UDC 502
DOI: 10.15587/1729-4061.2024.318593

POWER AND EMISSION ESTIMATION OF PLASTIC WASTE PYROLYSIS-DERIVED FUEL BLENDS IN INTERNAL COMBUSTION ENGINES

Sugeng Hadi Susilo
Corresponding Author
Assosiate Professor*
E-mail: sugeng.hadi@polinema.ac.id
Imam Mashudi
Assosiate Professor*
Santoso Santoso
Assosiate Professor*
Agus Hardjito
Assosiate Professor*
Dwi Pebrianti
Assosiate Professor
Department of Mechanical & Aerospace Engineering
International Islamic University Malaysia
Jl. Gombak, Selangor, Malaysia, 53100
*Department of Mechanical Engineering
State Polytechnic of Malang
Jl. Soekarno Hatta, 9, Malang, Indonesia, 65141

Energy, especially from fossil fuels, is essential for everyday life, while plastic waste is an increasing environmental threat. Plastic waste disposal methods such as landfilling and burning cause pollution. Therefore, a process is needed that converts plastic waste into fuel. The object of the study is the engine performance. The problem to be solved is the relationship between the use of a mixture of fossil fuels and pyrolysis fuel on the performance of internal combustion engines.

This research uses a systematic data collection process to obtain accurate and reliable results. The necessary equipment, including a dynamometer and gas analyzer, was prepared, and the engine was warmed up to a stable operating temperature of 80 °C. The motorbike is then positioned on the dynamometer with the rear tires aligned and the front tires secured to prevent movement. Data collection was carried out at engine speeds of 2000, 3000, 4000, 5000, and 6000 rpm, using three fuel mixtures: 10 % plastic pyrolysis fuel with 90 % RON 90, 20 % plastic pyrolysis fuel with 80 % 90 RON, and 30 % plastic pyrolysis fuel with 70 % RON 90. Each test was repeated three times, with the output power measured using a dynamometer and exhaust emissions (CO and HC levels) recorded using a gas analyzer. The test results show that the optimal fuel mixture to produce maximum engine power is a PE-RON 90 mixture with a ratio of 20:80, providing the best performance at medium to high engine speeds (3000–6000 rpm) with low CO emissions. The highest power output (1.05) occurs at 4000 rpm, while the PE-RON 90 30:70 alloy produces the best power performance at 6000 rpm (0.78 % CO). Additionally, the pyrolysis fuel blend significantly reduces CO and HC emissions, with the PE-RON 90 30:70 blend showing the lowest CO (0.78 % at 6000 rpm) and consistently reducing HC emissions across the rpm range

Keywords: plastic waste, pyrolysis, fuel mixture, power, exhaust gas, types of plastic

Received 23.09.2024
Received in revised form 22.11.2024
Accepted 09.12.2024
Published 27.12.2024

***How to Cite:** Susilo, S. H., Mashudi, I., Santoso, S., Hardjito, A., Prebianti, D. (2024). Power and emission estimation of plastic waste pyrolysis-derived fuel blends in internal combustion engines. Eastern-European Journal of Enterprise Technologies, 6 (9 (132)), 19–25. https://doi.org/10.15587/1729-4061.2024.318593*

1. Introduction

Plastic waste is a serious environmental problem worldwide, with increasing volumes and detrimental impacts on ecosystems. Conventional plastic management such as landfilling and burning is ineffective and causes air and soil pollution. As global plastic production increases, which now exceeds 450 million tons per year, millions of tons of plastic end up in the ocean, destroying wildlife and their habitats. Almost half of plastic production consists of polyolefins such as HDPE, LDPE and PP which have the potential to pollute the environment if not managed properly.

Plastic is a type of material that is often found in everyday life, and can be processed into alternative fuel through pyrolysis. The pyrolysis process can convert plastic waste into three fractions called liquid (which may have fuel properties) [1–3], solid (charcoal with a carbon structure and potentially used as an adsorbent or catalytic support) [4–6], and gas (with a high concentration of heat value equivalent to natural gas ~44 Mj/kg) at temperatures above 300 °C through thermal decomposition of the polymer structure [7]. The pyrolysis results are strongly influenced by several parameters such as raw material variability, temperature, residence time, thermal decomposition mechanisms and higher heating rates [8]. The technique commonly used in managing plastic waste is the pyrolysis technique. The temperature is maintained at around 540–830 °C [9]. Extraction of pure polypropylene from plastic waste containing various types of polymers can be done using the pyrolysis method because it does not require pure plastic [10]. Although some studies have revealed that fuels from plastic waste pyrolysis can reduce certain emissions, details about their impact on the broader emissions spectrum and long-term engine performance are lacking. Additionally, variability in the quality of the fuel produced from the pyrolysis process depends on the type of plastic being processed, resulting in the need for further standardization and testing.

New research is urgently needed to address this knowledge gap, with a focus on optimizing pyrolysis processes and

Copyright © 2024, Authors. This is an open access article under the Creative Commons CC BY license

fuel formulation to improve consistency and performance. Further studies should also explore the adaptation of existing engine technologies and the development of new technologies that can more efficiently use pyrolysis fuel.

