JOURNAL OF MECHANICAL ENGINEERING, SCIENCE, AND INNOVATION

ITATS

Research Article

Green Algae to Green Fuel: Optimizing the Composition of Bio-Oil Additive Mixture from the Pyrolysis Process and RON 90 for Enhanced Engine Performance

Journal of Mechanical Engineering, Science, and Innovation
e-ISSN: 2776-3536
2024, Vol. 4, No. 2
DOI: 10.31284/j.jmesi.2024.v4i2.6487
ejurnal.itats.ac.id/jmesi

Apip Amrullah[1], Herry Irawansyah[1], Abdul Ghofur[1], Rachmat Subagyo[1], Rizal Mahmud[2], Obie Farobie[3]

[1]Department of Mechanical Engineering, Lambung Mangkurat University, Indonesia.
[2]Teknologi Transportasi, National Research and Innovation Agency (BRIN), Indonesia
[3]Department of Mechanical and Biosystem Engineering, IPB University, Indonesia.

Corresponding author:
Apip Amrullah
Department of Mechanical Engineering, Faculty of Engineering, Lambung Mangkurat University
Email: apip.amrullah@ulm.ac.id

Abstract

This study explores the optimization of bio-oil additives derived from the pyrolysis of Ulva lactuca algae, blended with RON 90 gasoline to enhance engine performance and reduce emissions. Addressing the urgent need for sustainable energy, the research focuses on a relatively unexplored area—using algae-derived bio-oils in gasoline engines. The study aimed to identify the optimal blend ratio of bio-oil and gasoline to improve engine metrics such as brake specific fuel consumption (BSFC), thermal efficiency, and volumetric efficiency, while minimizing emissions like CO, CO_2, and NOx. Experiments were conducted with bio-oil blended at 5%, 10%, and 15% by volume with RON 90 gasoline in a single-cylinder gasoline engine. Results showed that increasing bio-oil concentration led to improved fuel efficiency and thermal efficiency, along with significant reductions in CO and HC emissions. However, NOx emissions presented a complex trend, increasing at lower bio-oil ratios but decreasing significantly at the highest concentration. These findings suggest that algae-derived bio-oil can effectively enhance gasoline engine performance and reduce environmental impact, offering a novel, sustainable alternative fuel option. The study underscores the importance of optimizing blend ratios to maximize benefits and manage emissions, contributing valuable insights to sustainable energy research.

Keywords: *Algae-derived bio-oil, Pyrolysis, RON 90 gasoline, Engine performance, Emission reduction*

Received: August 21, 2024; Received in revised: November 13, 2024; Accepted: November 18, 2024

Handling Editor: Ika Nurjannah

INTRODUCTION

The transition to sustainable energy sources is a critical global objective, driven by the need to reduce dependence on fossil fuels and mitigate environmental impacts such as air pollution and climate change. The transportation sector, predominantly reliant on internal combustion engines, is a major contributor to greenhouse gas emissions. While gasoline engines are widely used due to their high energy density and reliability, their environmental footprint necessitates the exploration of alternative fuels and additives that can reduce emissions without compromising performance.

In recent years, biofuels have gained attention as a potential solution, with bio-oils derived from various biomass sources being explored as additives to conventional fuels [1–3]. Among these, macroalgae have emerged as a particularly promising feedstock due to their rapid growth, high lipid content, and ability to sequester carbon dioxide [4,5]. The pyrolysis of algae biomass produces bio-oil, a complex mixture of hydrocarbons, which can be refined and blended with gasoline to enhance engine performance and reduce emissions. However, optimizing the composition of such bio-oil mixtures for use in internal combustion engines remains a challenge, particularly in terms of achieving the right balance between performance enhancement and emission reduction. Existing literature on bio-oil additives for gasoline engines emphasizes the significant impact of bio-oil composition and blend ratios on combustion characteristics. Studies have shown that bio-oils have the potential to enhance combustion properties in gasoline engines, but the effectiveness of these additives is closely tied to the specific composition and the proportion of bio-oil within the fuel mixture [6–9]. The concentration of bio-oil fractions in fuel blends can be calculated based on specific equations, emphasizing the importance of precise measurements and ratios in achieving desired combustion effects [6].

Additionally, the introduction of aromatics from catalytic-pyrolysis-derived bio-oil has been identified as a method to influence combustion behavior in gasoline engines [10]. Furthermore, research has demonstrated that bio-oil can be blended with glycerol and methanol within specific ratios to create homogeneous fuel mixtures, underscoring the intricate balance required for optimal performance [7]. Studies have also explored the fate of bio-carbon in co-processing products, shedding light on the distribution of bio-carbon in different fractions of the final products [11–13]. Moreover, investigations into the utilization of bio-additives in gasoline engines have shown promising results in terms of improving engine torque, efficiency, and combustion characteristics [14]. The addition of bio-based compounds like castor oil and biodiesel as cosolvents has been studied for their impact on phase stability and vapor pressure in methanol-gasoline blends, offering insights into alternative energy sources [15].

