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Original Research Article

The Testing of Waste Cooking Oil as Waste Recycle to Realising Green Technical Vocational Education and Training

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ABSTRACT

This research explores the role of Sustainable Development Goals in addressing waste management issues, particularly within Technical Vocational Education and Training institutions that focus on culinary practices. These institutions often generate significant amounts of waste cooking oil, and improper management can lead to environmental pollution. By integrating effective waste management strategies into vocational education, we can cultivate green Technical Vocational Education and Training principles that enhance environmental awareness and reduce pollution. As the depletion of fossil fuels underscores the need for alternative energy sources, utilising readily available waste materials, such as waste cooking oil, becomes increasingly relevant. This study highlights the potential of waste cooking oil as a sustainable raw material for biodiesel production, supported by findings from both experimental research and literature reviews. Key characteristics, including spray angle, injection pressure, and oil viscosity, have been identified as critical indicators for assessing the recyclability of waste cooking oil. The results demonstrate that waste cooking oil can be effectively converted into valuable raw materials for the renewable energy sector and waste management. This research serves as an implementation of the green Technical Vocational Education and Training concept, contributing to sustainable development in an environmentally friendly manner. Ultimately, this approach can significantly reduce waste and promote sustainable energy practices, aligning with broader sustainability goals.

KEYWORDS

Waste cooking oil, Sustainable development goals, Green technical vocational education and training, Sustainable energy, Biodiesel.

INTRODUCTION

The world is currently moving towards achieving Sustainable Development Goals (SDGs), which are essential for fostering global well-being [1]. The attainment of these goals is closely linked to the role and contributions of Technical Vocational Education and Training

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(TVET) [2]. As the challenges and issues in the TVET field continue to evolve, there is an urgent need for innovative and progressive solutions to address these challenges comprehensively. One significant issue is the avoidance of environmental degradation [3]. Indiscriminate waste disposal and other harmful practices contribute to pollution and demonstrate the direct impact of human activities on environmental sustainability and public health [4]. Vocational education plays a crucial role in preparing the industrial workforce with the green skills necessary for advancing environmentally friendly practices [5]. Green skills encompass three primary dimensions: knowledge, skills, and attitudes that workers require to promote sustainable development [6]. These skills are essential for fostering the competencies and values needed to support a resource-efficient society [7]. Therefore, integrating green skills into vocational education is vital for cultivating a workforce capable of tackling environmental challenges and contributing to sustainable development.

Many countries are transitioning toward a green economy model to achieve a robust economy while minimising carbon emissions and maximising resource efficiency [8]. This model emphasises the creation of green jobs that require workers with specialised green skills and competencies [9]. Thus, TVET institutions play a critical role in developing these skills, directly impacting economic development and community welfare. The advancement of greening TVET is crucial within the sustainable development framework, particularly in sectors such as energy and waste management. This integration involves not only TVET institutions but also early guidance within vocational education environments. Green TVET is an innovative approach that incorporates principles of environmental care and sustainability to achieve the SDGs [10]. It serves as a cross-sectoral theme in sustainable development, focusing on reorienting and enhancing existing vocational institutions and policies to strengthen the realisation of these goals [11]. The United Nations 2030 Agenda for Sustainable Development outlines 17 Sustainable Development Goals (SDGs) that address global challenges such as clean energy, responsible consumption and production, climate change, and environmental degradation [12]. Green TVET significantly contributes to these efforts, particularly in supporting responsible production and consumption (SDG 12) and ensuring access to affordable, clean, and sustainable energy (SDG 7) [13]. In light of the pressing global issues of climate change and resource depletion, investing in greening TVET presents a viable pathway toward ensuring economic sustainability and environmental stewardship [14]. Experts have proposed that green TVET has a five-dimensional framework at the institutional level [15], as shown in Figure 1.

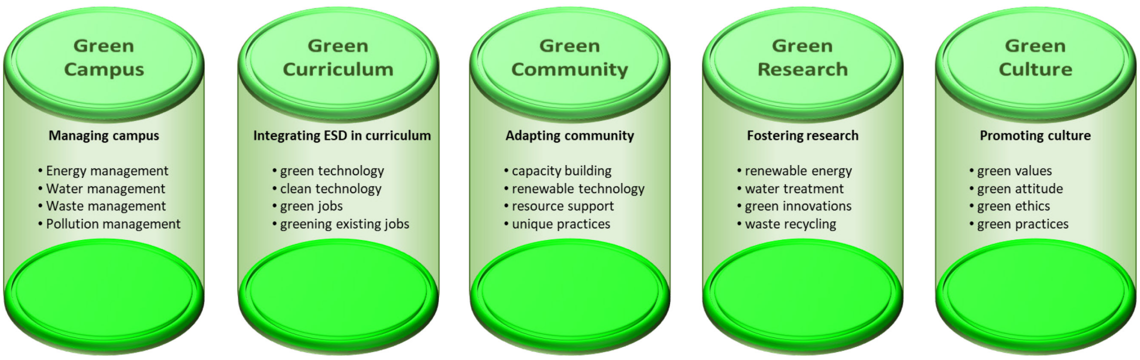

Figure 1. Five dimensions of greening TVET [16]

Despite the progress made, there remains a notable gap in research focusing on specific waste materials and their potential for supporting green TVET initiatives. Specifically, the current literature lacks comprehensive studies on how waste cooking oil − often discharged unsafely into the environment − can be effectively utilised as a resource in vocational education and training frameworks. This gap highlights the novelty of exploring waste cooking oil's conversion into biodiesel as part of green TVET practices. The testing and application of waste cooking oil in biodiesel production illustrate a sustainable approach to waste management that aligns with the principles of green technology.

The definition of green technology encompasses environmental monitoring, pollution prevention, and restoration across various sectors like agriculture, energy, and waste management [17]. The Indonesian Presidential Regulation No. 5 of 2006 emphasises the development of alternative energy sources [18, 19], positioning waste cooking oil as a critical feedstock for biodiesel production, thereby addressing both renewable energy demands and waste recycling in culinary-focused TVET institutions [20, 21]. Given the depletion of fossil fuel resources and the adverse environmental impacts associated with their use, there is an urgent need for alternative techniques to convert biomass waste into biofuels [22].

