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Performance of a nipa-based fuel blend on a multi-blend capable engine test motorcycle towards renewable biofuel solutions

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The performance of an alternative fuel and its blends into a gasoline engine was evaluated using a developed Multi-Blend Capable Engine (MBCE) from carb to EFI test motorcycle to enhance performance compatibility and environmental concerns of a nipa-based ethanol as renewable alternative feedstock fuel. It shows that the test motorcycle utilizing its stock carburetor systems is compatible up to E30H only, while the EFI modification was found compatible from E10 to 100% nipa hydrous ethanol or E100H as fuel using three different driving modes of the MBCE with decreased power versus speed performance by about 24% and mileage consumption by about 6.0%. However, emissions significantly improved in the test motorcycle with HC and CO meeting Euro 4 standards. The total carbon quantification was found to be 76-225 gCO_2e/km from nipa sap collection up to its utilization as an alternative gasoline fuel engine from E10 to E100H. The study safely recommends implementing up to E30H blend without any adjustments made on carb and EFI system motorcycles. To promote higher blend biofuel adoption in support of SDG 7 Clean and Affordable Energy, the study implies carburetor systems adjustments or EFI conversion for stock carb system motorcycles, while remapping must be made to EFI motorcycles.

Key words: *biofuels, fuel performance, engine performance, emission, carbon quantification*

1. Introduction

This research article intends to address some of the gaps in the full implementation of the Philippine Biofuels Act and in other countries with a similar intent [1], which aims to achieve higher anhydrous ethanol (E) blend utilization up to 85% (E85) by 2030, but has remained restricted primarily to E10 since the Act's approval in 2006. Vehicles are believed to be incompatible with higher fuel blend ratios, as evidenced by engine tests that reported difficult engine starts and rusting of metal parts, such as tanks and carburetors [25, 30]. The objective of this endeavour is to initiate performance testing of a nipa-based fuel in a test motorcycle from carbureted (Carb) into modified Electronic Fuel Injected (EFI) fuel system which optimizes the use of higher blends and or as a fuel, parallel to the intent of the Philippines RA 9367 and the United Nation's Sustainable Development Goal's SDG 7 or Affordable and Clean Energy.

Electric Vehicles (EVs) are one of the new trends in transportation [37, 57] nowadays; however, fleet electrification is not the only solution [43]. The importance of Internal Combustion Engines (ICE) should not be neglected, as they continue to be used, especially since the transportation sector is not the major contributor to environmental problems, but rather the energy sector [47]. EVs have their disadvantages, particularly in sourcing raw materials for batteries, which are often acquired through mining. These challenges can potentially be addressed through battery metal recycling [26] and improvements in battery design, as well as by enhancing safety, excitability, or response [17]. Although a lengthy charging system remains an issue, several methods are already underway to address this, such as optimization studies of charging stations [53] and battery performance interventions [16, 54]. Regarding conventional vehicles, the depletion of fossil fuels for petroleum products poses a prevailing dilemma for internal combustion engines (ICE), where biofuels and blends are expected to help mitigate this issue [5, 41]. In addition to sugarcane and corn, problems with bioethanol feedstock availability can be addressed from promising feedstocks such as sweet sorghum, cassava [28, 38] and other starchy crops [24, 45]. In this study, nipa was utilized as the feedstock for bioethanol production. As regional wars and conflicts affect petroleum supply and costs, considering the promising renewable feedstocks available in each country may support the continued use of internal combustion engines (ICE), provided they are equipped with efficient fuel systems capable of handling varying ethanol blend ratios or even pure ethanol, such as in flex-fuel engines and other Alternative Fuel Vehicles (AFVs) [14].

