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APPLICATION OF CORRELATION AND REGRESSION ANALYSIS TO THE OPTIMIZED BIODIESEL YIELD FROM USED COOKING OIL VIA ACID-CATALYZED ESTERIFICATION

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Abstract

This research examines the physicochemical characteristics of waste vegetable oil biodiesel blends based on viscosity, density, flash point, cloud point, pour point, and sulfur content. B20 to B100 blends were subjected to testing to determine their suitability as alternative fuels against regular diesel standards. An acid-catalyzed esterification and base-catalyzed transesterification in two steps were employed to decrease free fatty acid (FFA) content and enhance biodiesel yield. At optimized reaction conditions, a biodiesel yield of 96.3% was achieved, indicating the efficiency of the process. Experimental findings showed that viscosity of blends of biodiesel decreased consistently with an increase in temperature from 7.212 mm²/s at 10°C for B100 to 3.415 mm²/s at 50°C for B20. All the blends met the ASTM D445 standard for 40°C viscosity. At higher biodiesel blends the flash point increased indicating fuel safety. Whereas, the associated rise in pour and cloud points signified a reduced low-temperature fluidity. Through heatmap analysis, it was found that viscosity is strongly negatively correlated with temperature, while flash point, pour point, and blend concentration were positively correlated. Regression analysis shows strong linear relationships between viscosity, flash point, and blend composition, further establishing their temperature dependence and their suitability for predictive modeling. It is concluded that there is a need for control of production parameters and optimization of the blend ratios to realize maximum engine efficiencies and product conformity to standards. Biodiesel blends from waste vegetable oil are thus efficient alternatives to conventional diesel, whose various physicochemical properties have been successfully analyzed and optimized using statistical approaches.

Keywords: Used cooking oil, acid esterification, transesterification, biodiesel, physicochemical

Introduction

Alternative fuel research has been prompted by the desire to reduce environmental pollution and deterioration caused by the exploration and use of fossil fuels. Because of its many benefits, including its low emissions, low sulfur content, biodegradability, aromatic calorific content, renewability, and high combustion efficiency, biodiesel has been recognized as a sustainable alternative to petroleum diesel (Khairati, 2022). Furthermore, it has a low idle noise, simple cold starting, and less engine wear, all of which extend the life of the fuel injection equipment (López and Sotelo, 2019). In addition to being more lubricating than conventional fuels, biodiesels also emit less particulate matters, have a nice fruity smell, and produce less soot in vehicle exhaust (Zhao et al., 2021). Study has shown that biodiesels have a high cetane number, hence low carbon monoxide and hydrocarbon emissions, which are greenhouse gasses that give rise to global warming, are produced during its combustion (Hosseinzadeh-Bandbafha et al., 2022). On the other hand, certain drawbacks, like production costs and competition with the food chain, restrict its commercial products (Farouk et al., 20240). Despite being a renewable energy source, the majority of the oil used to make biodiesel comes from edible terrestrial oilseed plants, such as groundnut, corn, palm, cottonseed, coconut, canola, sesame, rapeseed, olive, sunflower, safflower peanut and soybean oils (Goh et al., 2020). The consistent reliance and increasing demand for edible oil as a feedstock for the production of biodiesel creates a siphon, which draws in a higher proportion into the fuel industry. As a result, the food industry's supply of edible oil causes shortages and inflation.

Additionally, the primary barrier to the product's commercialization has been the expense of producing biodiesel (Aransiola et al., 2019). This is mostly because of the high cost of the feedstock, which accounts for 75% of the overall cost of production (Khodadadi et al., 2020). Other factors that affect this include the price of crude petroleum, geographic location, crop output variations from season to season, base stock, and other considerations (Ong et al., 2024). The price of used cooking oil is approximately onethird that of edible oil, leading to significant reductions in overall production costs (Suzihaque *et al.,* 2022).

Other feedstocks, such as beef tallow, hog fat, yellow grease, algae, and used cooking oils, can be utilized to create biodiesel (Elgharbawy et al., 2021a). Biodiesel produced from used cooking oil is regarded as being extremely economically and environmentally sustainable since it minimises pollution from human activities and lessens environmental degradation (Sadaf *et al*., 2018). The annual production of used cooking oil is billions of gallons worldwide (Jha and Das, 2017). Used cooking oil to biodiesel conversion can enhance the living conditions of millions of individuals around the world, empower underprivileged communities and organizations, provide employment opportunities, particularly for young people, and assist lower high unemployment rates.

Furthermore, the health risks and danger of further environmental damage associated with the use of insufficient and ineffective techniques for disposing of spent cooking oil by households, restaurants, other companies, and industrial food producers is significantly reduced (Pugazhendhi et al., 2020).

It also prevents the conversion of land usage for the production of crops. In terms of chemistry, biodiesel is a blend of long-chain fatty acids and alkyl (methyl/ethyl) esters (Singh et al., 2021). Biodiesel is produced by a method known as transesterification. In this process, the reaction of a triglyceride (oil/fat) with an alcohol form esters and glycerol in the presence of a base or acidic catalyst (Chen *et al*., 2021). The choice of catalyst type is dependent on some factors such as cost, rate of production, reaction time, and corrosive property. Hence, the base catalysts are more desirable than acids catalysts due to their low cost, high yield of biodiesel, short reaction time, non-corrosion property (Bhatia et al., 2020). For the choice of the type of alcohol; methanol is the most commonly used alcohol due to its low cost ((Foo *et al*., 2022). It's also critical to note that free fatty acid (FFA) content of fat and oil varies, which may affect the reaction's outcome. Glycerol is a by-product of the direct transesterification process that produces biodiesel from oils with a low FFA level (Miyuranga *et al.,* 2023).