Research on combustion processes is initiated by transforming fuel into fine droplets using a nozzle [23]. A nozzle that can produce many tiny droplets is essential to improve fuel combustion efficiency because smaller droplets spread out more widely and provide a greater spray angle from the nozzle [24, 25]. The fuel characteristics significantly impact this dispersion, defined by the spray angle, especially when the pressure and nozzle orifice sizes are comparable [26, 27]. Furthermore, the fuel's viscosity − like that of waste cooking oil − affects the spray angle since excessive viscosity might prevent atomisation, producing bigger droplets and lowering combustion efficiency.

This research is likely to obtain findings through experiments supporting green TVET's realisation, such as the utilisation of waste cooking oil as a biodiesel feedstock in the context of Green TVET, which has not been widely investigated in the current literature. The main focus is not only on the technical testing of waste cooking oil but also on validating its use as a practical learning component that can be applied in the TVET curriculum to build green skills among vocational students to prepare a workforce capable of facing these challenges as the industry increasingly recognises the importance of green practices [3, 28].

This research aims to fill the existing gap by investigating the indicators of waste cooking oil, such as spray angle, injection pressure, and preheating temperature, to evaluate its viability as a raw material for sustainable recycling development efforts. By implementing green research practices within the green TVET framework through the utilisation of available waste resources, this study aims to shed light on the potential of waste cooking oil as a valuable asset in achieving sustainable energy solutions while supporting the objectives of green TVET [29]. Although previously published research has examined various aspects of alternative energy and vocational training, few studies have focused on specific technical factors. Thus, utilising the adopted method, the present work not only supports the waste recycling approach but also strengthens the capacity of TVET institutions to educate competent workers in sustainable practices. The proposed research hypothesis is that waste cooking oil, processed according to the proper technical indicators, can be converted into quality biodiesel and applied as a learning material in Green TVET to support sustainable development goals. This research is expected to make a real contribution to responding to environmental challenges through effectively utilising waste resources in vocational education, thereby supporting the formation of a greener and more sustainable TVET ecosystem.

MATERIALS AND METHODS

Material of waste cooking oil, primarily derived from the use of vegetable oils such as coconut oil in various culinary applications, is often sourced from the food processing industry, including restaurants and hospitality establishments. Typically, this used oil exhibits a higher viscosity compared to fresh vegetable or coconut oil. The accumulation of waste cooking oil within communities − especially when it is repeatedly used for food preparation − presents an opportunity for recycling into biodiesel.

Waste oil collection and sample preparation

Prior to its application as a feedstock for biodiesel production, waste cooking oil undergoes a thorough sample preparation process to ensure its suitability. This process begins with the collection of waste cooking oil, which may still contain food residues, water, and other impurities that can adversely affect the biodiesel production process. Once the waste cooking oil is collected, it is immediately subjected to a filtration process. This step involves passing the oil through a fine mesh or filter paper to remove solid particles, food contaminants, and other unwanted materials. This crucial step helps to reduce acidity levels and minimises the risk of fouling during the subsequent processing stages.

When used as a feedstock for biodiesel, waste cooking oil has distinct chemical and thermo-physical properties that differ from those of fossil diesel. These differences include factors such as higher density, increased viscosity, elevated bulk modulus, varying cetane number, and higher oxygen concentration, all of which significantly influence spray characteristics, the atomisation process (including droplet formation), combustion performance, and emissions [30]. This study focuses on evaluating the spray angle, injection pressure, and preheating temperature as methods to mitigate the viscosity of waste cooking oil, thereby enhancing its suitability for biodiesel production. Biodiesel typically requires a higher fuel volume than fossil diesel due to its lower heat energy content, which is compounded by a slower injection rate caused by its elevated viscosity [31]. Figure 2 shows a sample of used cooking oil filtered and put into a bottle.

Figure 2. Waste cooking oil after the filtration process, stored in a bottle

Experimental method

The experiment was organised in the energy conversion laboratory. Set up research by sampling waste cooking oil samples from restaurants as a control, and the diameter of the nozzle hole used was 0.5 mm. The preparation of waste cooking oil for testing involves applying an increased injection pressure, ranging from 1 bar to 3 bar when utilising kerosene, which can enhance the spray angle by up to 16° [26]. A copper pipe is used as the heater, designed in a coiled configuration with a diameter of 93 mm and a pipe wall thickness of 0.6 mm. The heater temperature is adjusted based on the viscosity of the waste cooking oil, which is measured using a viscometer. The experiments with 100% biodiesel exhibit higher penetration and spray tip speed but a narrower spray angle due to its high viscosity and considerable momentum compared to a blend of diesel and 20% biodiesel [32]. The preheating temperature is systematically adjusted to 350 °C, 360 °C, 370 °C, 380 °C, and 390 °C. The injection is controlled to range from 3 to 5 bar, using a valve for precise adjustments. The resulting spray angle is recorded using a camera setup capable of capturing high frame rates for detailed analysis, which includes a combination of a Samsung Smart Camera and Canon DSLR EOS. Physically, the waste cooking oil displays combustion characteristics with an average fuel combustion rate ranging from 0.0083 mL/s to 0.0189 mL/s. Additionally, the average capillarity rate of waste cooking oil ranges from

0.00480 mL/s to 0.01173 mL/s, while the average viscosity is recorded between 35.55 cP and 52.81 cP [33]. A specialised set of tools is utilised to facilitate the tests of cooking oil samples, as illustrated in Figure 3. The test is started by inserting waste cooking oil into the pressure vessel (1). Pressurised air is injected into the tube using a compressor (2), and the valve (3) is opened with a constant injection pressure that is read by the pressure gauge (4). The valve is opened, causing the waste cooking oil sample to flow through the pipe; then, in the middle of the pipe, it is heated by a heater (5) in the form of a coil pipe (6) until it reaches the nozzle (7). The vapour of the waste cooking oil sample from the nozzle will form a spray angle recorded by the camera (8). In order for the research to be carried out properly, the temperature of the waste cooking oil coming out of the pressure vessel until it exits the nozzle is measured at several points with a thermocouple (9), with the measurement results monitored using a data logger (10). The results of the camera recording are data for analysis.