Several engine performance tests were already conducted in the Philippines [30, 56] and abroad [11, 49] using different fuel blends using either hydrous or anhydrous ethanol on gasoline, where performance and emissions were found to be comparable and more environmentally friendly [33, 58] and as a renewable energy source [23, 32]. However, these blends were conducted at up to 25% ethanol-gasoline ratios except in the study up to E60 [22]. Other tests were also conducted on stationary, motorcycle engines, and passenger cars using a manual variable-fed fuel system up to 100% hydrous [7], fuel injection run by Arduino to E30 [39], and flex-fuel engines [9, 21] in an attempt to investigate the potential of higher fuel blends. Modification of a low-powered motorbike engine from carb to electronic fuel injection (EFI) was also conducted [19], which was found to improve fuel consumption at different speeds on a single fuel blend.

This pioneering test in the Philippines, conducted by modifying a carbureted motorcycle to an EFI test motorcycle or MBCE, utilises fuel blends containing up to 100% nipa-based bioethanol. The ethanol is produced through the distillation of the nipa sap or the sweet juice extracted from the peduncle of *Nypa fruticans*, a mangrove palm species [27]. The study aims to enhance sustainability in the transportation sector by contributing to global efforts to adopt cleaner energy solutions. It aligns with international sustainability goals while addressing local energy needs, reducing dependency on traditional fossil fuels, and mitigating the impacts of fuel price surges caused by conflicts in the Gulf region.

2. Materials and methods

2.1. Introduction

This paper is a continuation study of Mariano Marcos State University (MMSU) and Mapua University, which utilizes nipa sap as a bioethanol feedstock [29]. Performance testing was conducted on a carb modified to EFI to become a Multi-blend Capable Engine (MBCE) test motorcycle. The evaluation focused on power, fuel economy, and emissions using higher gasoline-ethanol fuel blends up to 100% bioethanol in a gasoline engine. A compatibility test was first conducted on the test motorcycle using its stock carburetor with no modifications to determine its compatibility with various fuel blends. Since ethanol, when used as a pure engine fuel or in higher blends, may pose compatibility or drivability issues, the carbureted test motorcycle used in this study was modified to become MBCE, addressing compatibility issues for the full utilization of higher fuel blends.

2.2. Fuel blend feedstock

The formulated blends underwent a neutralization process to address corrosion problems [30, 40] following the distillation of nipa sap, as per protocols developed by MMSU for hydrous (H) ethanol. Commercial E10 gasoline with a 100 RON rating was used as the base fuel blend for nipa bioethanol.

The properties of the nipa-based hydrous ethanol, as well as the formulated blends, were submitted and analyzed by the Department of Energy using ASTM standards to comply with the Philippine National Standards (PNS), as illustrated in Table 1.

Table 1. Properties, methods, and limits of bioethanol as per PNS

Properties	Test method	Limits
Appearance	Visual	Clear and bright
Acidity/alkalinity, pHe	ASTM D6423	6.5–9.0
Density at 20°C, kg/m^3	ASTM D4052	791.5 max
Ethanol content, %v/v	ASTM D5501	99.3 max
Methanol content, %v/v	ASTM D5501	0.5 max
Total acetic acid, %v/v	ASTM D1613	0.007 max
Heating value, MJ/kg	ASTM D4809	26.71 [36]

2.3. Compatibility test of the MBCE on its stock carb system

A compatibility test was first conducted on the carb-type in-use motorcycle, with its specifications listed in Table 2 and an actual photo provided in Fig. 1. The test motorcycle is rated at 10 HP, which is equivalent to approximately 7.5 kW at 8250 rpm.

Table 2. In-use motorcycle's specifications

Type (color)	Description
Honda XR 125 (Red Orange)	Carb type, 124.7 cc, single cylinder, 4-stroke engine, OHC, air cooled, 8.2 kW at 8250 rpm

Dynamometer tests and mileage runs were conducted to assess fuel blend compatibility, with no modifications or adjustments made to the motorcycle. The motorcycle is expected to run and operate without hard starting or other combustion-related issues to be considered as fuel compatible.

Fig. 1. Honda XR 125 in-use carb type motorcycle

2.4. Modification of the carb type in-use motorcycle to the MBCE test vehicle

Instead of using EFI In-Use motorcycles, the Honda XR 125 was modified to EFI and designated as the MBCE test vehicle, since the use of another In-Use EFI vehicle requires additional modifications aside from the remapping process.