Additionally, Misron et al. [16] reported on the performance improvement of a portable electric generator using an optimized bio-fuel ratio in a single-cylinder two-stroke engine, underscoring the potential benefits of bio-oil additives. Awat et al. [14] investigated the performance and emissions of a spark ignition engine operated with gasoline supplemented with pyro-gasoline and ethanol, further supporting the need for careful optimization of bio-oil blends. Finally, Goldbach et al. [17] examined the combustion performance of bio-gasoline produced by waste fish oil pyrolysis, providing additional evidence of the challenges and opportunities associated with bio-oil fuel additives. Despite significant progress in the development of bio-oil additives, several research gaps remain. Most studies have focused on the effects of bio-oil additives in diesel engines, with relatively few examining their use in gasoline engines. Additionally, there is limited research on the specific impact of algae-derived bio-oils, particularly those produced through pyrolysis, on the performance of gasoline engines. The variability in bio-oil composition due to different algae species and pyrolysis conditions further complicates the optimization process.

While previous studies have highlighted the potential benefits of bio-oil additives, they have not comprehensively examined the long-term effects on engine durability and maintenance. The interactions between bio-oil additives and critical engine components, including fuel injectors and catalytic converters, remain insufficiently understood. This study addresses these gaps by analyzing the performance and emissions characteristics of gasoline engines fueled with optimized bio-oil blends, with a particular focus on long-term engine health and sustainability. Uniquely, this research optimizes a bio-oil additive derived from the pyrolysis of green algae, blended with RON 90 gasoline, to enhance engine performance while reducing emissions. The novelty of this work lies in its exploration of algae-derived bio-oil as a gasoline additive, an area largely unexplored in existing literature. Through experimental testing of various blend ratios, emissions profiles, and impacts on engine performance, this study aims to identify a sustainable and effective fuel additive that could be adopted on a broad scale.

MATERIALS AND METHODS

Materials and Experimental Setup

The materials used in this study include bio-oil derived from the pyrolysis of Ulva lactuca algae, RON 90 gasoline, and a single-cylinder gasoline engine testbed. The algae were collected from East Lombok, West of Nusa Tenggara, and subjected to pyrolysis at temperatures ranging from 400°C to 600°C to produce the bio-oil. The RON 90 gasoline was obtained from a commercial supplier, meeting all standard fuel specifications. The experimental setup involved a single-cylinder gasoline engine equipped with sensors to monitor various performance parameters, fuel consumption, and exhaust gas composition (Figure 1).

To maintain constant engine speed and load during testing, a dynamometer provided a steady load, while an electronic throttle control regulated speed. The ECU was adjusted to synchronize fuel injection and ignition timing, ensuring consistent operation across different fuel blends. This setup enabled precise assessment of engine performance with various bio-oil-gasoline mixtures. The Vario 110 Karbu features a 108.2 cc carbureted engine producing 7.94 PS at 7,500 rpm and 8.4 Nm of torque at 5,500 rpm.