The chemical recycling method is to convert polymers into small molecular compounds through chemical processes such as pyrolysis or gasification and then rearrange them to form new materials [11]. Fuel from pyrolysis of plastic waste is considered to have the potential to reduce dependence on fossil fuels and make sustainable use of plastic waste [12]. In use, the fuel mixture resulting from pyrolysis of plastic waste can affect engine performance, especially the power produced by internal combustion engines. Based on test results on certain engines, the fuel mixture resulting from pyrolysis of plastic waste with a certain percentage can increase or decrease the engine's combustion power, depending on the characteristics of the pyrolysis fuel, such as calorific value and viscosity [13].

Therefore, research regarding the development of power analysis and exhaust emissions in a mixture of RON 90 fuel with fuel resulting from the pyrolysis of plastic waste in internal combustion engines is relevant.

2. Literature review and problem statement

Along with increasing attention to environmental problems and the need for alternative energy, research on plastic pyrolysis to produce alternative fuels has been carried out by many researchers. The pyrolysis process converts plastic waste into liquid fuel that can potentially be used in internal combustion engines. Plastic waste undergoes a pyrolysis process using a catalyst [14]. The use of pyrolysis to convert plastic into liquid oil. So, the volume of plastic waste is reduced and the liquid oil produced has a higher calorific value than fossil fuels. However, it has not been utilized optimally in replacing fossil fuels.

The catalyst can be a mixture of zeolite, clay, alumina and silicate in various ratios [15, 16]. The focus is on the influence of catalysts and their supports, catalyst synthesis methods on hydrogen production yields, and the impact of several important reaction parameters such as pyrolysis temperature, catalytic temperature, catalyst to plastic, and steam to plastic. So, it is necessary to test the quality of the pyrolysis fuel.

There are three types of pyrolytic reactions differentiated based on processing time and biomass temperature: slow pyrolysis, fast pyrolysis and flash pyrolysis [17]. Developed a simulation of the co-pyrolysis of xylan, a type of hemicellulose, and high-density polyethylene (PE). Using a hybrid kinetic equilibrium approach and correctly predicting the pyrolysis yield. Simulations were run at different temperatures (500–700 °C) and PE mixing proportions (10–90 wt %) and the results were compared with experimental data. So there needs to be further research regarding the combination of fuels for three types of pyrolytic reactions.

Plastic waste that has a high hydrogen content could be another option. Currently, the method that dominates the use of plastic waste raw materials is mechanical recycling [18]. However, it is difficult to sort large amounts of plastic waste with different qualities and compositions, and the resulting products are of lower quality than products made from genuine materials [19]. Pyrolysis liquid fuel is produced via thermal pyrolysis using a simple pilot scale small batch pyrolysis reactor in the absence of air and without any catalyst [20]. Converts cross-linked polyethylene (PE) foam into a porous carbon material. This process is made possible through sulfonation-based cross-linking, which enables efficient conversion of PE to carbon precursors, while maintaining the high porosity features of the foam precursors.

Pyrolysis recycling technology was chosen due to its superior effectiveness in addressing plastic pollution and increasing the ecological footprint of the process while mitigating emissions despite its limitations [21]. Combining methanol synthesis and pyrolysis plants maximizes circularity with an increase in fuel production of up to 44 %. In addition, careful consideration has been given to the processing of crude pyrolysis oil, with a focus on four potential pathways for its utilization, all aimed at maximizing the value and sustainability of pyrolysis oil in the broader context of waste to resource conversion [22].

However, there has not been a single study conducted that discusses the use of a mixture of fossil fuels and pyrolysis fuel. Therefore, it is necessary to conduct research on the relationship between the use of a mixture of fossil fuels and pyrolysis fuel on the performance of internal combustion engines.

3. The aim and objectives of the study

This research aims to obtain engine performance using a pyrolysis fuel mixture with RON 90 with pyrolysis fuel variations of 10 %, 20 % and 30 % in the internal combustion engine.

To achieve this aim, the following objectives are achieved:

– conduct experiments mixing pyrolysis fuel with RON 90 with various percentages to produce maximum engine power;

– conduct experiments mixing pyrolysis fuel with RON 90 with varying percentages to produce minimal CO and HC exhaust emissions.

4. Materials and methods

The object of the study is the engine performance. The main hypothesis of this research is that mixing fuel oil derived from plastic waste via pyrolysis with RON 90 gasoline can provide optimal engine performance while reducing harmful exhaust emissions such as CO and HC.

This research assumes that fuel produced from pyrolysis of plastic waste can be mixed with RON 90 gasoline for use in internal combustion engines, and that variations in the fuel mixture ratio will affect engine performance and exhaust emissions. In addition, it is assumed that this fuel mixture can produce optimal power at certain engine speeds while significantly reducing carbon monoxide (CO) and hydrocarbon (HC) emissions compared to conventional fuel. To support this assumption, the research also assumes that the data collection method using a dynamometer and gas analyzer will provide accurate and reliable results, with standardized test conditions, such as a stable engine operating temperature (80 °C) and test repeatability to reduce data variability.

