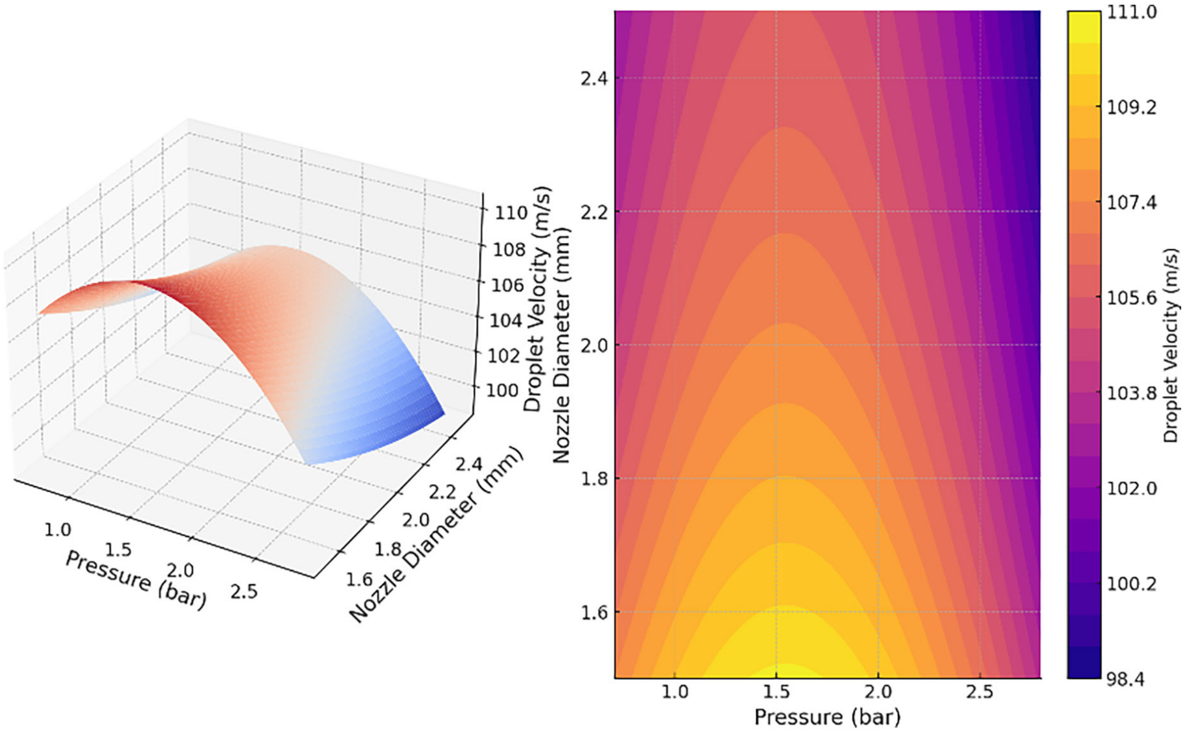

Figure 10: Surface plot and contour plot for droplet diameter vs. pressure and nozzle diameter.

droplets. Smaller nozzle diameters create a higher velocity jet, enhancing atomization and producing smaller droplets. Larger nozzle diameters reduce the jet velocity, leading to less effective atomization.

Figure 11 depicts the effect of pressure and nozzle diameter on droplet velocity. The surface plot on the left shows that increasing pressure leads to higher droplet velocities. The smallest nozzle diameter of 1.5 mm achieves the highest velocities, while larger diameters reduce the velocity. The contour plot on the right further illustrates that the highest velocities are achieved with high pressure and small nozzle diameters. At the highest pressure of 2.8 bar and a nozzle diameter of 1.5 mm, the droplet velocity increases to approximately 111 m/s. In contrast, with a nozzle diameter of 2.5 mm, the velocity drops to about 98 m/s under the same pressure conditions. The increased pressure elevates the kinetic energy of the droplets, enhancing their velocity. Smaller nozzle diameters create a more focused and higher velocity jet, resulting in faster droplets. Larger nozzle diameters disperse the jet, reducing droplet velocity.

Using RSM, the optimal conditions for achieving the smallest droplet diameter and highest velocity were determined to be a pressure of 2.8 bar, an oil flow rate of 30 ml/h, and a nozzle diameter of 2 mm. These settings maximize the atomization efficiency, producing fine droplets suitable for effective lubrication. This comprehensive analysis provides valuable insights into how MQL system parameters affect the spray characteristics of vegetable oils, supporting the development of more efficient and environmentally friendly lubrication practices in industrial applications. The RSM analysis demonstrates the critical influence of pressure, nozzle diameter, and flow rate on the spray characteristics of non-edible oils in MQL systems. High pressure and smaller nozzle diameters are essential for achieving the smallest droplet diameters and the highest velocities, optimizing the atomization process for effective lubrication. Flow rate adjustments have a less significant but still important role in fine-tuning the droplet characteristics. These findings provide a robust foundation for developing more efficient and environmentally friendly MQL systems for industrial applications.