Fig. 2. The MBCE Modification. (a) tank with fuel pump inside, (b) the ECU, (c) switch mode selector, (d) oxygen sensor, (e) CPS (at the other end side), (f) throttle body, (g) TPS manifold, (h) injector manifold

The modification done in the Honda XR 125 in Fig. 2 as shown above include: replacement of the carburetor to FI system with Throttle Body and Throttle Positioning Sensor (TPS) in the manifold connected to the engine head that transmits signal to the Electronic Communication Unit (ECU) and then back to the injectors; installation of crankshaft positioning sensor (CPS) for proper timing of the magneto/stator and alignment gears; installation of a new tank and fuel pump, installation of oxygen and temperature sensors; and the use of "Pitsbike" as the Electronic Control Unit or the ECU. Compared to flex-fuel vehicles utilizing blend software and sensors [51, 55]. The MBCE used switch mode optimized into three (3) settings. The switch installed in the steering wheel is set to mode "2", as shown in Fig. 2c, implying that the MBCE can accommodate fuel blends of 40% to 70% v/v ethanol in gasoline fuel.

The cost of modifying the stock carburetor system to a fuel injection (FI) system, making it an MBCE test vehicle, was 27,000 PHP, or approximately $500 USD.

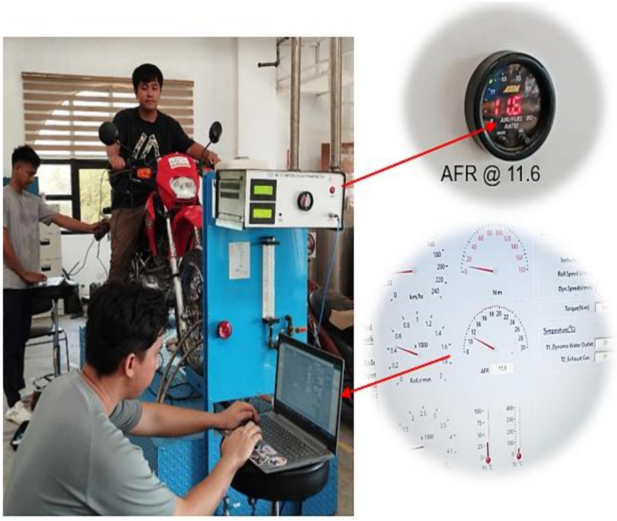

Fig. 3. Remapping and testing of the MBCE motorcycle

The MBCE test vehicle, as shown above in Fig. 3 during dynamometer testing, was equipped with a manual push-button switch to select the most appropriate setting among three different modes. In optimized mode, the MBCE must idle and operate under standard conditions, utilizing all hydrous fuel blends. This mode was remapped on a dynamometer using the 'Pitsbike' ECU software.

During the testing, the following switch modes were established: Mode 1 for E10 to E40H; Mode 2 for E40H to E70H; Mode 3 for E70H to E100H. The AFR setting between 11 and 13, using the dynamometer and the "Pitsbike" ECU software, served as an essential indicator to confirm that each mode is at its optimum setting. Remapping is necessary in the modification [10].

Response Surface Methodology (RSM) was employed using Minitab 21 software in this experiment to investigate the effect of ethanol fuel blends with varying ethanol content and vehicle speed on engine performance, specifically dyno power and torque. RSM was used to develop a model based on experimental test data.

Ethanol fuel blend and vehicle speed were taken as input parameters and modelled using Equation 1, a second-order polynomial equation, while dyno power and torque were the responses. Each *y* response was modelled using a second-order polynomial equation as follows:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum \sum_{i<j} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \varepsilon \qquad (1)$$

The i is the linear coefficient, j is the quadratic coefficient, β is the regression coefficient, k is the number of factors, and ε is a random error with mean zero [15]. Models were evaluated using Analysis of Variance (ANOVA) to determine the significance of the relationship between the input parameters and responses. Additionally, the quality of the models' fit was assessed using the coefficient of determination (R^2). The models were evaluated based on the significance value (p-value) at a 95% confidence level.