In this study there were several variations of plastic fuel mixtures-RON 90 (10:90), (20:80), (30:70). The RON 90 fuel used is Pertalite fuel. The fuel is mixed in the motorbike fuel tank according to the specifications in Table 1. Testing the power produced uses a dynotest tool, while testing exhaust emissions uses a gas analyzer. Tests were carried out at 2000, 3000, 4000, 5000 and 6000 rpm.

Table 1

Motorcycle specifications

Engine type	4-stroke SOHC engine
Diameter×stroke	57.3 mm 57.9 mm
Volume cylinder	150 cm^3
Fuel system	PGM_FI
Fuel	Gasoline
Maximum power	9.3 kW/8500 rpm
Compression comparison	10.6:1

The PGM-FI (Programmed Fuel Injection) fuel system is an advanced technology that regulates fuel spray very precisely based on engine operating conditions, which allows more efficient use of fuel and reduces emissions. The maximum power produced by this engine is 9.3 kW at 8500 rpm. It is representing a relatively high-power output, which is sufficient for motorcycle use in most riding conditions, from light to medium.

The experimental setup of power and exhaust emissions testing, as seen in the Fig. 1 was designed to evaluate the performance of a motorcycle engine fueled by a mixture of plastic waste pyrolysis oil and RON 90. The motorcycle was placed on a dynamometer to measure engine power. at various engine speeds (RPM), while exhaust emissions are analyzed using a gas analyzer which is connected directly to the exhaust system. Data collected from both devices is displayed on the monitor for further observation and analysis. This setup ensures accurate and representative engine testing under realistic operating conditions, Fig. 1.

Fig. 1. Experimental setup

In Fig. 1, experimental setup depicts the experimental setup used to test the performance and exhaust emissions of a motorcycle engine fueled by a mixture of plastic pyrolysis oil and RON 90. In this setup, the motorcycle is positioned on a dynamometer, a tool used to measure the engine. power and performance at various engine speeds (rpm). Meanwhile, a gas analyzer is connected to the exhaust system to analyze emission content, such as carbon monoxide (CO), hydrocarbons (HC) and other gases. The data collected from the dynamometer and gas analyzer is displayed on the monitor for further analysis. This setup is designed to simulate real-world motorcycle operating conditions and provide accurate data regarding the performance and exhaust emissions of the tested fuel mixture.

The data collection process in this research was carried out systematically to ensure accurate and reliable results. The initial step taken is to prepare all the necessary equipment, including a dynamometer, gas analyzer and other supporting equipment. Once the equipment is ready, the engine is heated to a stable working temperature of 80 °C to ensure consistent operating conditions. The motorcycle is then carefully positioned onto the dynamometer, with the rear tire aligned exactly in the center roll position. The front wheel was securely locked to prevent movement during the test, while the motorcycle was further stabilized by strapping the front tire and securing the sides to maintain an upright position throughout the process. Data collection was carried out three times for each engine speed setting of 2000, 3000, 4000, 5000 and 6000 rpm. Tests were carried out using three variations of fuel mixture, namely a combination of 10 % plastic pyrolysis fuel and 90 % RON 90, 20 % plastic pyrolysis fuel and 80 % RON 90 and 30 % plastic pyrolysis fuel and 70 % RON 90. In each test, the power output is measured and recorded using a dynamometer. At the same time, exhaust emissions, especially carbon monoxide (CO) and hydrocarbon (HC) levels, are measured and recorded using a gas analyzer. This multi-step procedure ensures comprehensive data collection on engine performance and emissions characteristics for each fuel blend, thereby providing a solid foundation for further analysis and interpretation.

5. Results of research power and emission of plastic waste pyrolysis-derived fuel blends in internal combustion engines

5. 1. Power test

Fig. 2 shows a comparison of power output at various engine speeds for motorcycles with different fuel mixture configurations. The blends are represented by the labels PP-RON 90 and PE-RON 90 in three different ratios: 10:90, 20:80, and 30:70. This analysis aims to evaluate the effect of changes in fuel component proportions on motorcycle engine performance at various speeds, from 2000 to 6000 rpm. This comparison is critical to identifying the optimal fuel formulation that provides maximum power.

Fig. 2 indicates that at 2000 rpm, the 10:90 PP-RON 90 mixture provides the most power (0.19 Hp) and the 30:70 PE-RON 90 mixture the least (0.04 Hp). The 10:90 PP-RON 90 produces 0.54 Hp at 3000 rpm, while the 30:70 PE-RON 90 produces 0.26 Hp. The PE-RON 90 10:90 blend produced 1.33 Hp at 4000 rpm, beating other PP blends, whereas the 20:80 blend produced 0.65 Hp. Power increases dramatically above 5000 rpm, with the 10:90 PP-RON 90 blend producing the most (3.68 Hp), followed by the 10:90 PE-RON 90 blend for 3.45 Hp and the 30:70 PE-RON 90 blend for 2.24 Hp. The 10:90 PP-RON 90 blend produces the most power (9.49 Hp) at 6000 rpm, while the 30:70 blend for PP and PE fuel produces the least (8.97 Hp). Mixtures with 10 % plastic pyrolysis oil produced the most power across engine speeds, indicating better combustion efficiency than mixtures with 20 % or 30 % plastic oil, which are affected by viscosity and atomization. PP-RON 90 performs better at high engine speeds (5000–6000 rpm), while PE-RON 90 plastic fuel blend performs somewhat better at low to medium speeds (2000–4000 rpm). This graph shows that 10:90 is the most efficient in all conditions.