The study provides significant insights into sustainable lubrication practices for the machining industry, emphasizing the potential for reducing lubricant consumption, enhancing machining efficiency, and supporting environmental sustainability. By optimizing spray characteristics of non-edible oils through careful control of pressure, nozzle diameter, and oil viscosity, the study demonstrates that effective lubrication can be achieved with minimal oil usage, aligning with the principles of Minimum Quantity Lubrication (MQL). This reduces waste and contributes to cost savings, as companies can lower their operational expenses through decreased lubricant consumption, reduced waste disposal costs, and improved tool performance. Additionally, the study highlights the environmental benefits of using biodegradable, non-edible vegetable oils over conventional

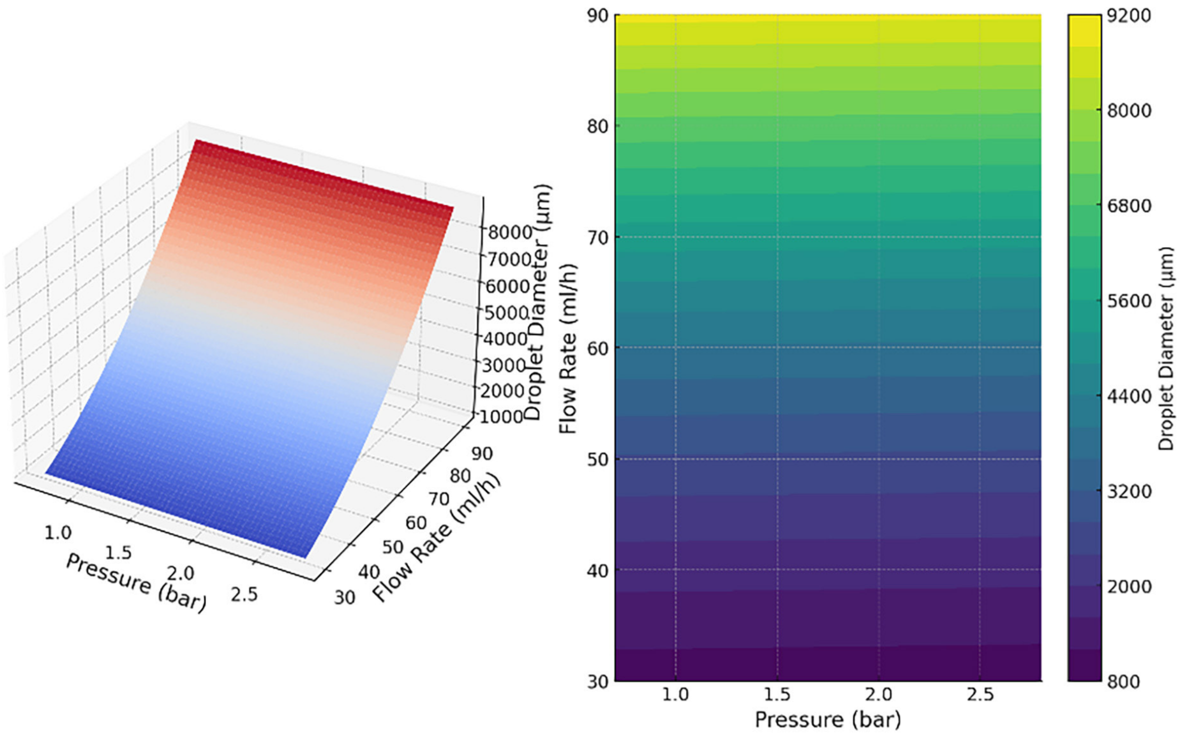

Figure 11: Surface plot and contour plot for droplet velocity vs. pressure and nozzle diameter.

petroleum-based lubricants, significantly lowering machining processes' environmental footprint. Furthermore, the research offers a detailed analysis of how different non-edible oils perform under various conditions, providing valuable guidance for their broader adoption in the industry [28]. As companies strive to meet stricter environmental regulations and pursue sustainability goals, these insights can help optimize MQL systems, making machining processes more environmentally friendly, efficient, and cost-effective.

5. CONCLUSIONS

This study aimed to investigate the effect of different MQL system parameters on the spray characteristics of various non-edible oils. The in-house developed MQL system, spray chamber system, and PDPA system were integrated to set up the experimental system. The spray was injected into the spray chamber through the MQL system. The droplet velocity and diameter of AI, CP, ML, and CI were determined by varying the pressure, the flow rate of oil, and nozzle diameter using the PDPA system. The conclusions made are as follows based on the experimental results.

- The spray characteristics of Azadirachta Indica, Ceiba Pentandra, Madhuca Longifolia, and Calophyllum Inophyllum were measured by varying the pressure (0.7–2.8 bar), the flow rate of oil (30–90 ml/h) and nozzle diameter (1.5–2.5 mm).
- The droplet diameter decreased while the pressure increased from 0.7 to 2.8 bar, whereas the droplet velocity increased.
- The droplet velocity and diameter difference were negligibly smaller for all the non-edible oils when the oil flow rate increased from 30 to 90 ml/h. The droplet diameter was smaller for the 2 mm nozzle than for the other.
- Among three different MQL system parameters, pressure and nozzle diameter are the parameters that influence spray characteristics the most.
- Droplet diameter increased in the order of Azadirachta Indica, Ceiba Pentandra, Madhuca Longifolia, and Calophyllum Inophyllum, respectively, for all the levels of MQL system parameters. However, the droplet velocity was obtained and vice versa.
- Larger diameter droplets with lower velocity were observed for higher viscosity fluid Calophyllum Inophyllum. On the other hand, smaller diameter droplets with higher velocity were found for lower viscosity fluid Azadirachta Indica.

- Discussion of experimental work in this paper provides additional information regarding the spray characteristics of non-edible oils under the effect of MQL system parameters and fluid properties. The study provides insight into the behavior of non-edible oil in the form of mist. Also, the results support the prediction of oil spray characteristics before the experimentation.

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