But when oil or fat with a high FFA content undergoes a transesterification reaction, a saponification reaction occurs, decreasing the catalyst's effectiveness and leading to a low ester conversion (Elgharbawy *et al*., 2021b). Due to its high FFA concentration, used cooking oil would not provide the intended outcome. Thus, it is crucial to minimize the FFA content as much as possible. In industrial processes, acid esterification is the most widely used method for treating FFAs, where FFAs react with an excess amount of methanol in the presence of sulfuric acid as a catalyst to form biodiesel and water (Anwar et al., 2018; Lahiri et al., 2023). Previous study show that 40:1 FFA to methanol molar ratio, acid esterification, and 10 weight percent H_2SO_4 as catalyst, Chai et al. (2014) could reduce the content of FFA to 0.5 weight percent from 5 weight percent at 65 °C. 1.5 weight percent H_2SO_4 was utilized by Kara et al. (2018) at 60 °C for three hours under a molar ratio of 15:1 methanol/oil and 700 rpm agitation. The maximum conversion rate of 92.6% decreased the FFA content from 21 to 1.5 weight percent. By an acid treatment process, Sianipar *et al.* (2017) lowered the palm oil FFA by 6% under 300 rpm stirring rate, molar ratio methanol: oil of 20:1, concentration of aluminium catalyst ($Al_2(SO_4)_3.14H_2O$), reaction time of three hours at 60 °C. FFAs were decreased from 36 to 0.82 weight percent. Three acids (HCl, H_2SO_4, *and* H_3PO_4) were examined by Sadaf *et al.* (2018) in relation to utilized frying oil with an FFA of 2.75 weight percent. Their study showed a significant decrease in FFA from 2.75 to 0.33 weight percent with a conversion of 88.8% at 60 °C and a 2.5:1 methanol to oil molar ratio, hence H_2SO_4 was the most effective catalyst. Thus, this study seeks to improve the percentage of biodiesel produced from used cooking oil through acid-catalyzed enhancement technique.

Materials and Methods

Materials

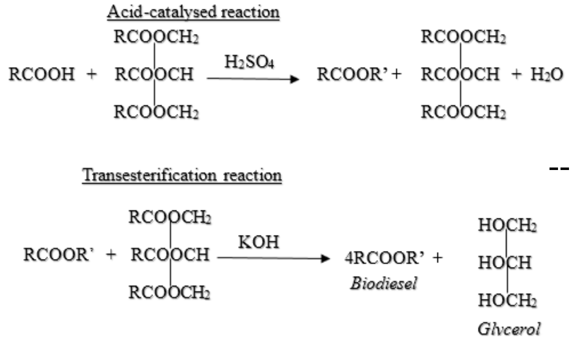
The used cooking oil utilized in this study was sourced from a local eatery in Lagos. Other materials include annular-grade methanol (99.8% purity), pure-grade isopropanol, potassium hydroxide pellets (Merck), concentrated sulfuric acid (H_2SO_4) and phenolphthalein. All other chemicals and solvents employed were of standard analytical quality from Sigma Aldrich Company.

Pretreatment

The FFA over 5% causes excessive catalyst consumption and soap generation, which hinders the creation of the product by making it harder to separate glycerol and biodiesel during the transesterification reaction (Sadaf et al., 2018). The first step in a typical transesterification process is to prepare the catalyst, which is accomplished by combining a strong base (potassium hydroxide) with alcohol (methanol) as shown in Eq 1.

$$CH_3OH + KOH \rightarrow K^+ + {}^-OCH_3 + H_2O \text{ ---------(Eq.1)}$$

The base separates into K+ and OH-ions throughout the reaction. The OH- increases the likelihood of soap production with FFA, an undesired reaction, by drawing hydrogen (H+) ions from methanol to create water (H_2O). This study suggests a two-step procedure to prevent soap production and so increase the output of biodiesel. The transesterification process comes in second, followed by an acid-catalyzed reaction (Eq. 2).



------(Eq.2)

Following acid-catalyzed pretreatment of the used cooking oil with sulfuric acid (H_2SO_4) and methanol to produce free fatty acid esters (Sianipar et al., 2017; Sadaf et al., 2018; Kara et al. (2018), the resulting mixture was subsequently dehydrated and then subjected to transesterification to yield biodiesel and glycerol.

Preparation of Catalyst and Used Cooking Oil

A mixture of 3.18 g potassium hydroxide and 100 ml methanol was prepared in a closed system to produce potassium methoxide (CH_3OK). The collected used cooking oil was filtered, heated to 65°C for 15 minutes, cooled, and settled before decantation to remove remaining water.

Analysis of Free Fatty Acid (FFA)

FFA content in the oil was measured in terms of a titration process. A base solution, which has 1 g of KOH dissolved in 1 ml of distilled water and stored in a burette, was titrated against 1 ml of used cooking oil. The experiment was performed in a conical flask using 10 ml of isopropanol and four drops of the indicator phenolphthalein.

$RCOOH_{(aq)}+KOH_{(aq)}\rightarrow RCOOK_{(aq)}+H_2O_{(L)}$ -----------(Eq.3)

The stoichiometric ratio of FFA to KOH is 1:1, meaning one mole of FFA reacts completely with one mole of KOH in Eq.3.

Acid-Catalyzed Esterification and Transesterification Reactions

To lower the FFA concentration and improve biodiesel output, an acid-catalyzed esterification step was employed. A catalyst solution was prepared by mixing 73 ml of concentrated sulfuric acid with 41.50 ml of methanol in a 500 ml flask fitted with a magnetic stirrer. This solution was subsequently introduced into 300 ml of preheated used cooking oil. The resulting mixture was maintained at 55 °C and stirred at 700 rpm for one hour. Following this, a transesterification reaction was performed using a methanol-to-oil molar ratio of 20:1. However, extra alcohol was supplied to complete the reaction since alcohol escapes from the process while it is happening. To complete the transesterification process, the previously prepared potassium methoxide (CH_3OK) was introduced into the product of the acid-catalyzed reaction within a sealed 500 ml flat-bottom flask. The reaction was conducted in a closed system to prevent methanol evaporation. Given that methanol boils at 65 °C, the reaction temperature was carefully maintained between 60 °C and 65 °C for one hour. Afterward, the mixture was transferred into a 500 ml separating funnel and allowed to stand undisturbed for 24 hours to enable the separation of biodiesel and glycerol layers. The biodiesel phase was then washed five times using tepid water until a neutral pH was achieved, effectively removing residual glycerol, catalyst, and other impurities.