See Fig. 3 for the ideal PP plastic waste-PE ratio for motor power production: 20–80 % Ron 90.

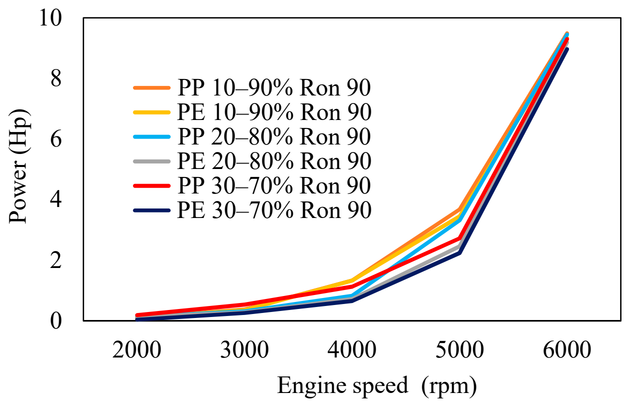

Fig. 2. The relationship between engine speed and engine power in pyrolysis fuel mixtures. PP and PE plastic types with RON 90

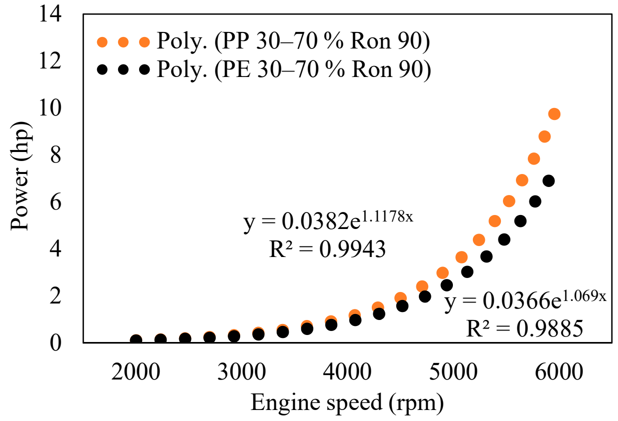

Fig. 3. The optimal ratio of PP plastic waste to PE in producing motor power

Fig. 3 shows that engine power increases exponentially with engine speed, for which the initial constant value of 0.03820 indicates almost no power at low engine speeds and the exponent 1.11781 indicates a faster power increase at higher engine speeds. At R^2=0.9943, this equation fits the data well, explaining 99.43 % of engine speed-power variability. The graph illustrates that both PP 20–80 % Ron 90 and PE 20–80 % Ron 90 plastic waste pyrolysis fuel blends perform similarly at low to medium engine speeds. High engine speeds (over 4000 rpm) boost engine power exponentially, with the PP mixture producing somewhat more power than the PE mixture.

While for the pyrolysis mixture made from PE plastic – RON 90, it shows an exponential relationship between variables x and y with the equation $y=0.0366e^{1.069x}$ and the coefficient of determination value $R^2=0.9885$ shows that 98.85 % of the variance in variable y can be explained by changes in the fuel mixture variable resulting from pyrolysis with RON 90.

5. 2. Gas emission test

Fig. 3 shows that carbon monoxide (CO) emission levels in percentage (%) from motorbikes at various engine speeds measured in rotations per minute (rpm), ranging from 2000 to 6000 rpm. Data are presented for various fuel blends labeled PP-Ron 90 and PE-Ron 90 in three different ratios: 10:90, 20:80, and 30:70. This analysis is to assess the effect of fuel mixture proportions on CO emission levels at various levels of engine operational speed. Understanding how fuel composition affects CO emissions is crucial in efforts to optimize motorbike performance.

Fig. 4 shows that at rpm 2000, performance was relatively similar across all blends, with the PE-RON 90 10:90 blend achieving the highest value (0.96) and the PE-RON 90 30:70 blend recording the lowest value (0.86). At 3000 rpm, the 20:80 PE-RON 90 blend showed the best results (0.92), while the 30:70 PP-RON 90 and PE-RON 90 blends had similar performance at 0.88, indicating increased performance with the content of higher plastic oil in PP Blend. At 4000 rpm, greater variations were observed, with the PE-RON 90 20:80 mixture producing the highest value (1.05) and the PP-RON 90 20:80 mixture showing the lowest value (0.77). The PE mix clearly outperforms the PP mix at this speed, especially at a ratio of 20:80. At rpm 5000, the PE-RON 90 20:80 mixture again leads with a value of 0.88, while the PE-RON 90 30:70 and PP-RON 90 mixtures follow with values of 0.84 and 0.80 respectively. The 20:80 PP-RON 90 blend remained the least effective at 0.69. At 6000 rpm, the highest value was recorded for the 30:70 PE-RON 90 blend (0.78), which indicated better performance from a higher proportion of plastic oil at high engine speeds, while the 10:90 PP-RON 90 blend showed the lowest value (0.48). Overall, PE blends consistently outperform PP blends, particularly at medium to high engine speeds, with the PE-RON 90 20:80 blend emerging as the most effective at most speeds, balancing performance and emissions. At maximum speed, a higher plastic oil content (30:70) provides better performance, especially with PE blends, underlining the importance of optimizing the fuel mixture ratio and pyrolysis oil type for efficient engine operation.