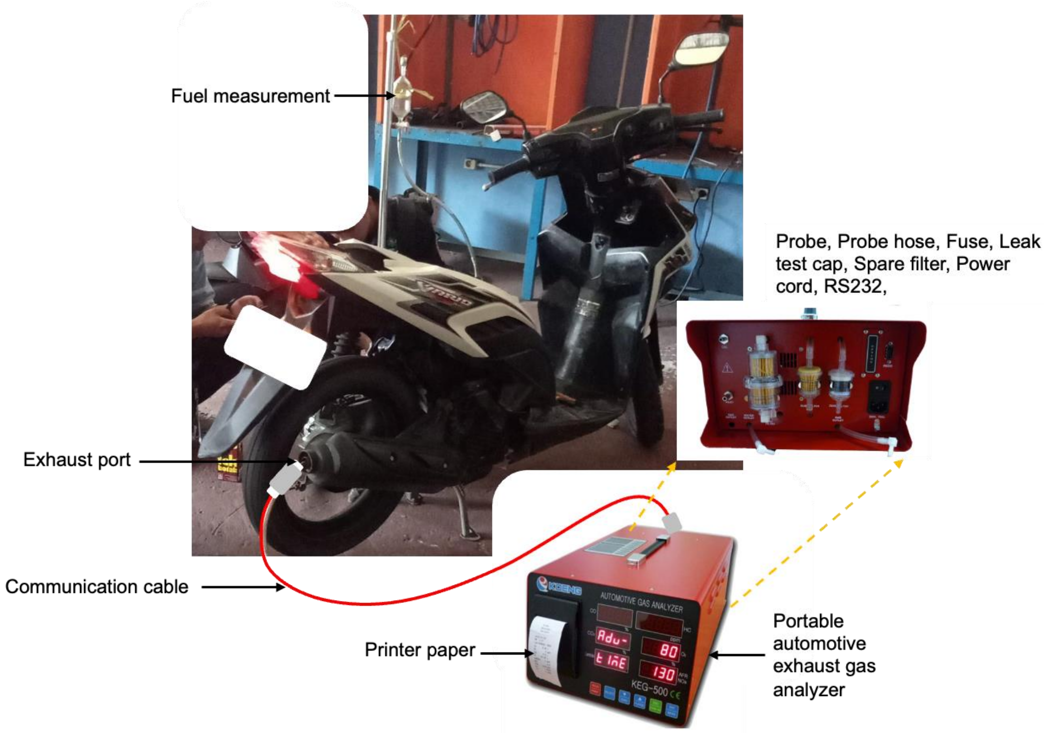

Figure 1. Experimental setup

The engine was modified to accommodate different bio-oil-gasoline blends, running at a constant speed and load during tests. The carburetor was calibrated for stable fuel delivery, and the electronic control unit (ECU) was adjusted to ensure consistent fuel injection and ignition timing for each blend ratio. This setup allowed precise assessment of performance across various fuel mixtures. The scooter, with dimensions of 1,870 x 685 x 1,070 mm, weighs 100 kg, holds 4.5 liters of fuel, and reaches a top speed of 90 km/h. Additional features include LED lighting, dual rear shocks, spacious under-seat storage, and a secure ignition system, enhancing both functionality and reliability.

Blend Preparation

Bio-oil was blended with RON 90 gasoline at different ratios, specifically 5%, 10%, and 15% by volume. Each blend was prepared by accurately measuring the bio-oil and gasoline volumes using calibrated laboratory equipment to ensure precision in the blend ratios. The components were then thoroughly mixed to achieve a homogeneous mixture. The selected blend ratios were based on preliminary studies and a literature review, designed to capture a broad spectrum of potential effects on engine performance.

Testing Procedure

Each blend was tested under identical operating conditions, with data collected on combustion efficiency, power output, specific fuel consumption (SFC), Brake Specific Fuel Consumption (BSFC), and exhaust emissions (CO, CO_2, O_2, HC, and NOx). BSFC was calculated using the equation (1):

$$BSFC = \frac{\dot{m}_f}{P_b} \quad (1)$$

where $\dot{m}_f$ is the mass flow rate of fuel (kg/h) and P_b is the brake power (kW) produced by the engine. This provides a measure of fuel efficiency relative to power output.

Volumetric Efficiency was calculated by comparing the actual intake air flow rate ($\dot{m}_a$) to the theoretical maximum intake air flow rate under ideal conditions, using the equation (2):

$$\eta_v = \frac{\dot{m}_a}{\rho_a . V_d . N/2} \quad (2)$$

where η_v is the volumetric efficiency, ρ_a is the air density (kg/m^3), V_d is the engine displacement volume (m^3), and N the engine speed in RPM. This indicates the engine's air intake capacity for each fuel blend.

The engine was run for a specified period to ensure steady-state conditions before measurements were taken. The tests were repeated three times for each blend to ensure reproducibility and statistical validity. The results were compared to those obtained using pure RON 90 gasoline as a baseline.

RESULTS AND DISCUSSIONS

Effect of pyrolysis temperature on product distribution

The bio-oil production trend observed in the Figure 2 reveals a clear, non-linear relationship with the reaction temperature during pyrolysis. Initially, as the temperature increases from 400°C to 500°C, bio-oil production rises, peaking at around 500°C.

This increase can be attributed to the enhanced thermal decomposition of biomass polymers, such as cellulose, hemicellulose, and lignin, into volatile compounds that condense into liquid bio-oil [17]. The temperature range of 450-550°C is often cited in the literature as optimal for maximizing bio-oil yield, balancing the rates of primary pyrolysis reactions and secondary reactions that favor liquid production [19]. However, as the tem-