Physicochemical Properties Determination

According to ASTM D-445, the Digital Viscometer SVM 3000 (Anton Paar) was used to determine viscosity at various temperatures. To ascertain the flash point, an automated Pensky-Martens closed-cup device with a temperature range of 60–190°C in accordance with ASTM D93–11 Standard Test Methods was used. ASTM D6371-05 was used to calculate the cloud and pour points. While the sulphur content, which establishes the fuel's pollution level, was calculated in accordance with ASTM D5453, the density was measured using a density bottle.

Table 1: ASTM D 975-13 Specification of Biodiesel and Diesel

Property	Testing Method (D)	Biodiesel Limits	Diesel Limits
Density (g/cm$^{3)}$	1298	0.88	0.86
Sulphur(ppm)	5453	15	15
Pour point (^{o}C)	97	-5 to 10	35
Cloud point(^{o}C)	2500	-3 to 15	35
Flash point (^{o}C)	93	100-170	100-130
Viscosity, 40 ^{o}C (mm^2/s)	445	1.9 - 6.0	1.3 – 24.0

Results and Discussion

Outcome of Biodiesel Production

A total of 300 ml of feedstock was utilized during the production, resulting in 289 ml of biodiesel, representing a 96.35% yield, and 11 ml of glycerol, accounting for 3.7% of the original volume (Figure 1). This high conversion efficiency can be attributed to the prior acid-catalyzed esterification, which effectively minimized the free fatty acid (FFA) content before proceeding with the transesterification step. The performance characteristics of the biodiesel under cold conditions—specifically density, sulfur content, pour point, cloud point and—along with flash point for each blend, are summarized in Table 1 and represented in Figure 1. In earlier research, Chai et al. (2014) achieved successful FFA content reduction from 5 wt% to 0.5 wt% using a high methanol-to-FFA molar ratio of 40:1 with 10 wt% H_2SO_4 catalyst at 65 °C. Similarly, Kara et al. (2018) obtained 92.6% conversion when FFAs were lowered from 21 wt% to

1.5 wt.% by employing 1.5 wt.% sulfuric acid at 60 °C under a methanol-to-oil molar ratio of 15:1 and agitated at 700 rpm for a period of three hours. Sianipar et al. (2018) proved the FFA reduction from 36 wt.% to 0.82 wt.% utilizing aluminum sulfate ($Al_2(SO_4)_3 \cdot 14H_2O$) catalyst at 60 °C, methanol-to-oil molar ratio of 20:1, and stirring rate of 300 rpm. Besides, Sadaf et al. (2018) compared the performance of certain acid catalysts (HCl, H_2SO_4, and H_3PO_4) used in the degumming of used cooking oil with an original FFA value of 2.75 wt%, and the authors concluded that H_2SO_4 worked best to cut down the FFA to 0.33 wt% through an 88.8% conversion efficiency with a methanol-to-oil molar ratio of 2.5:1 at a temperature of 60 °C. In comparison to these investigations, this work achieved a superior conversion efficiency of 96.3%, demonstrating the effectiveness of the optimized reaction conditions. This was as a result of use of a catalyst concentration of 5 wt% H_2SO_4, which introduced adequate proton activity for effective esterification without triggering extensive side reactions. Use of a methanol-to-oil molar ratio of 20:1 was utilized, where efficient high FFA conversion and economic consumption of methanol were balanced. Reaction temperature was controlled between 60°C to 65°C to improve reaction kinetics without considerable methanol evaporation. Additionally, a stirring rate of 700 rpm allowed efficient mass transfer from oil to methanol phases in order to achieve an improved extent of reaction within a comparatively short period of 1 hour.

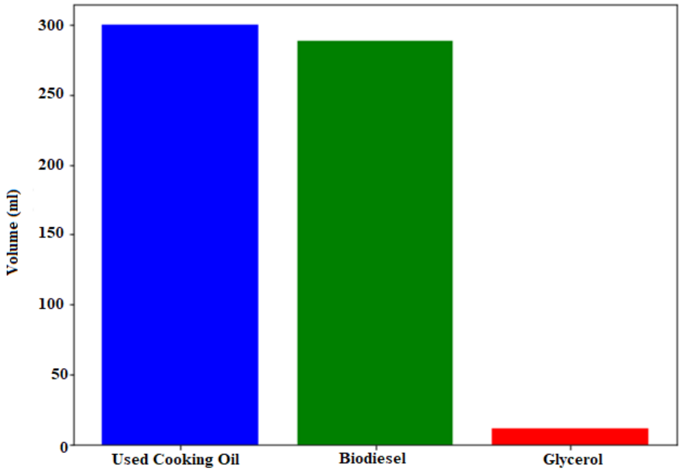


Figure 1: Production Chart for Biodiesel from Used Cooking Oil

Effect of Biodiesel Blends on Flash Point

The property of a fuel that specifies its safety during handling and storage is the flash point. It is the minimum temperature at which a fuel will vaporize to create an ignitable mixture in air. Its flammability increases with decreasing flash point (Abed et al., 2018; Anekwe, 2019). The ASTM limits for petroleum-diesel and biodiesel are 100–130°C and 100–170°C, respectively, as indicated in Table 1. All of the results for the blends and B100 were below the upper limit but over the lower limit. Furthermore, when the amount of biodiesel blend increases the temperature rises, as indicated in Figure 2. The outcome suggests that there is little chance of a fire breaking out in the event of an accident; consequently, biodiesels produced from used cooking oil, whether blended or unblended, are thought to be incredibly safe alternative fuels.