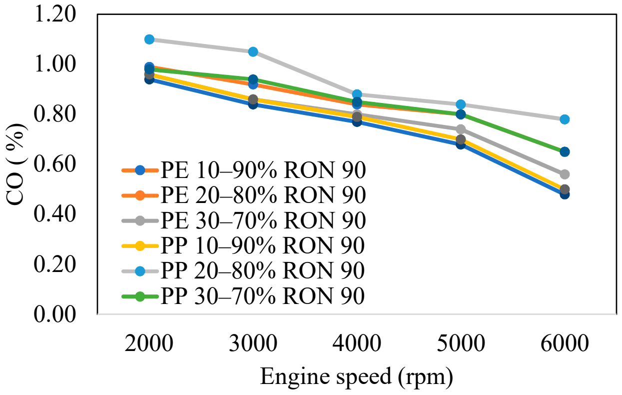

Fig. 4. Relationship between engine speed and CO gas emissions in pyrolysis fuel mixtures PP and PE plastic types with RON 90

Whereas from the regression equation obtained the optimal ratio value in the mixture of 30 %:70 %, both plastic waste from PP or PE (Fig. 5).

The optimal mixture ratio for plastic pyrolysis fuels made from PP and PE combined with RON 90 is 30 %:70 %. For the PP-RON 90 plastic fuel mixture, the equation $Y=-0.0157x^2-0.0137x+0.976$ was derived. This equation indicates a decreasing effect on CO gas emissions as fuel mixture percentage increases quadratically. It means that higher fuel mixture ratios significantly impact CO emissions. The $-0.0137x$ term represents a weaker negative linear effect, while the constant 0.976 reflects the baseline CO emissions for pure fuel without any pyrolysis plastic waste. The equation effectively predicts changes in emissions as the fuel composition varies. An R^2 value of 0.9838 indicates the model is highly accurate, explaining 98.38 % of the variability in observed data.

Similarly, for the PE-based pyrolysis material, the equation $Y=-0.0043x^2-0.0483x+1.038$ was obtained, with an R^2 value of 0.9839. This quadratic relationship suggests turning points or complex factors such as carbon deposits or high-temperature chemical reactions influencing emissions at higher mixture ratios. The coefficients indicate that while the quadratic effect dominates, the linear term contributes to changes in CO emissions. The constant 1.038 represents CO emissions from pure RON 90 fuel. With 98.39 % of data variability explained by the model, it provides excellent predictive accuracy for how PE fuel mixtures affect emissions. Both models highlight that emissions depend on the type and percentage of pyrolysis plastic waste mixed with RON 90 fuel, with quadratic effects playing a crucial role.

Fig. 6 shows the concentration of hydrocarbons (HC) in parts per million (ppm) emitted by motorbikes at various engine speeds, from 2000 to 6000 rpm. HC concentrations were measured for various fuel blends characterized as PP-Ron 90 and PE-Ron 90 in three different ratios: 10:90, 20:80, and 30:70. This analysis is important for identifying how various fuel mixture ratios affect hydrocarbon emissions, which are critical indicators of engine combustion efficiency and their impact on air pollution.

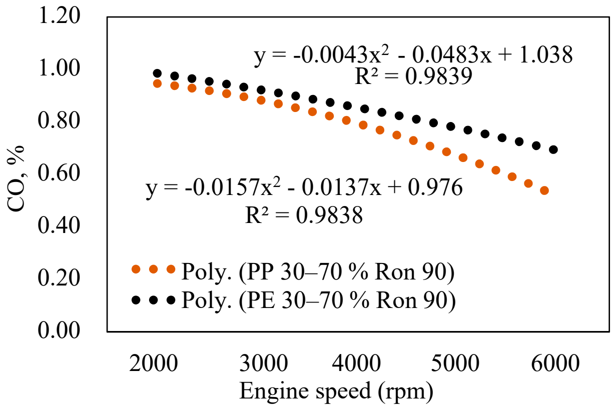

Fig. 5. Plastic fuel mixture ratio (PP and PE) — RON 90 optimal (30 %:70 %)