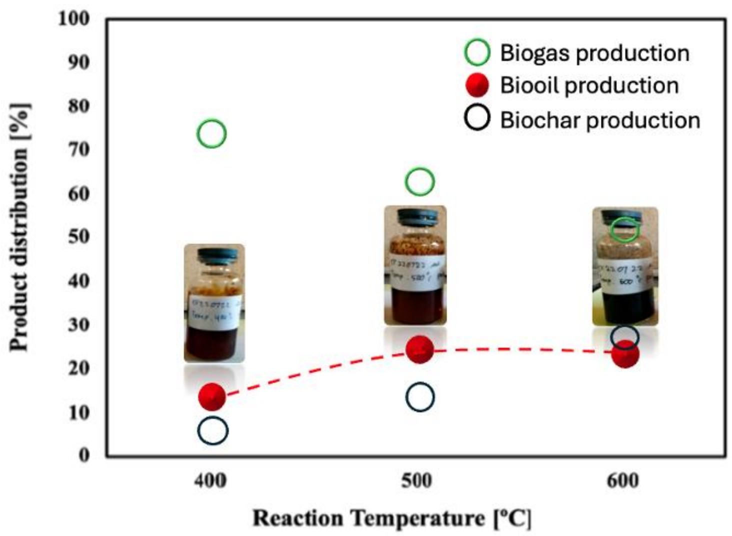

Figure 2. Product distribution from pyrolysis of *Ulva lactuca*

perature rises beyond 500°C, bio-oil production begins to decline. This decrease is likely due to the onset of secondary cracking reactions, where larger liquid molecules are broken down into lighter gases, reducing the overall liquid yield [20]. Additionally, higher temperatures promote the formation of biochar and biogas at the expense of bio-oil, as the increased energy leads to further gasification and polymerization processes. This trend is well-documented in studies such as those by Kato et al. [21] and Gui et al. [22], all of which report similar findings, indicating that while moderate temperatures are ideal for liquid yield, excessive heat shifts the balance towards gaseous and solid products. Thus, the bio-oil yield curve underscores the importance of carefully controlling the pyrolysis temperature to optimize liquid bio-oil production.

Characteristics of bio-oil production

Figure 3 illustrates the chemical composition of a complex sample, where carboxylic acids. The prevalence of carboxylic acids in a complex sample, comprising 48% of the total composition, significantly influences the sample's acidic nature and chemical properties [23]. Carboxylic acids are recognized for their thermal stability and functional characteristics, making them vital components in various materials science applications [23]. These acids can be pivotal in shaping the sample's characteristics, particularly in terms of its chemical behavior and reactivity [24]. Aliphatic hydrocarbons, comprising 24% of the sample, represent the next most abundant group, contributing to the sample's non-aromatic and hydrophobic characteristics. The presence of phenolics at 15% adds another layer of complexity, as these compounds are known for their aromatic structures and potential antioxidant activity, which could impact the sample's reactivity and stability.

In contrast, the remaining components, including N-aromatic compounds (6%), amines/amides (4%), ketones (2%), and furan derivatives (1%), are present in smaller quantities but still contribute to the overall chemical diversity of the sample. N-aromatic compounds and amines/amides, though less abundant, introduce nitrogen-containing functional groups, which may be important for specific chemical interactions or biological activity. Ketones and furan derivatives, despite their low percentages, indicate the presence of oxygenated functionalities that could influence the sample's chemical behavior. Together, these varied compounds create a complex chemical environment, with carboxylic acids playing a leading role, complemented by a range of other functional groups that collectively define the sample's unique properties.

When considering the use of this bio-oil as a fuel additive in a gasoline engine, its

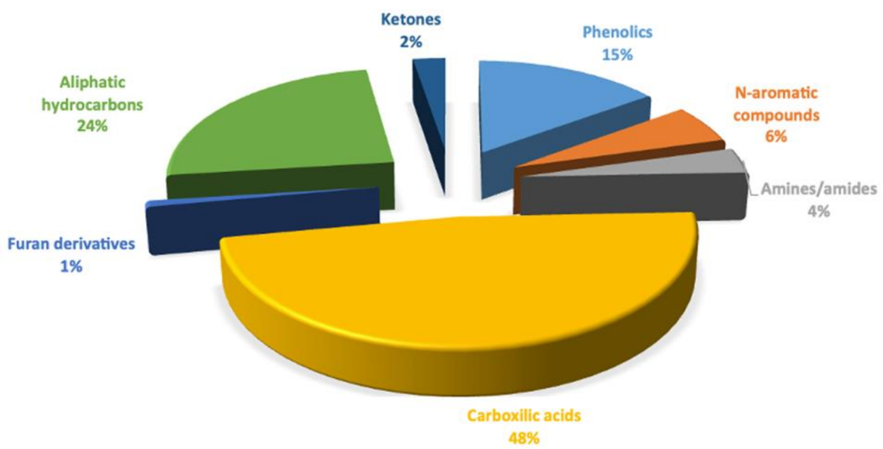

Figure 3. Bio-oil composition

Table 1. Engine performance with the different percentages of bio-oil additive

Metric / Emission	Pure Gasoline (G90)	(5% Bio-Oil)	(10% Bio-Oil)	(15% Bio-Oil)
Brake Specific Fuel Consumption (BSFC) g/kWh	310	209	291	290
Thermal Efficiency	28%	28.20%	29.01%	30.00%
Volumetric Efficiency	89%	89%	90%	91%

composition plays a critical role in determining its impact on combustion and engine performance. The presence of oxygenated compounds such as carboxylic acids, phenolics, and ketones can indeed influence combustion efficiency by promoting a more complete burn [25]. Among these compounds, ketones like cyclopentanone are known for their resistance to autoignition, making them appealing for use in internal combustion engines [25]. Furthermore, reactive intermediates like benzoyl radicals are crucial in combustion reactions, highlighting the complex chemistry involved in combustion processes [26]. However, these compounds also introduce challenges, such as increased acidity, potential engine corrosion, and the formation of undesirable emissions, such as NOx from nitrogenous compounds. The presence of aliphatic hydrocarbons is beneficial, as they contribute to an energy density similar to conventional gasoline. Therefore, while bio-oil shows promise as a fuel additive, its use would require careful consideration of its effects on engine wear, emissions, and overall performance to ensure it provides a net benefit.