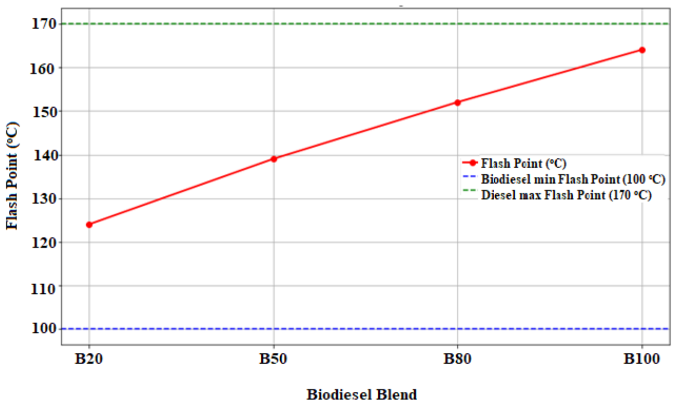


Figure 2: Effect of Biodiesel Blends on Flash Point

Effect of Biodiesel Blends on Pour and Cloud Points

The temperature at which fuels start to crystallize into wax is known as the cloud point. The typical temperature range for biodiesel is between -15°C and 3°C, which is lower than that of gasoline and diesel (35°C). This suggests that, by nature, biodiesel is more likely than petroleum-diesel to produce wax crystal in cold climes. The unblended values came out to be 5°C. As seen in Figure 3, the blended, on the other hand, has values that vary from -3°C to 2°C, indicating a rise in temperature with increasing % of biodiesel mix. Although these values fall within the recommended range, when utilizing them, caution is required since fuel below its cloud point may lose some of its lubricating qualities and clog fuel filters, which might cause engine issues (Abdalla, 2018; Anekwe, 2019). Therefore, the use of in-tank fuel warmers or certain additives and manufacturing techniques can improve the performance of biodiesel in cold areas.

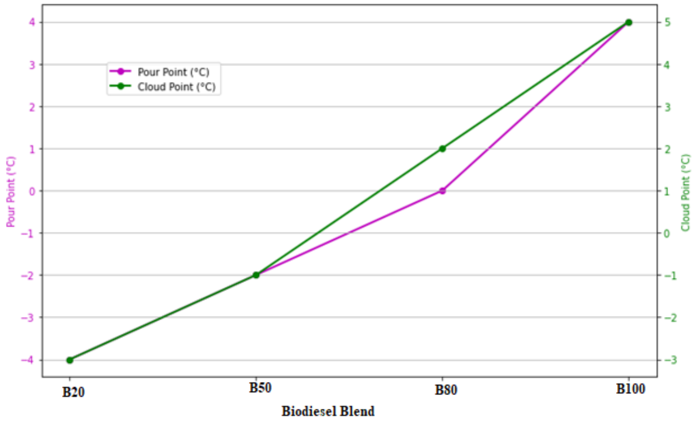


Figure 3: Effect of Biodiesel Blends on Pour and Cloud Points

Pour point is the lowest temperature at which a fuel remains in the flowing state. It is a significant property since it indicates the lowest temperature at which the fuel exists in a liquid state before it starts to solidify (Abdalla, 2018). The ASTM limit for biodiesel is between -5°C and 10°C, while the ASTM standard for diesel is 35°C (Table 1). Although the blended had values of -4°C to 0°C, which increased with a rise in temperature as the proportion of biodiesel mix increased, the unblended values were 4°C (Figure 3). Because they need to be kept heated, high pour point fuels are more difficult to utilize in colder climates. Some strategies include storing diesel-powered equipment in heated buildings, insulating fuel filters and fuel lines, and heating fuel lines (Abed et al., 2018; Anekwe, 2019).

Effect of Biodiesel Blends on Density

The density of a fuel is defined as its weight per unit volume of the vessel in which it is contained. Although denser fuels have a higher energy content, diesel and biodiesel have values of 0.86 and 0.880 g/cm3, respectively, according to ASTM D1298 Testing Method (Table 1). The blended value varied from 0.8625 to 0.8792 g/cm3, which is somewhat less than the ASTM standard for biodiesel, whereas the unblended value was 0.8883 g/cm3. Figure 4's result demonstrates that density rises as the proportion of biodiesel blend increases. However, these figures are greater than the ASTM value for diesel, suggesting that the ideal air-to-fuel ratios for full combustion may not be impacted by the use of either blended or unblended biodiesel (Abdalla, 2018; Anekwe, 2019).

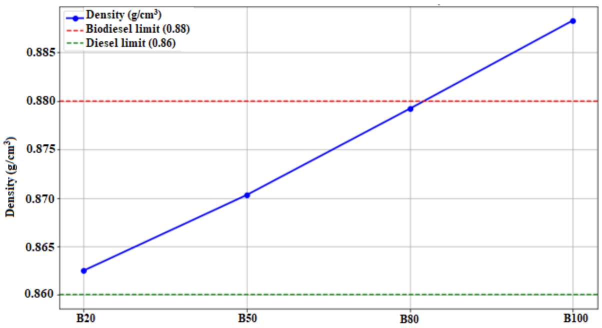


Figure 4: Effect of Biodiesel Blends on Density

Effect of Biodiesel Blends on Sulphur Content

According to the ASTM D5453 standard (Table 1), the acceptable sulfur content for both diesel and biodiesel is capped at 15 ppm. This limitation exists because sulfur compounds in fuel can produce sulfur dioxide (SO_2) and sulfate (SO_4^{2-}) particulates during combustion, contributing significantly to air pollution. In this study, the unblended biodiesel recorded a sulfur concentration of 2.30 ppm, while the blends ranged from 5.70 ppm to 14.40 ppm. As shown in Figure 5, sulfur levels declined as the proportion of biodiesel in the blend increased, aligning with the U.S. Environmental Protection Agency (EPA) standard for on-road diesel fuel implemented on June 1, 2006. Fuels exceeding the ASTM sulfur threshold can have serious environmental and health consequences, including acid rain, which damages engine components like cylinder liners and valve guides, leading to premature engine wear. Additionally, exposure to high sulfur emissions can aggravate respiratory illnesses, increase mucus production, and intensify symptoms of bronchitis and asthma (Abdalla, 2018).