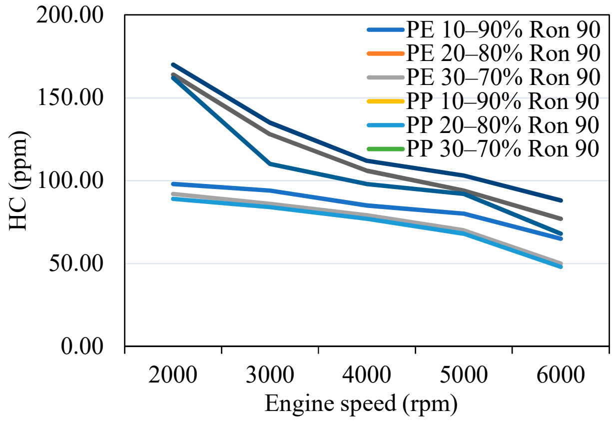

Fig. 6. Relationship between engine speed and HC gas emissions

Fig. 6 shows that performance trends across different rpm levels for various fuel mixtures. At 2000 rpm, performance values are similar, with the highest recorded in the PE-RON 90 10:90 mixture (157) and the lowest in the PP and PE 30:70 mixtures (150). This indicates that at low engine speeds, lower plastic oil content mixtures perform slightly better, with PE-based blends outperforming PP-based ones. At 3000 rpm, variations become more apparent, with the PE-RON 90 30:70 blend achieving the highest performance (143) and the 10:90 PP-RON 90 blend the lowest (110). This suggests that higher plastic oil content enhances efficiency at medium speeds. At 4000 rpm, differences widen further, with the PE-RON 90 30:70 blend leading (132) and the 10:90 PP-RON 90 blend lagging (98), reinforcing the superior performance of PE-based mixtures at higher oil contents. At 5000 rpm, the PE-RON 90 30:70 mixture remains the best performer (117), followed by the PP 30:70 mixture (103), while the PP 10:90 mixture records the lowest value (92). Similarly, at 6000 rpm, the PE-RON 90 30:70 blend achieves the highest performance (89), and the PP 10:90 mixture the lowest (68). Overall, PE-based mixtures, particularly in the 30:70 ratio, excel at higher speeds, while lower oil content (10:90) favors low-speed performance. This analysis highlights the need to optimize fuel ratios, with PE 30:70 blends being the most efficient for high-speed performance.

6. Discussion of results research power and emission of plastic waste pyrolysis-derived fuel blends in internal combustion engines

Fig. 2 shows that plastic fuel mixtures with RON 90 impact engine power, with higher plastic content leading to reduced power. This is due to the lower viscosity of polypropylene (PP) compared to polyethylene (PE). PP has a viscosity of 0.66–0.78 cP, while PE is at 1.95 cP. Higher viscosity makes fuel thicker and harder to flow, which negatively affects atomization, resulting in incomplete combustion and reduced power. Furthermore, the higher flash point of plastic fuel, compared to RON 90, causes delayed combustion and low combustion pressure, further reducing engine power.

Fig. 3 shows that the exponential increase in engine power with engine speed can be explained by fuel combustion efficiency. At low speeds, combustion is less efficient, resulting in lower power. However, at higher speeds, combustion becomes faster and more efficient, increasing power exponentially. For PE pyrolysis mixture RON 90, with the equation y=0.0366e^1.069x and R^2=0.9885, the power increases more efficiently. The difference in power at high speeds, where the PP blend produces slightly more power than PE, can be explained by the higher carbon content of PP.

At low speeds (2000 rpm), the 10 % PP mixture produces the highest power due to better atomization and volatility, enhancing combustion efficiency. The 30 % PE mixture, with higher viscosity, shows the lowest power output. At medium engine speeds (3000 rpm), the 10 % PP mixture still produces the highest power, benefiting from PP's higher fuel volatility and better combustion at elevated speeds. At high engine speeds (4000–6000 rpm), the 10 % PP mixture continues to outperform others, with the highest power at 6000 rpm reaching 9.49 Hp. Conversely, mixtures with higher PE content show reduced performance due to increased viscosity hindering atomization and combustion efficiency. This is different from the research results regarding the potential of plastic pyrolysis oil-diesel blends in diesel engines, where the maximum power is 1.92 kW at 2500 rpm in a mixture of 5 % pyrolysis-diesel fuel. Which uses high density polyethylene (HDPE) plastic material [23]can be used to prepare fuel as an alternative fuel. The batch pyrolysis reactor was fabricated to produce plastic pyrolysis oil (PPO. This makes it possible to use fuel resulting from pyrolysis from plastic waste, as an alternative fuel for motorized vehicles.

Fig. 4 shows that higher plastic fuel content leads to increased CO emissions. This is because plastic fuels burn more slowly due to their high flame temperature, resulting in incomplete combustion and higher CO concentrations. At low engine speeds, incomplete combustion occurs due to insufficient air supply, causing high CO emissions. At 2000 rpm, the PE-RON 90 10:90 mixture performs slightly better, suggesting PE's smoother combustion properties at lower speeds. At 3000 rpm, the PE-RON 90 20:80 mixture shows the best performance, benefiting from lower viscosity and better combustion efficiency. At higher rpms, PE mixtures again outperform PP mixtures, with PE's stable structure improving fuel atomization and combustion efficiency. At 6000 rpm, the PE-RON 90 30:70 mixture provides the best performance, showing that higher PE content optimizes combustion at high speeds by improving fuel viscosity and atomization.

Fig. 5 shows that A mixture of PP and PE plastic pyrolysis fuel with RON 90 significantly influences CO emissions, with an optimal ratio of 30 %:70 %. For PP-RON 90, where increasing the proportion of plastic fuel increases CO emissions, especially at high ratios. R^2=0.9838 indicates this model explains 98.38 % of the data variation.