Effects of bio-oil and commercial fuel blend on engine performance and gas emissions

Table 1 shows the compares the engine performance metrics when using pure gasoline (denoted as G90) and gasoline with varying percentages of bio-oil additive (5%, 10%, and 15%). The key metrics provided include Brake Specific Fuel Consumption (BSFC), Thermal Efficiency, and Volumetric Efficiency.

Brake Specific Fuel Consumption (BSFC) which measures the fuel efficiency by calculating the amount of fuel consumed per unit of power produced (g/kWh), shows a clear decreasing trend with increasing bio-oil content. Starting at 310 g/kWh for pure gasoline, the BSFC decreases progressively to 209 g/kWh with 5% bio-oil, 291 g/kWh with 10% bio-oil, and 290 g/kWh with 15% bio-oil. This indicates that the addition of bio-oil enhances fuel efficiency, as less fuel is required to produce the same amount of power [27]. Similarly, Janyalertadun et al. [28] and Friso [29] noted that thermal efficiency and volumetric efficiency also improve with higher bio-oil concentrations. The heightened thermal efficiency is attributed to a more effective combustion process likely facilitated by the oxygenated compounds present in bio-oil, which promote a more thorough burn.

Conversely, Khan et al. [30] reported an increase in BSFC and a decrease in brake thermal efficiency when using waste oil biodiesel blends, contrasting the general trend observed with bio-oil. This suggests that the source and composition of the biofuel significantly impact engine performance. Additionally, Suhel et al. [31] highlighted challenges associated with biodiesel, such as higher BSFC, lower brake thermal efficiency, and poor cold flow properties, which may hinder its commercialization in the automotive sector.

Furthermore, thermal efficiency, reflecting the engine's ability to convert fuel energy into useful work, increases with higher percentages of bio-oil. The efficiency rises from 28% with pure gasoline to 28.2% with 5% bio-oil, 29.01% with 10% bio-oil, and reaches 30.00% with 15% bio-oil. This suggests a more efficient combustion process, likely driven by the oxygenated compounds in bio-oil that promote a more complete burn. Additionally, volumetric efficiency, a measure of the engine's capacity to fill its cylinders with air, also improves with the addition of bio-oil. The efficiency increases from 89% with pure gasoline to 88% with 5% bio-oil, 90% with 10% bio-oil, and 91% with 15% bio-oil. This improvement indicates that bio-oil may enhance the air-fuel mixture's combustion properties, leading to better air intake and overall engine performance.

In addition to evaluating engine performance, this study also conducted tests on exhaust emissions, as presented in Figure 4. The data presented in Figure 4 illustrates the impact of adding bio-oil to gasoline on exhaust emissions, including carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), hydrocarbons (HC), and nitrogen oxides (NOx). The addition of bio-oil to gasoline has been shown to significantly influence exhaust emissions, including carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and nitrogen oxides (NOx). The data indicates a marked reduction in CO emissions, decreasing from 0.9% with pure gasoline to as low as 0.07% with 15% bio-oil, which suggests a more complete combustion process. This finding aligns with the work of Khalid et al., [32], who reported that the use of biodiesel blends can effectively reduce CO emissions due to improved combustion characteristics. Similarly, HC emissions, which reflect unburned fuel, decrease from 60 ppm with pure gasoline to 41 ppm with 15% bio-oil, further supporting the notion of enhanced combustion efficiency (Valencia et al.,) [33].

The reduction in CO_2 levels, from 4.8% to 2.6% with increasing bio-oil content, may be attributed to the lower carbon content in bio-oil or altered combustion characteristics, as noted by Tzanetakis et al.,[34]. The initial decrease in oxygen content in the exhaust,