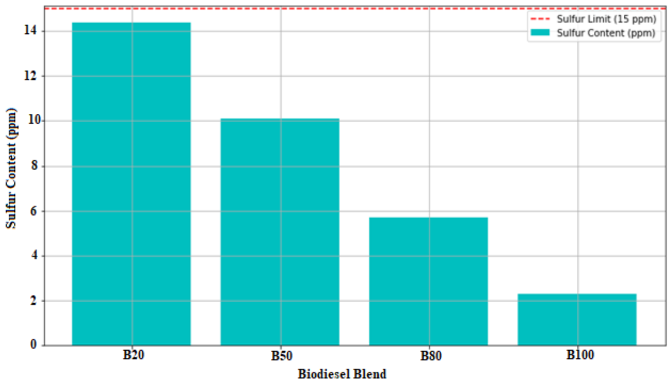


Figure 5: Sulphur Content Variation with Biodiesel Blends

Effect of Temperature Variation on Viscosity

Viscosity is oil resistance to flow at a given temperature. The reading of viscosity for all the blends of biodiesel was within the recommended range of 1.9 to 6.0 mm²/sec at a reference temperature of 40°C for diesel and biodiesel. B100 and B80 at 10°C and B100 at 20°C had higher-than-recommended viscosity reading. Fuel fluidity is impacted by higher viscosity. As a result, fuel injector atomization and accuracy are decreased (Alias et al., 2018). Additionally, it suggests that the engine combustion chamber would get more gasoline, which could not burn as cleanly as fuel with low viscosity. In reality, unburned oxidized gasoline will build up at the engine's rings, valves, injector tips, and piston sidewalls. Poor combustion is the result, which causes greenhouse gas emissions. Maintaining the proper viscosity is so crucial. But viscosity works better at higher temperatures. This is because, as the temperature rises, fuel's viscosity falls (Figure 6).

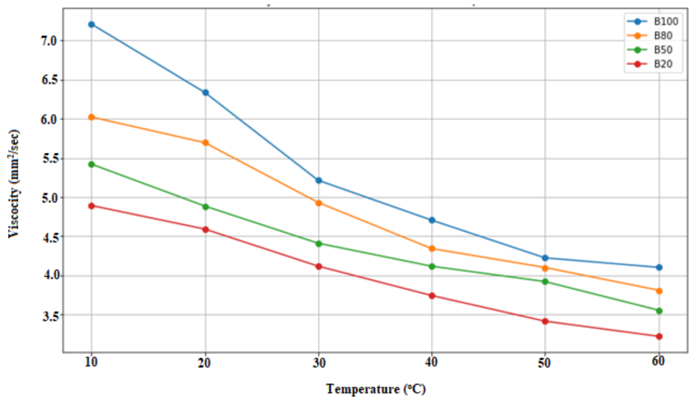


Figure 6: Viscosity -Temperature variations of Biodiesel Blends

Correlation analysis on Physicochemical Properties of Biodiesel Blends

The physicochemical properties correlation study of different biodiesel blends (B20, B50, B80, and B100) indicates strong trends that are significant in determining fuel behavior at different concentrations of biodiesel. The most significant correlation achieved is between flash point and percentage of biodiesel. As the percentage of biodiesel in the blend increases, the flash point also increases. This is a positive relationship in the sense that increasing concentration of biodiesel increases the safety of storage and handling of the fuel because increased flash point implies lower danger for flammability under environmental ambient conditions (Mattos *et al*., 2015).

Likewise, pour point and cloud point also increase with positive correlation with biodiesel concentration. As these cold flow properties rise with more and more biodiesel proportion added in the blend, the cold temperature performance would be more deteriorated. B100 thus possesses the maximum cloud and pour points value, which means greater fuel solidification tendency or gel tendency in low temperatures. These are especially relevant to biodiesel and cold climates, in which engine performance and fuel flow may suffer from degraded performance of low-temperature flow (Wcisło *et al.,* 2024)

In addition, fuel density rises stepwise with increasing proportion of biodiesel, with a distinct positive trend. This trend reflects the inherent physical properties of biodiesel such that it tends to be denser than petroleum diesel. Although high density is desirable in the energy content per volume, there are also effects on engine calibration and combustion efficiency that leads to fuel system tuning when operating on high biodiesel blends (Ferreiro *et al*., 2025).

Unlike the other properties, sulfur content is highly negatively correlated with biodiesel concentration. With an increase in the percentage of biodiesel in the blend, sulfur levels decrease significantly. This is due to the fact that the biodiesel composition is nearly sulfur-free relative to standard diesel. The fuel is hence cleaner burning with increased biodiesel concentration, reducing harmful sulfur oxide emissions and helping meet environmental sustainability objectives.

While they do so, they illuminate biodiesel blending's subtle trade-offs. While more biodiesel content has environmental advantages on the downstream front—i.e., lower sulfur content and higher flash points—so does it make cold flow property and handling of fuel more complex (Alviso *et al*., 2020). Such findings may benefit decision making associated with proper blending of blending biodiesel most apt for a given climatic region as well as regulatory concerns. The physicochemical property correlation analysis of the blends of biodiesel is given as a correlation heatmap, which visually displays the direction and magnitude of the relationship among the different properties Figure 7.