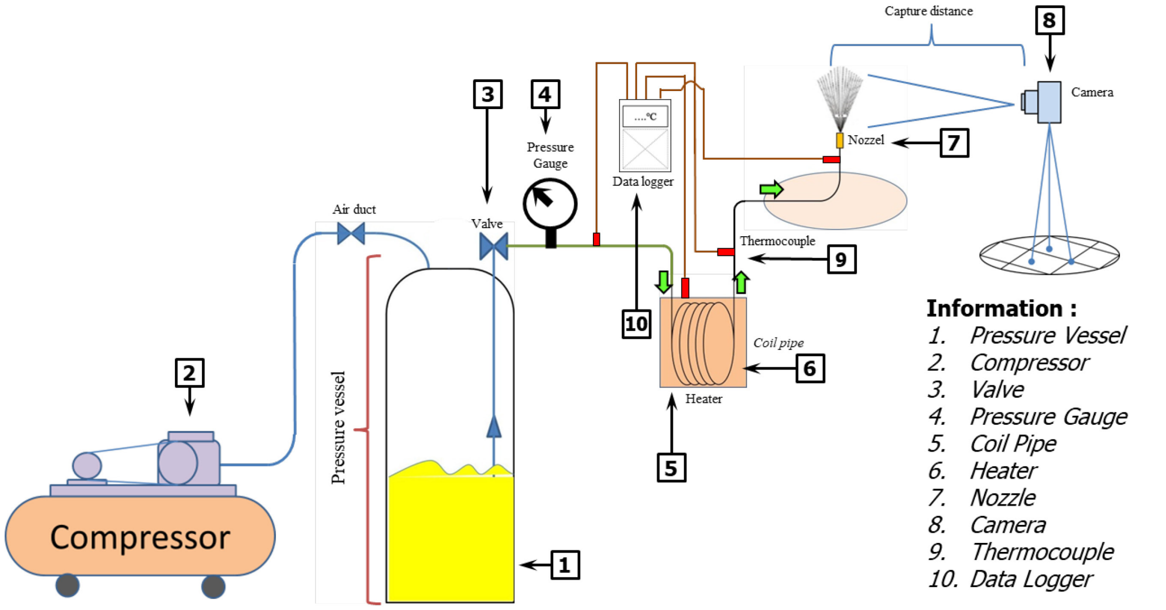

Figure 3. Illustration of the procedure for utilising waste cooking oil to achieve different spray patterns by varying pressure and temperature

RESULT AND DISCUSSION

The experimental results of this study revealed varying spray angle data attributed to the fatty content present in waste cooking oil. The fatty acid content is influenced by a decrease in viscosity and an increase in preheating temperature. The multi-component fatty acid profile of the waste cooking oil includes Methyl Laurate, Methyl Tetradecanoate, Methyl Palmitate, Methyl Palmitoleate, Methyl Lenoleate, Methyl Cis-11-eicosenoate, Methyl Docosanoate [34]. The diversity in these fatty acid components contributes to variations in the boiling point temperature [35]. As illustrated in Figure 4 (a−e), the experimental data show that at heater temperatures of 350 °C, 360 °C, 370 °C, 380 °C and 390 °C, the corresponding spray angles are 21.63°, 21.85°, 21.90°, 22.39°, and 23.26°, respectively. Furthermore, the analysis of spray angles at an injection pressure of 4 bar is detailed in Figure 5. The resulting spray angles for this pressure, at the same heater temperature variations, are 23.33°, 23.87°, 23.90°, 24.03°, and 24.30°, as depicted in Figure 5 (a−e). For an injection pressure of 5 bar, the spray angles recorded are 24.64°, 24.69°, 24.81°, 25.20°, and 25.24°, as shown in Figure 6 (a−e). These findings underscore the significant influence of both preheating temperature and injection pressure on the spray angle of waste cooking oil, indicating a clear correlation between these variable and the atomisation performance of biodiesel derived from waste cooking oil.

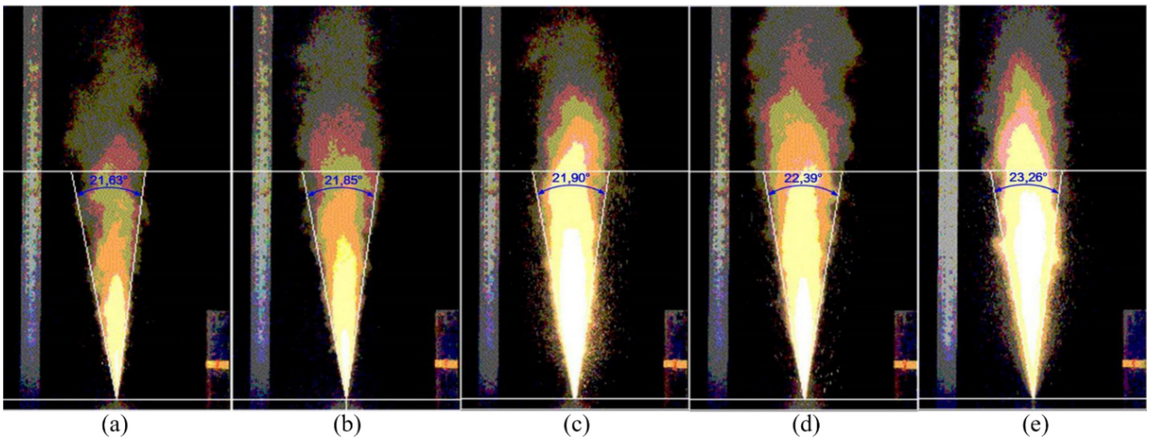

Figure 4. Spray angle of waste cooking oil at an injection pressure of 3 bar with heater temperatures of 350 °C (a), 360 °C (b), 370 °C (c), 380 °C (d), and 390 °C (e)