In contrast, the PE-RON 90 blend has the same R^2=0.9839. The negative quadratic and linear effects are smaller than PP, but the initial CO emissions are higher (1.038). The quadratic relationship in both mixtures reflects complex factors, such as the formation of carbon deposits or chemical reactions, which are significant at high ratios. Both models are very accurate in predicting CO emissions.

Fig. 6 reveals that higher plastic fuel content also increases HC emissions. This is due to the slow combustion and incomplete burning of plastic fuels, leading to higher HC concentrations. At low rpm, poor mixing of air and fuel increases HC emissions, as some hydrocarbons fail to react fully with air due to insufficient air supply.

The study's limitations include using a 150 cm^3 engine with RON 90 fuel (Pertalite). Future research can focus on improving combustion efficiency and reducing harmful emissions by combining pyrolysis plastic waste-derived fuels with conventional fuels. This approach could enhance internal combustion engine performance, provide more sustainable energy alternatives, and help reduce environmental impact. The findings could have significant implications for engine technology, environmental policies, and automotive waste management.

The weakness of this research lies in the limited scope of testing carried out. This research does not include a variety of motorbikes with different engine volumes and compression levels, so it is not able to evaluate fuel performance on various types of engines. In addition, this research has not tested different fuel mixtures, so their effects on efficiency and emissions cannot be analyzed thoroughly. Furthermore, in-depth laboratory tests on the physical and chemical characteristics of pyrolysis fuel have not been carried out, which means that technical data to support the development of alternative fuels that are more environmentally friendly and applicable are still limited.

7 Conclusions

1. The research results show that the optimal fuel mixture ratio to produce maximum engine power is a PE-RON 90 mixture with a ratio of 20:80. At medium to high engine speeds (3000–6000 rpm), this mixture consistently provides the best performance, with relatively low CO emission values and high power. At 4000 rpm, the PE-RON 90 20:80 blend delivers the highest power rating of 1.05, while at 6000 rpm, the PE-RON 90 30:70 blend provides the best power performance with a 0.78 for CO emissions. Overall, the PE-RON 90 20:80 blend emerged as the most efficient fuel ratio in producing high power, striking a balance between engine performance and emission reduction.

2. The pyrolysis fuel mixture can affect exhaust emissions, especially carbon monoxide (CO) and hydrocarbons (HC). At high engine speeds, the PE-RON 90 30:70 blend showed significant reductions in CO and HC emissions, with the lowest CO value recorded at 0.78 at 6000 rpm and lower HC emissions throughout the rpm range.

Conflict of interest

The authors declare that they have no conflicts of interest with respect to this research, whether financial, personal, authorial or otherwise, that could influence the research and the results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

Thank you to the State Polytechnic of Malang and International Islamic University Malaysia for support of this research and thank you to the journal publisher who has published this paper.

References

1. Miandad, R., Rehan, M., Barakat, M. A., Aburiazaiza, A. S., Khan, H., Ismail, I. M. I. et al. (2019). Catalytic Pyrolysis of Plastic Waste: Moving Toward Pyrolysis Based Biorefineries. Frontiers in Energy Research, 7. https://doi.org/10.3389/fenrg.2019.00027