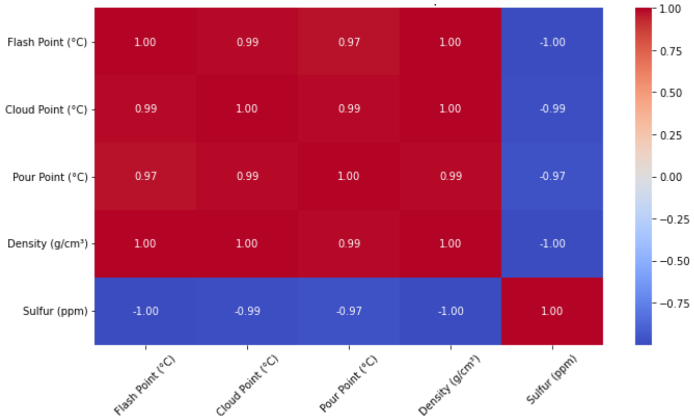


Figure 7. Correlation matrix of Physicochemical Properties of Biodiesel blend

Regression analysis on Physicochemical Properties of Biodiesel Blends

Regression analysis of the physicochemical properties of the blends of biodiesel identifies prominent trends showing the influence of temperature on the quality and performance of biodiesel. Of all the parameters of concern, viscosity showed strong negative correlation with temperature for the entire set of blends (B100, B80, B50, B20), again indicating fluidity of the biodiesel is enhanced by higher temperature. This reverse trend was consistent with basic fluid dynamics and is paramount to engine operation, particularly in cooler temperatures. Density also showed a consistent but gentle reduction with temperature, suggesting slight thermal expansion of the biodiesel, although within acceptable fuel tolerances. Flash point, a vital safety and volatility factor, followed an increasing or constant trend with temperature, reflecting biodiesel to be thermally stable over a broad range of conditions. Cloud point and pour point, both cold flow factors, raised steadily, especially in the higher proportion of biodiesel, reflecting a tendency towards solidification at lower temperatures and need to be treated with care in low temperatures. Sulfur content, already low owing to the environmentally friendly combustion properties of biodiesel, decreased with rising temperature, further bearing witness to the environmental benefit of biodiesel over fossil diesel (Kassem and Çamur, 2017; Tutunea, 2018). Generally, the regression plots bring out the temperature-dependent nature of biodiesel properties, observing that although most values fall within ASTM and EN fuel quality ranges, operation-related factors such as climate and engine design must guide biodiesel application strategies (Cunha *et al*., 2020). The large values of coefficients of determination (R^2) indicate that the regression models are highly reliable. These also emphasize temperature regulation and blend optimization in formulating biodiesel in order to assess regulatory as well as engine efficiency compliance. Hence, regression analysis is useful to gain good understanding of thermal characteristics of biodiesel blends with ease, thereby aiding predictive modeling in industry as well as automotive usages (Figure 8).

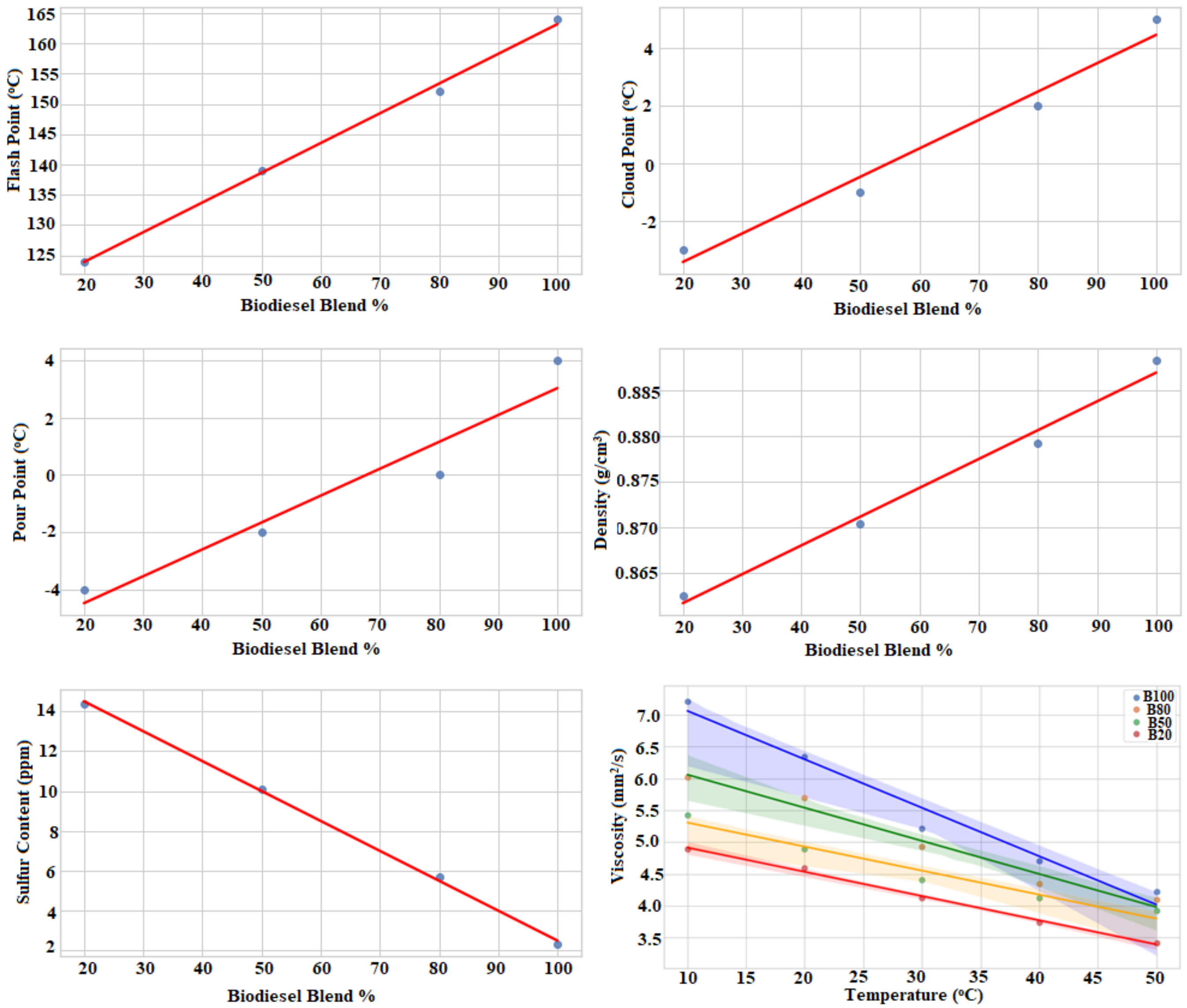


Figure 8: Regression Analysis of Physicochemical Properties of Biodiesel Blend

The outcome of correlation and regression analysis provided statistically significant results of inter-relationship and temperature dependency of significant physicochemical biodiesel blends' properties. The heatmap of correlation depicted very strong negative inter-relationships of temperature with density and viscosity, which further supports that increased temperatures decrease resistance to fluid flow and mass per unit volume. Regression analysis also corroborated these trends, especially for viscosity, which had high linear fit with blends, suggesting its sensitivity to temperature change (Wahyudi et al., 2023). Furthermore, flash point and pour point properties also demonstrated linear behavior with high biodiesel content, exhibiting blend-sensitive thermal properties. All these analyses combined affirm the significance of temperature control and blend optimization in biodiesel production and use. These optimized conditions in aggregate played a role in the increased biodiesel yield achieved here, wherein hitherto reduced catalyst amounts, reduced agitation rates, or excessive methanol surplus had restricted total conversion efficiency (Samuel *et al*., 2019).