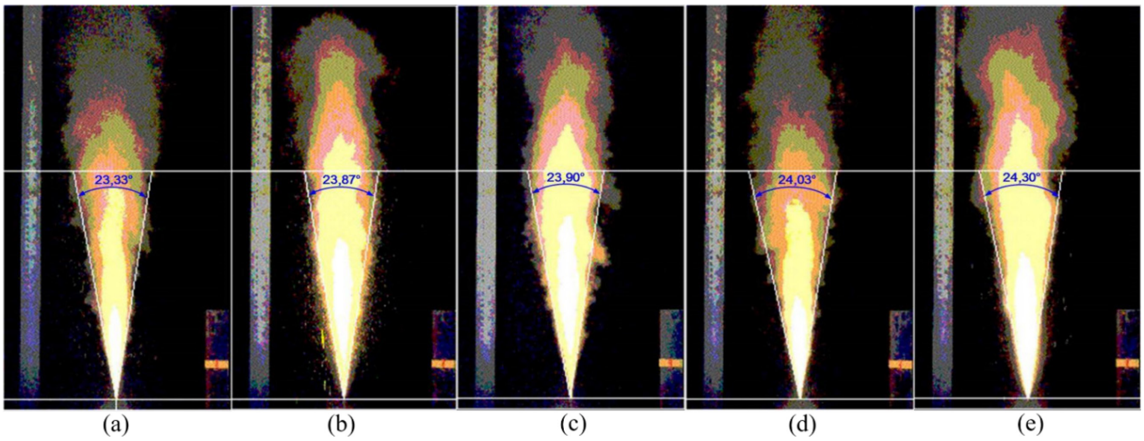

Figure 5. Spray angle of waste cooking oil at an injection pressure of 4 bar with heater temperatures of 350 °C (a), 360 °C (b), 370 °C (c), 380 °C (d), and 390 °C (e)

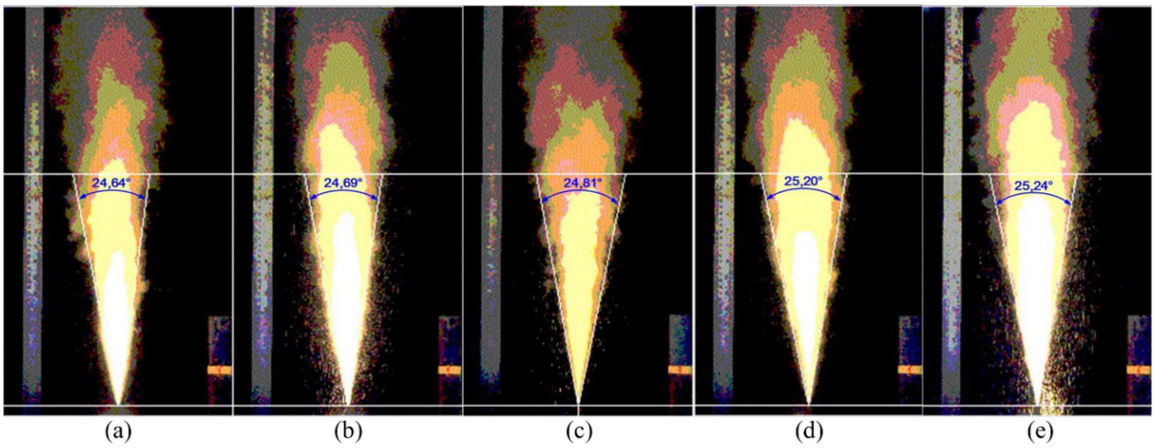

Figure 6. Spray angle of waste cooking oil at an injection pressure of 5 bar with heater temperatures of 350 °C (a), 360 °C (b), 370 °C (c), 380 °C (d), and 390 °C (e)

The figures presented above illustrate that the spray's angle at the nozzle's tip increases as the injection pressure rises from 3 bar to 5 bar. This correlation is further supported by the graph in **Figure 7**, which also illustrates the relationship between spray angle and heater temperature in the range of 350 °C to 390 °C.

It can be seen in Figure 7 that the magnitude of the spray angle is affected by the increase in the temperature of the waste cooking oil due to reduced viscosity and density values. Specifically, as the heater temperature rises from 350 °C to 390 °C, the fluid temperature increases from 160 °C to 240 °C, causing the viscosity of waste cooking oil to decrease from 6.2 cP to 2.1 cP. Viscosity is also significantly influenced by the presence of free fatty acids. A limited concentration of free fatty acids in the oil can lower viscosity. In contrast, a higher concentration may lead to deposits forming on the nozzle, which can interfere with fuel atomisation [36]. Figure 7 indicates that these deposits at the nozzle tip can cause a reduction in spray angle under specific heater temperatures and injection pressures.

The solution is to heat the waste cooking oil to reduce free fatty acids so that the oil's viscosity decreases [37, 38]. Additionally, replacing the nozzle can prevent the build-up of free fatty acid and glycerol deposits at the nozzle tip. Research on waste cooking oil may benefit from alternative methods, such as a rapid non-catalytic amidation reaction performed at room temperature to effectively reduce the free fatty acid content [39, 40].

The increase in injection pressure has a pronounced effect on the spray angle, enhancing it from 21.63° to 25.24°. The energy supplied by the injection pressure is critical for deforming the waste cooking oil into droplets. Greater injection pressures provide more energy, which leads to the generation of smaller droplets through the even distribution of this energy. The resulting smaller droplets can penetrate the ambient environment more effectively than larger droplets, which contributes to an increased spray angle as the spray develops laterally [41].

However, measuring the spray angle poses challenges, particularly in determining the edge of the cone shape of the fuel spray. The atomisation at the spray's edges results in a gradation of colour between the fuel spray and the surrounding air, making it difficult to delineate the boundary. Accurately defining this boundary necessitates the use of high-resolution cameras and collaborative image-processing software to enhance clarity [42]. The results from the processing and measurement (image processing) yield a graph that illustrates the correlation between injection pressure, heater temperature, and the formation of the spray angle, as presented in Figure 7.