3. Results and discussion

3.1. Ethanol and fuel blend properties

One of the limitations of this study is the use of hydrous ethanol instead of anhydrous ethanol. If testing performs well with hydrous ethanol as a blend, it is expected to perform even better with anhydrous ethanol [46, 52]. Table 3, as shown below, is the Physical and Chemical properties of the nipa bioethanol used in this study.

Table 3. Properties of nipa ethanol

Properties	Results	Remarks
Appearance	Clear and bright	Passed
Acidity/alkalinity, pHe	7.2	Passed
Density 20°C, kg/m^3	809.8	Higher
Ethanol content, %v/v	95.63	Lower
Methanol content, %v/v	0.01	Passed
Total acetic acid, %v/v	0.008	Passed
Heating value, MJ/kg	27.23	Higher

As expected, the ethanol purity used in this study, 95.63%, was lower compared to the PNS of 99.3%, but it was slightly higher in terms of heating value. Important to note in this result is the total acid content of 0.008% compared to the PNS 0.007%, which improves the initial study with 0.001% acid content [30, 52], addressing corrosion issues. The minimum 0.01% to the allowed PNS of 0.50% methanol content proved that the nipa-based bioethanol prepared and utilized in this study is harmless compared to the allowed maximum limit.

All hydrous ethanol fuel blends formulated as presented in Table 4 below exhibit slightly lower densities compared to the maximum 915 kg/m^3 allowed with higher water content when compared to the PNS shown in Table 1 above.

The presence of water in hydrous ethanol has a positive influence on combustion characteristics, as shown in Table 4, enhancing octane ratings and reducing the tendency for engine knock [18]. However, hydrous blends have lower heating values, reflecting their reduced energy content per unit of fuel due to the moisture content of the resulting mixture. This impacts fuel efficiency, but is compensated for by a decrease in emissions of particulates and nitrogen oxides, as observed in previous studies on the combustion benefits of hydrous ethanol [6, 20].

3.2. Compatibility comparison of the test motorcycle using the alternative fuel and its blend

The performance curve of the test motorcycle in terms of power versus its speed, both with its stock carburetor and after its modification into MBCE using different fuel blends, is shown in Fig. 4.

Table 4. Physical and chemical properties of fuel blend

Test/analysis	Hydrous alcohol-fuel blend							
	E10	E20H	E30H	E40H	E50H	E60H	E70H	E80H
Density @15°C, kg/m^3	761	765	769	773	776	780	785	789
Ethanol content, %v/v	10.1	19.5	34.82	44.89	56.07	65.43	73.08	82.24
Methanol content, %v/v	< 0.1	< 0.1	0.41	0.34	0.32	0.25	0.17	0.11
RON rating	107.8	108	> 110.0	> 110.0	> 110.0	> 110.0	> 110.0	> 110.0
Vapor pressure at 37.80 kPa	48.5	47.4	45.7	44.6	42.8	40.6	36.6	31.6
Water, %v/v	0.098	0.17	0.244	0.357	0.411	0.527	0.609	0.673
Heating value, gross, MJ/kg	43.26	41.67	39.98	38.3	36.69	35.2	33.74	32.08