Furthermore, the ASTM biodiesel limit was met by all of the biodiesel's physicochemical characteristics, including flash points for both blended and unblended fuel. This suggests that the fuel is safe to use, transport, and store. For both the blended and the unblended, some other properties such as density, sulphur content, pour point, cloud point, and viscosity were also covered in the ASTM standard (Fakai *et al*., 2024). This study is in good agreement with other researchers' work regarding used vegetable oil conversion to biodiesel.

Conclusion

The process of turning used cooking oil into biodiesel offers both financial and environmental advantages. The problem of high FFA content, which frequently hampers biodiesel production, was effectively resolved in this study using a combined two-step method of acid-catalyzed esterification and transesterification. The results of a comparative study of a few physicochemical characteristics showed that the biodiesel made from spent cooking oil met ASTM biodiesel standards. Furthermore, the correlation and regression analyses taken together indicate that temperature has significant effects on the physicochemical properties of biodiesel blends, especially viscosity, and that very strong linear correlations exist between many properties, testifying to their predictive and diagnostic value in determining biodiesel quality. Therefore, the adoption of biodiesel in higher concentrations not only improves engine reliability under low-temperature conditions but also promotes environmental and health safety by curbing harmful emissions.

Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

Ethics Declarations

Conflict of interest

The authors declare no competing interests.

Ethics approval and consent to participate

Not applicable.

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Consent for publication

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References

Abdalla, I. E. (2018). Experimental studies for the thermo-physiochemical properties of Biodiesel and its blends and the performance of such fuels in a Compression Ignition Engine. *Fuel*, *212*, 638-655. https://doi.org/10.1016/j.fuel.2017.10.064.

Alias, N. I., Jayakumar, J. K., and Zain, S. M. (2018). Characterization of waste cooking oil for biodiesel production. *Jurnal Kejuruteraan*, *1*(2), 79-83. http://dx.doi.org/10.17576/jkukm-2018-si1(2)-10.

Alviso, D., Saab, E., Clevenot, P., & Romano, S. D. (2020). Flash point, kinematic viscosity and refractive index: variations and correlations of biodiesel–diesel blends. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *42*(6), 347. https://doi.org/10.1007/s40430-020-02428-w.

Anekwe, O. J. (2019). *Evaluation of the biofuel properties of the methyl, ethyl esters and ester/diesel blends of three seeds oils* (Doctoral dissertation, Doctoral dissertation]. Nnamdi Azikiwe University, Awka, p 230).

Anwar, M., Rasul, M. G., Ashwath, N., and Rahman, M. M. (2018). Optimisation of second-generation biodiesel production from Australian native stone fruit oil using response surface method. *Energies*, *11*(10), 2566. https://doi.org/10.3390/en11102566.

Aransiola, E. F., Ehinmitola, E. O., Adebimpe, A. I., Shittu, T. D., and Solomon, B. O. (2019). Prospects of biodiesel feedstock as an effective ecofuel source and their challenges. *Advances in Eco-Fuels for a Sustainable Environment*, 53-87. https://doi.org/10.1016/B978-0-08-102728-8.00003-6.

Bhatia, S. K., Gurav, R., Choi, T. R., Kim, H. J., Yang, S. Y., Song, H. S., ... and Yang, Y. H. (2020). Conversion of waste cooking oil into biodiesel using heterogenous catalyst derived from cork biochar. *Bioresource technology*, *302*, 122872. doi.org/10.1016/j.biortech.2020.122872.

Chai, M., Tu, Q., Lu, M., and Yang, Y. J. (2014). Esterification pretreatment of free fatty acid in biodiesel production, from laboratory to industry. *Fuel processing technology*, *125*, 106-113. https://doi.org/10.1016/j.fuproc.2014.03.025.

Chen, C., Chitose, A., Kusadokoro, M., Nie, H., Xu, W., Yang, F., and Yang, S. (2021). Sustainability and challenges in biodiesel production from waste cooking oil: An advanced bibliometric analysis. *Energy Reports*, *7*, 4022-4034. https://doi.org/10.1016/j.egyr.2021.06.084

Cunha, C. L., Torres, A. R., & Luna, A. S. (2020). Multivariate regression models obtained from near-infrared spectroscopy data for prediction of the physical properties of biodiesel and its blends. *Fuel*, *261*, 116344.

Elgharbawy, A. S., Sadik, W., Sadek, O. M., and Kasaby, M. A. (2021). A review on biodiesel feedstocks and production technologies. *Journal of the Chilean Chemical Society*, *66*(1), 5098-5109.

Elgharbawy, A. S., Sadik, W. A., Sadek, O. M., and Kasaby, M. A. (2021). Maximizing biodiesel production from high free fatty acids feedstocks through glycerolysis treatment. *Biomass and Bioenergy*, *146*, 105997. https://doi.org/10.1016/j.biombioe.2021.105997

Fakai, U. R., Utono, A. Z., and Bui, M. N. (2024). Evaluating Biodiesel Properties from Waste

Cooking Oil for Sustainable Energy Applications. https://doi.org/10.55529/jeet.46.1.8.

Farouk, S. M., Tayeb, A. M., Abdel-Hamid, S. M., & Osman, R. M. (2024). Recent advances in transesterification for sustainable biodiesel production, challenges, and prospects: a comprehensive review. *Environmental Science and Pollution Research*, *31*(9), 12722-12747.

Ferreiro, S. P., Alviso, D., & Romano, S. D. (2025). Variations and correlations of the flash point, refractive index and density of soybean biodiesel, diesel and their binary and ternary blends with n-butanol. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *47*(11), 570. https://doi.org/10.1007/s40430-025-05861-x.

Foo, W. H., Koay, S. S. N., Chia, S. R., Chia, W. Y., Tang, D. Y. Y., Nomanbhay, S., and Chew, K. W. (2022). Recent advances in the conversion of waste cooking oil into value-added products: A review. *Fuel*, *324*, 124539. https://doi.org/10.1016/j.fuel.2022.124539

Goh, B. H. H., Chong, C. T., Ge, Y., Ong, H. C., Ng, J. H., Tian, B., ... and Józsa, V. (2020). Progress in utilisation of waste cooking oil for sustainable biodiesel and biojet fuel production. *Energy Conversion and Management*, *223*, 113296. https://doi.org/10.1016/j.enconman.2020.113296.