2. Budsaereechai, S., Hunt, A. J., Ngernyen, Y. (2019). Catalytic pyrolysis of plastic waste for the production of liquid fuels for engines. RSC Advances, 9 (10), 5844–5857. https://doi.org/10.1039/c8ra10058f
3. Aziz, A. N., Al-Dadah, R., Kuznetsova, I., Mahmoud, S., Dhesi, S., Effiong, C., Kanu, E. (2021). Conversion of Mixed Waste of Wood and Plastic to Clean Fuels Using Pyrolysis in Nigeria – Numerical Study. Proceedings of the 7th World Congress on Mechanical, Chemical, and Material Engineering. https://doi.org/10.11159/htff21.135
4. Olalo, J. (2021). Characterization of Pyrolytic Oil Produced from Waste Plastic in Quezon City, Philippines Using Non-catalytic Pyrolysis Method. Chemical Engineering Transactions, 86, 1495–1500. https://doi.org/10.3303/CET2186250
5. Nafii, A., Irawan, B. (2024). Effect of ethanol and water fuel mixture in direct injection diesel engine on power and specific fuel consumption. Evrimata: Journal of Mechanical Engineering, 1 (2), 44–50. https://doi.org/10.70822/evrmata.vi.36
6. Suhartono, S., Romli, A., Harsanti, M., Suharto, S., Achmad, F. (2022). Characteristics study of liquid fuel from pyrolysis of polyethylene plastic waste. Jurnal Teknologi, 84 (4), 57–64. https://doi.org/10.11113/jurnalteknologi.v84.17517
7. Santoso, S., Yulianto, F. A., Yudiyanto, E., Aditya, C., Sabarudin, S. (2024). The Effect of Fuel Pump Pressure and Number of Injector Holes on 150cc Matic Motorcycle Performance. Asian Journal Science and Engineering, 2 (2), 117. https://doi.org/10.51278/ajse.v2i2.1020
8. Aragaw, T. A., Mekonnen, B. A. (2021). Current plastics pollution threats due to COVID-19 and its possible mitigation techniques: a waste-to-energy conversion via Pyrolysis. Environmental Systems Research, 10 (1). https://doi.org/10.1186/s40068-020-00217-x
9. Selvaranjan, K., Navaratnam, S., Rajeev, P., Ravintherakumaran, N. (2021). Environmental challenges induced by extensive use of face masks during COVID-19: A review and potential solutions. Environmental Challenges, 3, 100039. https://doi.org/10.1016/j.envc.2021.100039
10. Al Aiti, M., Jehnichen, D., Fischer, D., Brünig, H., Heinrich, G. (2018). On the morphology and structure formation of carbon fibers from polymer precursor systems. Progress in Materials Science, 98, 477–551. https://doi.org/10.1016/j.pmatsci.2018.07.004
11. Naufal Hana Rizqullah, Monasari, R., Utami Handayani, S., Aditya, C. (2024). Effect of mixing plastic pyrolysis oil with pertamax and variation of ignition timing on performance and emissions. Evrimata: Journal of Mechanical Engineering, 1 (1), 21–24. https://doi.org/10.70822/evrmata.vi.18
12. Desnia, E., Rosie, E., Hartono, S. B., Simanullang, W. F., Anggorowati, A. A., Lourentius, S. (2024). Optimization of pyroliysis of polypropylene and polyethylene based plastic waste become an alternative oil fuel using bentonite catalyst. E3S Web of Conferences, 475, 05006. https://doi.org/10.1051/e3sconf/202447505006
13. Mustapa, M. S. B., Setiawan, A., Gumono, G. (2023). The Effect of Active Carbon from Coconut Shell as an Adsorbent on Motorcycle Exhaust Gas Emissions and Engine Performance. Asian Journal Science and Engineering, 2 (1), 13–21. https://doi.org/10.51278/ajse.v2i1.675
14. Kurniawan, S., Pebrianti, D. (2023). Optimization Study of the Ratio of Bioethanol Bioaceton Ron 90 on the Power and Emissions of a 110cc Gasoline Motor. Asian Journal Science and Engineering, 2 (1), 22. https://doi.org/10.51278/ajse.v2i1.759
15. Al-Fatesh, A. S., AL-Garadi, N. Y. A., Osman, A. I., Al-Mubaddel, F. S., Ibrahim, A. A., Khan, W. U. et al. (2023). From plastic waste pyrolysis to Fuel: Impact of process parameters and material selection on hydrogen production. Fuel, 344, 128107. https://doi.org/10.1016/j.fuel.2023.128107
16. Mottaa, I. L., Marchesanb, A. N., Guimarãesc, H. R., Chagasc, M. F., Bonomic, A., Macielb, M. R. W., Filho, R. M. (2024). Co-Pyrolysis of Lignocellulosic Residues and Plastics: a Simulation Approach to Predict Product Yields. Chemical Engineering Transactions, 109, 139–144. https://doi.org/10.3303/CET24109024
17. Rizqiani, F., Irawan, B. (2024). Effect of a Mixture of Gasoline and Ethanol in a Direct Injection System Engine on Power and Specific Fuel Consumption. Evrimata: Journal of Mechanical Engineering, 1 (3), 63–68. https://doi.org/10.70822/evrmata.v1i03.34
18. Stallkamp, C., Hennig, M., Volk, R., Stapf, D., Schultmann, F. (2024). Pyrolysis of mixed engineering plastics: Economic challenges for automotive plastic waste. Waste Management, 176, 105–116. https://doi.org/10.1016/j.wasman.2024.01.035
19. Sánchez-Borrego, F. J., Álvarez-Mateos, P., García-Martín, J. F. (2021). Biodiesel and Other Value-Added Products from Bio-Oil Obtained from Agrifood Waste. Processes, 9 (5), 797. https://doi.org/10.3390/pr9050797
20. Putra Gitama, N., Hidayat, N., Pebrianti, D. (2024). Effect of Coconut Shell-Based Active Carbon Adsorbent on Motorcycle Exhaust Gas Emissions. Evrimata: Journal of Mechanical Engineering, 1 (3), 88–96. https://doi.org/10.70822/evrmata.v1i03.57
21. Majzoub, W. N., Al-Rawashdeh, M., Al-Mohannadi, D. M. (2024). Toward Building Circularity in Sustainable Plastic Waste Conversion. ACS Sustainable Chemistry & Engineering, 12 (23), 8642–8661. https://doi.org/10.1021/acssuschemeng.4c00383
22. Hossain, S. T., Mahmud, M. A. P. (2024). Optimizing process parameters and materials for the conversion of plastic waste into hydrogen. Engineering Research Express, 6 (4), 045319. https://doi.org/10.1088/2631-8695/ad829f
23. Yaqoob, H., Ali, H. M., Sajjad, U., Hamid, K. (2024). Investigating the potential of plastic pyrolysis oil-diesel blends in diesel engine: Performance, emissions, thermodynamics and sustainability analysis. Results in Engineering, 24, 103336. https://doi.org/10.1016/j.rineng.2024.103336