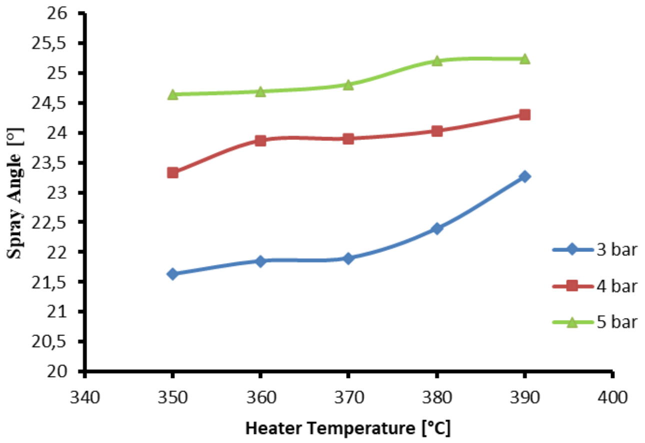

Figure 7. Correlation graph of spray angle vs. injection pressure and heater temperature

For the theoretical spray angle value, one can use the Borman formula [43]:

$$\theta = 0.05 \left(\frac{\Delta p d_0^2}{\rho_L v_L^2}\right)^{1/4} \tag{1}$$

At Δp = 5 bar = $5 \cdot 10^5$ Pa, v_L = 9.05 m/s, ρ_L = 0.78 kg/m^3, and d_0 = 0.5 mm, the resulting angle value is:

$$\theta = 0.05\left(\frac{5\cdot 10^5 \times 0.5^2}{0.78\times 9.05^2}\right)^{\frac{1}{4}} = 24.44°$$

The results of the spray angle tests showed values ranging from 21° to 25°, which closely align with the expected outcomes for optimal spray characteristics during biodiesel production. However, further research is essential to enhance the cost-effectiveness of biodiesel production through the transesterification of waste cooking oil. As indicated by Maheshwari *et al.* (2022), certain catalysts demonstrate greater cost-effectiveness and require less methanol than some previously used catalysts in biodiesel production [44]. This finding suggests a promising avenue for future research that could lead to more economical processes. The experimental tests, in conjunction with a thorough literature review, confirm that waste cooking oil can be effectively recycled into biodiesel raw materials. Key measurement indicators, including spray angle, injection pressure, and preheating temperature, play a crucial role in reducing the viscosity of waste cooking oil, making it suitable for conversion into biodiesel. The test results serve as a foundation for ongoing efforts in waste recycling, indicating that while initial testing has provided valuable insights, further development for large-scale recycling of waste cooking oil is warranted.

Moreover, managing waste cooking oil goes beyond merely addressing environmental concerns, recognising the significant potential of this waste product as a heat energy store. Notably, waste cooking oil possesses favourable heat-absorbing properties, with a latent heat of 97.7 kJ/kg for melting and a thermal conductivity of 0.155 W/(m K) [45]. This positions waste cooking oil as an attractive candidate for innovative recycling applications [46]. In accordance with the hierarchy of waste management practices grounded in the 3R initiative (Reduce, Reuse, Recycle), our findings support the following approach: (1) Reduce waste generation at its source; (2) Reuse waste wherever possible to minimise disposal; and (3) Recycle waste when reduction or reuse is not feasible [38]. This systematic framework is visually represented in **Figure 8**, illustrating the sequential priority of waste management strategies.

Therefore, waste cooking oil presents a significant opportunity for further development into valuable resources [47]. This research has practical implications for TVET institutions, particularly in preparing workers to acquire the competencies associated with green skills [48]. These competencies encompass responsible waste utilisation that safeguards the environment, discourages littering, and promotes healthy practices by avoiding the reuse of frying oil, which can be harmful to human health [49]. The application of these competencies represents a series of actions aimed at effectively implementing green TVET principles. Consequently, the recycling of waste cooking oil aligns with the dimensions of green TVET, emphasising the importance of waste recycling as a vital aspect of this initiative [50]. The implementation flow model that illustrates this process is presented in **Figure 9**.

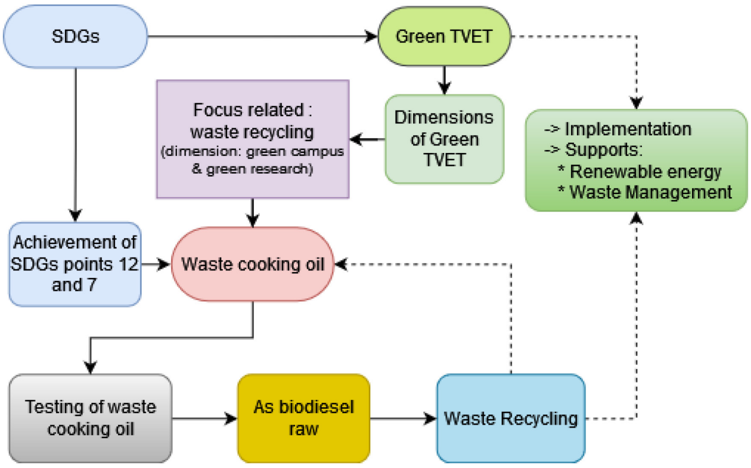

Figure 9. Implementation flow model

In addition to spray angle and injection pressure, the viscosity of vegetable oil plays a crucial role in its performance. Studies indicate that lower viscosities result in a larger spray angle, a phenomenon this research aims to address by reducing the viscosity of waste cooking oil through a preheating treatment. In fact, as the preheating temperature increases, there is a corresponding increase in the spray angle. Higher temperatures of the cooking oil reduce both viscosity and density, thereby enhancing the spray characteristics [51]. The correlation between spray angle and heater temperature is evident, with increasing temperatures of 350 °C, 360 °C, 370 °C, 380 °C and 390 °C consistently leading to larger spray angles.

Furthermore, the oil spray is affected not only by spray angle, injection pressure, and viscosity but also by the distribution of oil droplet size. An ideal fuel exhibits atomisation characterised by small and uniform droplet sizes. Empirical evidence shows that injection pressure and viscosity critically affect the droplet distribution of coconut oil [52]. Research on the spray trajectory originating from the nozzle tip significantly impacts droplet size − specifically, droplets tend to be smaller as they move further away from the nozzle [53]. The results underscore the importance of further exploration into the recycling of waste cooking oil, not only for biodiesel production but also for its potential utilisation as a sustainable energy resource, contributing to broader environmental goals.