Hosseinzadeh-Bandbafha, H., Nizami, A. S., Kalogirou, S. A., Gupta, V. K., Park, Y. K., Fallahi, A., ... and Tabatabaei, M. (2022). Environmental life cycle assessment of biodiesel production from waste cooking oil: A systematic review. *Renewable and Sustainable Energy Reviews*, *161*, 112411. https://doi.org/10.1016/j.rser.2022.112411.

Jha, A., and Das, S. (2017). Waste cooking oil–revolution in biodiesel production. *Fermentation Technology*, *6*(2),1-2. DOI: 10.4172/2167-7972.1000143

Kara, K., Ouanji, F., Lotfi, E. M., El Mahi, M., Kacimi, M., and Ziyad, M. (2018). Biodiesel production from waste fish oil with high free fatty acid content from Moroccan fish-processing industries. *Egyptian Journal of Petroleum*, *27*(2), 249-255. https://doi.org/10.1016/j.ejpe.2017.07.010.

Kassem, Y., and Çamur, H. (2017). A laboratory study of the effects of wide range temperature on the properties of biodiesel produced from various waste vegetable oils. *Waste and biomass valorization*, *8*(6), 1995-2007. https://doi.org/10.1007/s12649-016-9753-4.

Khairati, M. (2022). Glycerol Refining. *Journal of Mathematical and Science Networking, 4*4(2), 35-40.

Khodadadi, M. R., Malpartida, I., Tsang, C. W., Lin, C. S. K., and Len, C. (2020). Recent advances on the catalytic conversion of waste cooking oil. *Molecular Catalysis*, *494*, 111128. https://doi.org/10.1016/j.mcat.2020.111128.

López, E. R., and Sotelo, J. L. G. (2019). Biodiesel from used frying oils: Current status and future trends. Fuel, 99(2), 1-12.

Lahiri, A., Daniel, S., Kanthapazham, R., Vanaraj, R., Thambidurai, A., and Peter, L. S. (2023). A critical review on food waste management for the production of materials and biofuel. *Journal of Hazardous Materials Advances*, *10*, 100266. https://doi.org/10.1016/j.hazadv.2023.100266

Mattos, R. A. D., Bastos, F. A., & Tubino, M. (2015). Correlation between the composition and flash point of diesel-biodiesel blends. *Journal of the Brazilian Chemical Society*, *26*, 393-395.

Miyuranga, K. V., Arachchige, U. S., Marso, T. M. M., and Samarakoon, G. (2023). Biodiesel production through the transesterification of waste cooking oil over typical heterogeneous base or acid catalysts. *Catalysts*, *13*(3), 546. https://doi.org/10.3390/catal13030546.

Ong, J. S. J., Malik, M. S. A., Othman, N., and Wahid, M. A. (2024). Soybean And Waste Cooking Oil Based Feedstocks as A Sustainable Biofuel. *Jurnal Mekanikal*, 39-50. https://doi.org/10.11113/jm.v47.474.

Pugazhendhi, A., Alagumalai, A., Mathimani, T., and Atabani, A. E. (2020). Optimization, kinetic and thermodynamic studies on sustainable biodiesel production from waste cooking oil: An Indian perspective. *Fuel*, *273*, 117725. https://doi.org/10.1016/j.fuel.2020.117725.

Sadaf, S., Iqbal, J., Ullah, I., Bhatti, H. N., Nouren, S., Nisar, J., and Iqbal, M. (2018). Biodiesel production from waste cooking oil: an efficient technique to convert waste into biodiesel. *Sustainable cities and society*, *41*, 220-226. https://doi.org/10.1016/j.scs.2018.05.037.

Samuel, O. D., Oreko, B. U., Oyejide, J. O., Idi, S., & Fayomi, O. S. (2019). Experimental and empirical study of diesel and biodiesel produced from blend of fresh vegetable and waste vegetable oil on density, viscosity, sulphur content and acid value. In *Journal of Physics: Conference Series* (Vol. 1378, No. 4, p. 042024). IOP Publishing.

Sianipar, R. N. R., Ariyani, D., and Nata, I. F. (2017). Conversion of palm oil sludge to biodiesel using alum and KOH as catalysts. *Sustainable Environment Research*, *27*(6), 291-295. https://doi.org/10.1016/j.serj.2017.07.002.

Singh, D., Sharma, D., Soni, S. L., Inda, C. S., Sharma, S., Sharma, P. K., and Jhalani, A. (2021). A comprehensive review of biodiesel production from waste cooking oil and its use as fuel in compression ignition engines: 3rd generation cleaner feedstock.

Journal of Cleaner Production, *307*, 127299. https://doi.org/10.1016/j.jclepro.2021.127299.

Suzihaque, M. U. H., Syazwina, N., Alwi, H., Ibrahim, U. K., Abdullah, S., and Haron, N. (2022). A sustainability study of the processing of kitchen waste as a potential source of biofuel: Biodiesel production from waste cooking oil (WCO). *Materials Today: Proceedings*, *63*, S484-S489. https://doi.org/10.1016/j.matpr.2022.04.526.

Tutunea, D. R. A. G. O. S. (2018). Study of the variation of kinematic viscosity and density of various biodiesel blends with temperature. *Rev. Chem*, *69*, 1645-1648. https://doi.org/10.37358/rc.18.7.6387.

Wahyudi, W., Nadjib, M., & Apriyanto, A. (2023). Correlation between Physical Properties and Specific Fuel Consumption in Jatropha-Used Cooking Oil Biodiesel Mixtures. *Semesta Teknika*, *26*(2), 148-158. https://doi.org/10.18196/st.v26i2.20163.

Wcisło, G., Leśniak, A., Kurczyński, D., & Pracuch, B. (2024). Experimental Investigation of Physicochemical Properties of the Produced Biodiesel from Waste Frying Oil and Its Blend with Diesel Fuel. *Energies*, *17*(16), 4175. https://doi.org/10.3390/en17164175.

Zhao, Y., Wang, C., Zhang, L., Chang, Y., and Hao, Y. (2021). Converting waste cooking oil to biodiesel in China: environmental impacts and economic feasibility. *Renewable and Sustainable Energy Reviews*, *140*, 110661. https://doi.org/10.1016/j.rser.2020.110661.