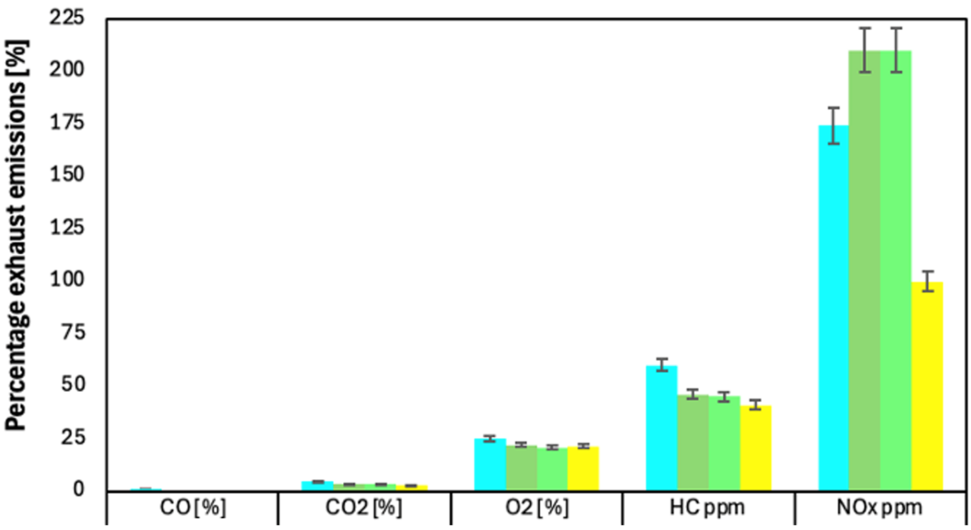

Figure 4. Gas emission results

followed by a slight increase at the highest bio-oil concentration, reflects changes in combustion dynamics influenced by the bio-oil, which contains oxygenated compounds that can enhance combustion efficiency (Lujaji et al.,)[35]. Regarding NOx emissions, the data presents a complex trend. NOx emissions increase from 174.2 ppm with pure gasoline to 210 ppm with 5% and 10% bio-oil, likely due to elevated combustion temperatures and altered oxygen availability (Ren et al.,)[36]. However, at 15% bio-oil, NOx emissions drop significantly to 100 ppm, indicating that higher concentrations of bio-oil may create a combustion environment that reduces NOx formation. This observation is consistent with findings from Adam et al.,[37], who noted that the combustion of biodiesel blends can lead to varying NOx emissions depending on the fuel composition and combustion conditions. In summary, the incorporation of bio-oil into gasoline appears to enhance combustion efficiency, as evidenced by reductions in CO and HC emissions. However, it also introduces complexities in managing NOx emissions, particularly at lower bio-oil concentrations, necessitating further investigation into the optimal blending ratios for achieving desired emission profiles.

CONCLUSIONS

This study demonstrated that bio-oil from *Ulva lactuca* algae, when blended with RON 90 gasoline, enhances engine performance and reduces emissions. Blending bio-oil at 5%, 10%, and 15% by volume improved brake specific fuel consumption, thermal efficiency, and volumetric efficiency, while decreasing CO and HC emissions. However, NOx emissions increased at lower blends but decreased at 15% bio-oil, indicating the need for precise optimization of blend ratios to balance performance with environmental benefits. This research highlights the potential of algae-derived bio-oil as a sustainable fuel additive, pointing to the importance of further studies on long-term engine impacts and the optimal ratios for minimizing emissions and enhancing engine efficiency

ACKNOWLEDGEMENTS

The authors express their gratitude to the Institute for Research and Community Service (LPPM) at Universitas Lambung Mangkurat for funding this study. The research was supported by PNBP funds from Universitas Lambung Mangkurat, under the DIPA for 2024 (SP DIPA-023.17.2.677518/2024) and under the grant number 1090.118/UN8.2/PG/2024.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FUNDING

The author(s) disclosed receipt of financial support for the research, authorship, and/or publication of this article.

REFERENCES

[1] G. Li, R. Wang, J. Pang, *et al.*, "Production of renewable hydrocarbon biofuels with lignocellulose and its derivatives over heterogeneous catalysts," *Chemical Reviews*, vol. 124, no. 6, 2024. doi: 10.1021/acs.chemrev.2c00756.

[2] B. A. Bryan, D. King, and E. Wang, "Biofuels agriculture: Landscape-scale trade-offs between fuel, economics, carbon, energy, food, and fiber," *GCB Bioenergy*, vol. 2, no. 6, pp. 330–345, 2010. doi: 10.1111/j.1757-1707.2010.01056.x.

[3] A. Amrullah, A. Syarief, and M. Saifudin, "Combustion behavior of fuel briquettes made from ulin wood and gelam wood residues," *International Journal of Engineering Transactions B: Applications*, vol. 33, no. 11, pp. 2365–2371, 2020. doi: 10.5829/ije.2020.33.11b.27.

[4] A. Amrullah, O. Farobie, S. Septarini, *et al.*, "Synergetic biofuel production from co-pyrolysis of food and plastic waste: Reaction kinetics and product behavior," *Heliyon*, vol. 8, no. 8, 2022. doi: 10.1016/j.heliyon.2022.e10278.

[5] O. Farobie, N. Syaftika, I. Masfuri, *et al.*, "Green algae to green fuels: Syngas and hydrochar production from *Ulva lactuca* via sub-critical water gasification," *Algal Research*, vol. 67, 2022, Art. no. 102834. doi: 10.1016/j.algal.2022.102834.

[6] H. Abdullah and H. Wu, "Bioslurry as a fuel. 4. Preparation of bioslurry fuels from biochar and the bio-oil-rich fractions after bio-oil/biodiesel extraction," *Energy & Fuels*, vol. 25, no. 3, pp. 1235–1245, 2011. doi: 10.1021/ef101535e.