CONCLUSION

Based on the findings from experimental research and literature reviews, the following key points can be stated. There is a significant relationship between injection pressure, heater temperature, and the spray angle of waste cooking oil. Specifically, a higher injection pressure, resulting in smaller droplets and a wider spray angle, may hinder effective oil penetration into the environment. Conversely, increasing the heater temperature reduces the viscosity of waste cooking oil, facilitating a finer spray as the oil transitions from liquid to vapour. However, this process can lead to the accumulation of free fatty acids and glycerol at the nozzle tip, which may cause the spray angle to decrease under certain conditions of heater temperature and injection pressure.

Furthermore, due to its abundance and low cost, recycled waste cooking oil emerges as a valuable raw material within the renewable energy and waste management sectors, particularly for biodiesel production. The utilisation of waste cooking oil for biodiesel not only represents a significant stride toward sustainable development but also contributes to mitigating reliance on fossil fuels. By promoting environmentally friendly practices, this approach addresses key challenges related to climate change and enhances the overall sustainability of energy production.

NOMENCLATURE

Symbols

Δp	pressure of the injector	[kPa]
υ_L	liquid flow velocity	[m/s]
ρ_L	liquid density	[kg/m^3]
d_0	spray diameter	[mm]

Greek letters

θ	spray angle	[°]

Abbreviations

SDGs	Sustainable Development Goals
TVET	Technical Vocational Education and Training

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REFERENCES

1. E. Dugarova and N. Gülasan, "Challenges and opportunities in the implementation of the sustainable development goals," United Nations Dev. Program. United Nations Res. Inst. Soc. Dev., no. March, pp. 1–101, 2017.
2. E. A. Hanushek, G. Schwerdt, L. Woessmann, and L. Zhang, "General education, vocational education, and labor-market outcomes over the lifecycle," J. Hum. Resour., vol. 52, no. 1, pp. 48–87, 2017, https://doi.org/10.3368/jhr.52.1.0415-7074R.
3. C. C. Chinedu, A. Saleem, and W. H. N. Wan Muda, "Teaching and Learning Approaches: Curriculum Framework for Sustainability Literacy for Technical and Vocational Teacher Training Programmes in Malaysia," Sustain., vol. 15, no. 3, 2023, https://doi.org/10.3390/su15032543.
4. S. T. Ghulam and H. Abushammala, "Challenges and Opportunities in the Management of Electronic Waste and Its Impact on Human Health and Environment," Sustain., vol. 15, no. 3, 2023, https://doi.org/10.3390/su15031837.
5. H. Li, S. I. Khattak, and X. Lu, "Greening the Way Forward : A Qualitative Assessment of Green Technology Integration and Prospects in a Chinese Technical and Vocational Institute," Sustainability, vol. 15, no. 6, 2023, https://doi.org/https://doi.org/10.3390/su15065187.
6. Warju, S. P. Harto, Soenarto, and M. D. Hartmann, "Evaluating the Implementation of Green School (Adiwiyata) Program: Evidence from Indonesia," Int. J. Environ. Sci. Educ., vol. 12, no. 6, pp. 1483–1501, 2017, [Accessed: 1.11.2024] http://www.ijese.net/makale/1914.
7. F. Bassi, "Resource Efficiency and Circular Economy in European SMEs : Investigating the Role of Green Jobs and Skills," Sustainability, vol. 13, no. 21, 2021, https://doi.org/https://doi.org/10.3390/su132112136.

8. I. Mikhno, V. Koval, G. Shvets, O. Garmatiuk, and R. Tamošiūnienė, "Green economy in sustainable development and improvement of resource efficiency," Cent. Eur. Bus. Rev., vol. 10, no. 1, 2021, https://doi.org/https://doi.org/10.18267/j.cebr.252.
9. A. Setiawan, "Greening TVET for Sustainable Development," Universitas Pendidikan Indonesia, Bandung, Indonesia, 2019. [Accessed: 1.11.2024] https://agroindustri.upi.edu/id/greening-tvet-for-sustainable-development.
10. R. B. Mustapha, "Green and Sustainable Development for TVET in Asia," Innov. Vocat. Technol. Educ., vol. 11, no. 2, 2016, https://doi.org/10.17509/invotec.v11i2.2147.
11. S. Mcgrath and L. Powell, "International Journal of Educational Development Skills for sustainable development : Transforming vocational education and training beyond 2015," Int. J. Educ. Dev., vol. 50, pp. 12–19, 2016, https://doi.org/10.1016/j.ijedudev.2016.05.006.
12. D. Tremblay, C. Villeneuve, and P. Faubert, "Alignment of the 2030 Agenda to the port industry," Sustain. Dev., no. June, pp. 1–15, 2024, https://doi.org/10.1002/sd.3108.
13. G. V. Auktor, Green Industrial Skills for a Sustainable Future. United Nations Industrial Development Organization, Vienna, Austria, 2020.
14. L. Zhang, M. Xu, H. Chen, Y. Li, and S. Chen, "Globalization, Green Economy and Environmental Challenges: State of the Art Review for Practical Implications," Front. Environ. Sci., vol. 10, no. March, pp. 1–9, 2022, https://doi.org/10.3389/fenvs.2022.870271.
15. S. Majumdar, "Developing a Greening TVET Framework," UNESCO-UNEVOC Int. Cent., no. 1987, pp. 1–14, 2012, [Accessed: 1.11.2024] https://unevoc.unesco.org/fileadmin/user_upload/docs/Greening_TVET_Framework-Bonn-Final_Draft.pdf.
16. R. Lamichhane and R. E. Echaveria, "Green TVET for a Sustainable Future," Manila, 2017. [Accessed: 1.11.2024] https://v4.cpsctech.org/publications/papers-and-presentations/Ram-Hari-Lamichhane/2017-08-Greening-TVET-for-Sustainable-Future.pdf.
17. E. U. P Pandey, M. A. Khalid, and S. Aqeel Ahmad, "Paradigm Shift in Municipal Solid Waste Treatment and Disposal Technology: a Review," IJRAR19J2083 Int. J. Res. Anal. Rev., vol. 6, no. 1, pp. 944–949, 2019.
18. President Of The Republic Of Indonesia, "National Energy Policy (Presidential Regulation No.5/2006 Date January 25,2006)," vol. 4, no. 5, pp. 25A-27A, 2006.
19. E. I. Rhofita, R. Rachmat, M. Meyer, and L. Montastruc, "Mapping analysis of biomass residue valorization as the future green energy generation in Indonesia," J. Clean. Prod., vol. 354, p. 131667, 2022, https://doi.org/https://doi.org/10.1016/j.jclepro.2022.131667.
20. N. Kusminingrum, "Bahan Bakar Nabati Sebagai Salah Satu Alternatif Untuk Mendukung Penggunaan Bahan Bakar "Ramah Lingkungan" (in Indonesian, Biofuels as an Alternative to Support the Use of Sustainable Fuels)," J. Jalan Jemb., vol. 25, no. 2, 2018, [Accessed: 1.11.2024] http://jurnal.pusjatan.pu.go.id/index.php/jurnaljalanjembatan/article/view/320.
21. M. Ayoub et al., "A Comprehensive Review on Oil Extraction and Biodiesel Production Technologies," Sustainability, vol. 13, no. 2, 2021, https://doi.org/https://doi.org/10.3390/su13020788.
22. A. I. Osman et al., "Optimizing biomass pathways to bioenergy and biochar application in electricity generation, biodiesel production, and biohydrogen production," Environmental Chemistry Letters, vol. 21, no. 5. pp. 2639–2705, 2023, https://doi.org/10.1007/s10311-023-01613-2.
23. M. D. Faik and Y. Zhang, "Liquid-phase dynamics during the two-droplet combustion of diesel-based fuel mixtures," Exp. Therm. Fluid Sci., vol. 115, no. September 2019, p. 110084, 2020, https://doi.org/10.1016/j.expthermflusci.2020.110084.
24. Y. Tang, D. Lou, C. Wang, P. Tan, Z. Hu, and Y. Zhang, "Joint Study of Impingement Combustion Simulation and Diesel Visualization Experiment of Variable Injection Pressure in Constant Volume Vessel," vol. V, 2020, https://doi.org/10.3390/en13236210.

25. S. Cardona, R. Payri, F. J. Salvador, and J. Gimeno, "Effects of varying the liquid fuel type and air co-flow conditions on the microscopic spray characteristics in an atmospheric annular co-flow spray burner 1-s2.0-S001623612203842X-main.pdf," Fuel, vol. 335, 2023, https://doi.org/https://doi.org/10.1016/j.fuel.2022.127018.
26. K. Vinukumar, "Experimental Evaluation on Different Viscous Fluids Spray Characteristics in Injector Using Constant Volume Chamber," IOSR J. Mech. Civ. Eng., vol. 1, no. 1, pp. 46–50, 2012, https://doi.org/10.9790/1684-0114650.
27. M. Zaccara, C. Carvallo, A. Montanaro, J. Gimeno, L. Allocca, and G. Cardone, "Engine Combustion Network "" Spray G "": Wall heat transfer characterization by infrared thermography," Exp. Therm. Fluid Sci., vol. 142, no. June 2022, p. 110825, 2023, https://doi.org/10.1016/j.expthermflusci.2022.110825.
28. R. Kukana and O. P. Jakhar, "An appraisal on enablers for enhancement of waste cooking oil-based biodiesel production facilities using the interpretative structural modeling approach," Biotechnol. Biofuels, vol. 14, no. 1, pp. 1–13, 2021, https://doi.org/10.1186/s13068-021-02061-2.
29. Monika, S. Banga, and V. V Pathak, "Biodiesel production from waste cooking oil: A comprehensive review on the application of heterogenous catalysts," Energy Nexus, vol. 10, p. 100209, 2023, https://doi.org/https://doi.org/10.1016/j.nexus.2023.100209.
30. Mohan, W. Yang, K. L. Tay, and W. Yu, "Experimental study of spray characteristics of biodiesel derived from waste cooking oil," Energy Convers. Manag., vol. 88, pp. 622–632, 2014, https://doi.org/10.1016/j.enconman.2014.09.013.
31. A. S. Cheng, A. Upatnieks, and C. J. Mueller, "Investigation of the impact of biodiesel fuelling on NOx emissions using an optical direct injection diesel engine," Int. J. Engine Res., vol. 7, no. 4, pp. 297–318, 2006, https://doi.org/10.1243/14680874JER05005.
32. M. Al-Dawody, K. Al-Farhany, N. H. Hamza, and D. A. Hamza, "Numerical study for the spray characteristics of diesel engine powered by biodiesel fuels under different injection pressures," J. Eng. Res., vol. 10, no. 1B, pp. 264–289, 2022.
33. F. Adi, E. Saleh, and R. Mursidi, "Physical Characteristic of Discarded Cooking Oil Combustion as The Energy Sources for Wick Stove Fery," J. Tek. Pertan. Sriwij., vol. 1, no. 2, pp. 84–92, 2012, [Accessed: 1.11.2024] https://ejournal.unsri.ac.id/index.php/tekper/article/download/11347/5295.
34. I. K. G. Wirawan, A. Ghurri, and W. N. Septiadi, "Distribusi Ukuran Droplet Bahan Bakar Minyak Jelantah Sepanjang Region Semburan Nosel Seberhana (in Indonesian, Droplet Size Distribution of Waste Cooking Oil Fuel Along the Spray Region of a Simple Nozzle)," J. Mech., vol. 9, no. 1, pp. 16–21, 2018, https://doi.org/10.23960/mech.v9.i1.201803.
35. W. Yuan, A. C. Hansen, and Q. Zhang, "Vapor pressure and normal boiling point predictions for pure methyl esters and biodiesel fuels," Fuel, vol. 84, no. 7–8, pp. 943–950, 2005, https://doi.org/10.1016/j.fuel.2005.01.007.
36. P. S. Yadav, A. A. Chaturwedi, A. Sahu, A. Yadav, A. Fraynjiya, and R. Gautam, "Effect of Nozzle Geometry and Fuel Modification on Atomization and Emission Characteristics in CI Engine: A Review," Emerg. Trends Mech. Ind. Eng. Sel. Proc. ICETMIE 2022, pp. 13–32, 2023.
37. H. Noureddini, B. C. Teoh, and L. D. Clements, "Viscosities of Vegetable Oils and Fatty Acids," Chem. Biomol. Eng. Res. Publ., vol. 69, no. 12, pp. 1189–1191, 1992, [Accessed: 1.11.2024] https://core.ac.uk/download/pdf/17225476.pdf.
38. G. Manikandan, P. R. Kanna, D. Taler, and T. Sobota, "Review of Waste Cooking Oil (WCO) as a Feedstock for Biofuel—Indian Perspective," Energies, vol. 16, no. 4, pp. 1–17, 2023, https://doi.org/10.3390/en16041739.
39. S. ~A. Flannery, B.~P.Teukolsky et al., "Scholar (8)," Convergence in the information industries. Telecommunications, broadcasting and data processing 1981-1996, vol. 26, no. 1. pp. 125–150, 2004.