[7] M. Zhang and H. Wu, "Phase behavior and fuel properties of bio-oil/glycerol/methanol blends," *Energy & Fuels*, vol. 28, no. 2, pp. 1436–1445, 2014. doi: 10.1021/ef501176z.

[8] Á. Ibarra, E. C. Rodríguez, U. Sedrán, *et al.*, "Synergy in the cracking of a blend of bio-oil and vacuum gasoil under fluid catalytic cracking conditions," *Industrial & Engineering Chemistry Research*, vol. 55, no. 2, pp. 301–309, 2016. doi: 10.1021/acs.iecr.5b04502.

[9] P. Palmay, "Influence of Γ-Fe_2O_3 nanoparticles added to gasoline–bio-oil blends derived from plastic waste on combustion and emissions generated in a gasoline engine," *Energies*, vol. 17, no. 12, Art. no. 2843, 2024. doi: 10.3390/en17122843.

[10] Z. Wang, K. Wan, J. Xia, *et al.*, "Pyrolysis characteristics of coal, biomass, and coal–biomass blends under high heating rate conditions: Effects of particle diameter, fuel type, and mixing conditions," *Energy & Fuels*, vol. 29, no. 6, pp. 3730–3737, 2015. doi: 10.1021/acs.energyfuels.5b00646.

[11] G. Fogassy, N. Thégarid, Y. Schuurman, *et al.*, "The fate of bio-carbon in FCC co-processing products," *Green Chemistry*, vol. 14, no. 6, pp. 1361–1367, 2012. doi: 10.1039/c2gc35152h.

[12] A. Amrullah, O. Farobie, H. Irawansyah, *et al.*, "Synergistic enhancement of bio-oil production, quality, and optimization from co-pyrolysis purun tikus (*Eleocharis dulcis*) and plastic waste using response surface methodology," *Process Safety and Environmental Protection*, vol. 170, pp. 150–163, 2024. doi: 10.1016/j.psep.2024.04.079.

[13] A. Amrullah and S. E. Teguh, "Coconut shell bio-oil distillation: Its characteristic and product distribution," *IOP Conference Series: Earth and Environmental Science*, vol. 1038, Art. no. 012018, 2022. doi: 10.1088/1755-1315/1038/1/012018.

[14] O. I. Awad, O. M. Ali, B. Zhou, *et al.*, "Utilization of additive from waste products with gasoline fuel to operate spark ignition engine," *Scientific Reports*, vol. 12, Art. no. 11599, 2022. doi: 10.1038/s41598-022-11599-6.

[15] J. Xu, Y. Y. Xue, M. Liu, *et al.*, "Performance of castor oil in methanol-gasoline as a bi-functional additive," *Key Engineering Materials*, vol. 777, pp. 232–239, 2018. doi: 10.4028/www.scientific.net/kem.777.232.

[16] N. Misron, S. Rizuan, C. A. Vaithilingam, *et al.*, "Performance improvement of a portable electric generator using an optimized bio-fuel ratio in a single-cylinder two-stroke engine," *Energies*, vol. 4, no. 11, pp. 1937–1949, 2011. doi: 10.3390/en4111937.

[17] A. Goldbach, H. M. França, V. W. Rodolfo, *et al.*, "Combustion performance of bio-gasoline produced by waste fish oil pyrolysis," *Chemical Industry & Chemical Engineering Quarterly*, vol. 28, no. 1, pp. 75–85, 2022. doi:

10.2298/ciceq200810010g.
[18] X. Shi, H. Liu, X. Zhang, *et al.*, "Numerical simulation on effects of biomass type on its fast pyrolysis in a fluidized bed reactor," *Industrial & Engineering Chemistry Research*, vol. 62, no. 4, pp. 1975–1988, 2023. doi: 10.1021/acs.iecr.3c01454.
[19] E. Salehi, J. Abedi, and T. G. Harding, "Bio-oil from sawdust: Pyrolysis of sawdust in a fixed-bed system," *Energy & Fuels*, vol. 23, no. 6, pp. 3767–3772, 2009. doi: 10.1021/ef900112b.
[20] R. Azargohar, S. Nanda, B. V. S. Rao, *et al.*, "Slow pyrolysis of deoiled canola meal: Product yields and characterization," *Energy & Fuels*, vol. 27, no. 10, pp. 6228–6239, 2013. doi: 10.1021/ef400941a.
[21] M. S. Zan Gui, S. A. Jourabchi, H. K. Ng, *et al.*, "Comparison of the yield and properties of bio-oil produced by slow and fast pyrolysis of rice husks and coconut shells," *Applied Mechanics and Materials*, vol. 625, pp. 626–631, 2014. doi: 10.4028/www.scientific.net/amm.625.626.
[22] Y. Kato, R. Enomoto, M. Akazawa, *et al.*, "Characterization of Japanese cedar bio-oil produced using a bench-scale auger pyrolyzer," *SpringerPlus*, vol. 5, Art. no. 1417, 2016. doi: 10.1186/s40064-016-1848-7.
[23] L. Chen, J. Zhu, C. Báez, *et al.*, "Highly thermal-stable and functional cellulose *nanocrystals* and nanofibrils produced using fully recyclable organic acids," *Green Chemistry*, vol. 18, no. 15, pp. 3835–3843, 2016. doi: 10.1039/c6gc00687f.
[24] Y. Luo, T. Song, H. M. Ji, *et al.*, "Preliminary investigations of the mechanisms involved in the ultrasonication-assisted production of carboxylic cellulose nanocrystals with different *structural* carboxylic acids," *ACS Sustainable Chemistry & Engineering*, vol. 9, no. 1, pp. 369–379, 2021. doi: 10.1021/acssuschemeng.0c08929.
[25] T. N. Pham, T. Sooknoi, S. Crossley, *et al.*, "Ketonization of carboxylic acids: Mechanisms, *catalysts*, and implications for biomass conversion," *ACS Catalysis*, vol. 3, no. 11, pp. 2456–2473, 2013. doi: 10.1021/cs400501h.
[26] A. *Mardyukov* and W. Sander, "Matrix isolation and IR characterization of the benzoyl and benzoylperoxy radicals," *European Journal of Organic Chemistry*, vol. 2010, no. 8, pp. 1374–1378, 2010. doi: 10.1002/ejoc.201000153.
[27] S. P. Pandey and R. Prakash, "Performance and emission analysis of blends of bio-oil *obtained* by catalytic pyrolysis of *Argemone mexicana* seeds with diesel in a CI engine," *Environmental Science and Pollution Research*, vol. 29, pp. 4684–4696, 2022. doi: 10.1007/s11356-022-24648-4.
[28] A. Janyalertadun, C. Santaweesuk, and S. Sanongraj, "Fuel production, performance, and emission of a CI engine using waste plastics oil," *World Journal of Engineering*, vol. 14, no. 4, pp. 293–298, 2017. doi: 10.1108/wje-08-2016-0044.
[29] D. Friso, "Brake thermal efficiency and BSFC of diesel engines: Mathematical modeling and comparison between diesel oil and biodiesel fueling," *Applied Mathematical Sciences*, vol. 8, no. 91, pp. 4547–4559, 2014. doi: 10.12988/ams.2014.46444.
[30] M. B. Khan, A. H. Kazim, A. Shabbir, *et al.*, "Performance and emission analysis of high purity biodiesel blends in diesel engine," *Advances in Mechanical Engineering*, vol. 12, no. 1, Art. no. 1687814020974156, 2020. doi: 10.1177/1687814020974156.
[31] A. Suhel, N. A. Rahim, M. R. Abdul Rahman, *et al.*, "An experimental investigation on the effect of ferrous ferric oxide nano-additive and chicken fat methyl ester on performance and emission characteristics of compression ignition engine," *Symmetry*, vol. 13, no. 2, Art. no. 265, 2021. doi: 10.3390/sym13020265.
[32] A. Khalid, M. D. Anuar, Y. Ishak, *et al.*, "Emissions characteristics of small diesel engine fuelled by waste cooking oil," *MATEC Web of Conferences*, vol. 13, Art. no. 06006, 2014. doi: 10.1051/matecconf/20141306006.

[33] G. Valencia, C. A. Peñaloza, and J. D. Forero, "Combustion and performance study of low-displacement compression ignition engines operating with diesel–biodiesel blends," *Applied Sciences*, vol. 10, no. 3, Art. no. 907, 2020. doi: 10.3390/app10030907.

[34] T. Tzanetakis, S. Moloodi, N. Farra, *et al.*, "Comparison of the spray combustion characteristics and emissions of a wood-derived fast pyrolysis liquid-ethanol blend with number 2 and number 4 fuel oils in a pilot-stabilized swirl burner," *Energy & Fuels*, vol. 25, no. 11, pp. 5469–5478, 2011. doi: 10.1021/ef200904w.

[35] F. Lujaji, A. A. Boateng, M. A. Schaffer, *et al.*, "Pyrolysis oil combustion in a horizontal box *furnace* with an externally mixed nozzle," *Energy & Fuels*, vol. 30, no. 5, pp. 3900–3907, 2016. doi: 10.1021/acs.energyfuels.6b00318.

[36] H. Ren, D. M. Lou, P. Q. Tan, *et al.*, "Experimental study on urea dosing strategy for SCR on *an* engine fuelled with bio-diesel," *Advanced Materials Research*, vol. 848, pp. 286–292, 2013. doi: 10.4028/www.scientific.net/amr.848.286.

[37] A. A. Adam, A. Khalid, N. Jaat, *et al.*, "Performance and emissions characteristics of crude jatropha oil biodiesel blends in a diesel engine," *International Journal of Automotive and Mechanical Engineering*, vol. 11, pp. 2462–2472, 2015. doi: 10.15282/ijame.11.2015.25.0206.