40. J. B. Tarigan, B. Ginting, S. Perangin-angin, R. N. Sari, P. F. Sianipar, and E. K. Sitepu, "Homogenizer-intensified amidation of free fatty acids in waste cooking oil for biodiesel production," South African J. Chem. Eng., vol. 46, no. 1, pp. 271–276, 2023, https://doi.org/https://doi.org/10.1016/j.sajce.2023.08.011.
41. Y. Lei et al., "Investigation on Primary Breakup of High-Pressure Diesel Spray Atomization by Method of Automatic Identifying Droplet Feature Based on Eulerian–Lagrangian Model," Energies, vol. 15, no. 3, 2022, https://doi.org/10.3390/en15030867.
42. K. Czernek, M. Ochowiak, and S. Włodarczak, "Effect of rheological properties of aqueous solution of na-cmc on spray angle for conical pressure-swirl atomizers," Energies, vol. 13, no. 23, 2020, https://doi.org/10.3390/en13236309.
43. A. A. S. D. Pramana, I. G. B. W. Kusuma, and I. M. Widiyarta, "Pengujian Performance Biodiesel Biji Alpukat Di Tinjau Dari Karakteristik Panjang Penyemprotan Dan Ukuran Butiran (in Indonesian, Performance Testing of Avocado Seed Biodiesel in Review of the Characteristics of Spray Length and Grain Size)," Log. J. Ranc. Bangun dan Teknol., vol. 15, no. 3, p. 164, 2015, [Accessed: 1.11.2024] http://ojs.pnb.ac.id/index.php/LOGIC/article/view/494.
44. P. Maheshwari et al., "A review on latest trends in cleaner biodiesel production: Role of feedstock, production methods, and catalysts," J. Clean. Prod., vol. 355, p. 131588, 2022, https://doi.org/10.1016/j.jclepro.2022.131588.
45. M. Irsyad, Amrizal, Harmen, Amrul, M. D. Susila Es, and A. R. Diva Putra, "Experimental study of the thermal properties of waste cooking oil applied as thermal energy storage," Results Eng., vol. 18, no. November 2022, p. 101080, 2023, https://doi.org/10.1016/j.rineng.2023.101080.
46. M. C. Bobadilla, R. Fernández Martínez, R. L. Lorza, F. S. Gómez, and E. P. V. González, "Optimizing biodiesel production fromwaste cooking oil using genetic algorithm-based support vector machines," Energies, vol. 11, no. 11, pp. 1–19, 2018, https://doi.org/10.3390/en11112995.
47. W. A. Wan Mahari et al., "Generating alternative fuel and bioplastics from medical plastic waste and waste frying oil using microwave co-pyrolysis combined with microbial fermentation," Renew. Sustain. Energy Rev., vol. 153, no. May 2021, p. 111790, 2022, https://doi.org/10.1016/j.rser.2021.111790.
48. M. Pavlova and C. S. Chen, "Facilitating the development of students' generic green skills in TVET: an ESD pedagogical model," TVET@ Asia, no. 12, pp. 1–21, 2019.
49. W. M. Jahonga, P. R. Ngore, and V. W. Muramba, "Transforming and Greening Tvet for Sustainable Development in Western Kenya," Eur. J. Res. Reflect. Manag. Sci., vol. 3, no. 2, pp. 63–71, 2015.
50. M. Tanveer, S. A. R. Khan, M. Umar, Z. Yu, M. J. Sajid, and I. U. Haq, "Waste management and green technology: future trends in circular economy leading towards environmental sustainability," Environ. Sci. Pollut. Res., vol. 29, no. 53, pp. 80161–80178, 2022, https://doi.org/10.1007/s11356-022-23238-8.
51. A. D. A. Sulistyo, I. K. Gede, and A. Ghurri, "Analisa Sudut Sebaran Minyak Kelapa Di Ujung Nosel Menggunakan Pemanas Awal Tipe Coil (in Indonesian, Analysis of Coconut Oil Spray Angle at the Nozzle Tip Using Coil-Type Preheater)," in Konferensi Nasional Engineering Perhotelan IV, 2016, vol. 2016, no. 1, pp. 61–66, [Accessed: 1.11.2024] https://simdos.unud.ac.id/uploads/file_penelitian_1_dir/2cbb26357ba7b09b09fa966e418236b1.pdf.
52. D. A. Sulistyo, I. K. G. Wirawan, and A. Ghurri, "Uji Karakteristik Distribusi Butiran Minyak Kelapa Pada Semburan Nosel Burner Sederhana (in Indonesian, Characteristic Test of Coconut Oil Grain Distribution in the Simple Burner Nozzle Spray)," J. METTEK, vol. 3, no. 1, pp. 29–35, 2017, [Accessed: 1.11.2024] https://ojs.unud.ac.id/index.php/mettek/article/view/31947.

53. J. J. G. van Thiel, "Data-driven condition monitoring of maritime diesel engines through machine learning algorithms : a case study on fuel injection nozzles," Master Thesis, Eindhoven University of Technology, 2020.

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