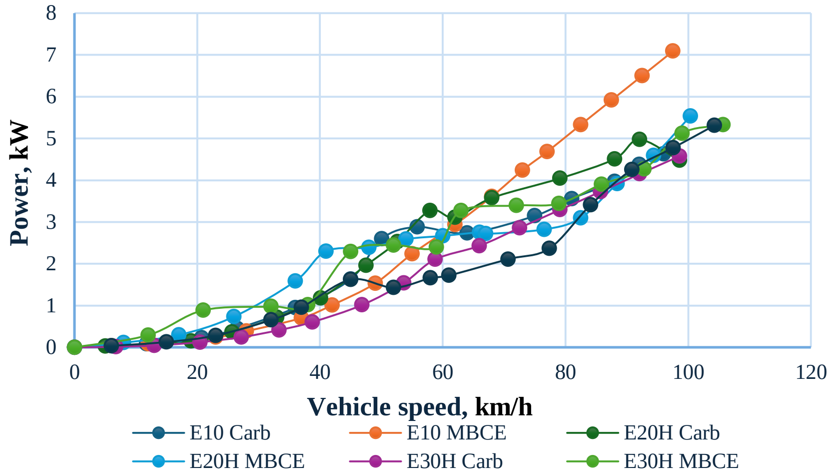

Fig. 4. Performance curve compatibility comparison between carburetor and MBCE-equipped in-use motorcycle

Although MBCE was observed to provide better power performance compared to its speed when compared to Carb, as shown in the figure, it is still considered comparable in terms of performance [42] when hydrous blends are used as fuel. The claim is supported based on the P-value of 0.594, which is greater than 0.05, and the F-value of 0.771, which is less than the F-critical of 2.186.

It is more important to note, as implied in Fig. 4 above, that the test vehicle with its stock carb was only compatible up to E30H, while the MBCE can operate up to E40H.

3.3. Performance of the alternative fuel on the MCBE test motorcycle

In Table 5, the model's evaluation using ANOVA is presented. The models are significant, as indicated by p-values less than 0.05. Thus, the factors have a substantial effect on the responses.

Table 5. ANOVA results for response parameters

Responses	p	F	R^2	Adj R^2
Dyno Power	< 0.01	774.86	0.9594	0.9582
Torque	< 0.01	207.96	0.8683	0.8596
p = significance value; f = f-statistic; R^2 = coefficient of determination; Adj R^2 = adjusted coefficient of determination				

Additionally, the very high R^2 values for both models indicate that they fit the responses well. Mode 1 of MBCE was found to have better power performance, approximately 24.9% better than Mode 2 and 25.45% better than Mode 3. The power output performance refers to dynamometer power.

Equations 2 and 3 below present the second-order polynomial equation for determining the response of dyno power and torque to input parameters. The contour (a) and surface plots (b) were plotted below in Fig. 5 and 6 based on the effect of input parameters on dyno power and torque, respectively.

$$\text{Dyno Power} = 0.284 - 0.02160\ \text{Ethanol Content} + 0.03176\ \text{Vehicle Speed} + 0.000191\ \text{Ethanol Content} \times \text{Ethanol Content} + 0.000220\ \text{Vehicle Speed} \times \text{Vehicle Speed} - 0.000128\ \text{Ethanol Content} \times \text{Vehicle Speed} \quad (2)$$

$$\text{Torque} = 4.81 - 0.1643\ \text{Ethanol Content} + 0.4184\ \text{Vehicle Speed} + 0.001102\ \text{Ethanol Content} \times \text{Ethanol Content} - 0.001814\ \text{Vehicle Speed} \times \text{Vehicle Speed} - 0.000340\ \text{Ethanol Content} \times \text{Vehicle Speed} \quad (3)$$

The succeeding figures, as shown below in Fig. 5 and Fig. 6, demonstrate the flexibility of the MBCE modification in different switch modes capable of utilizing different fuel blends as sustainable engine fuel with decreased fuel economy in km/L, similar to a finding that an increased blend decreases net power [3] and of lower performance [12]. Perhaps due to the diminishing heating values of the increased fuel blends [4, 6, 33].

This trend is also reflected in torque, as shown in Fig. 6, which presents the adverse effect of ethanol on torque. The reduction in torque due to increasing ethanol content is more pronounced and stronger at lower vehicle speeds. This is indicated by the interaction of ethanol content and vehicle speed, where the negative coefficient (–0.000340) slightly reduces torque at high ethanol and high speed, making the ethanol effect more noticeable at lower speeds.

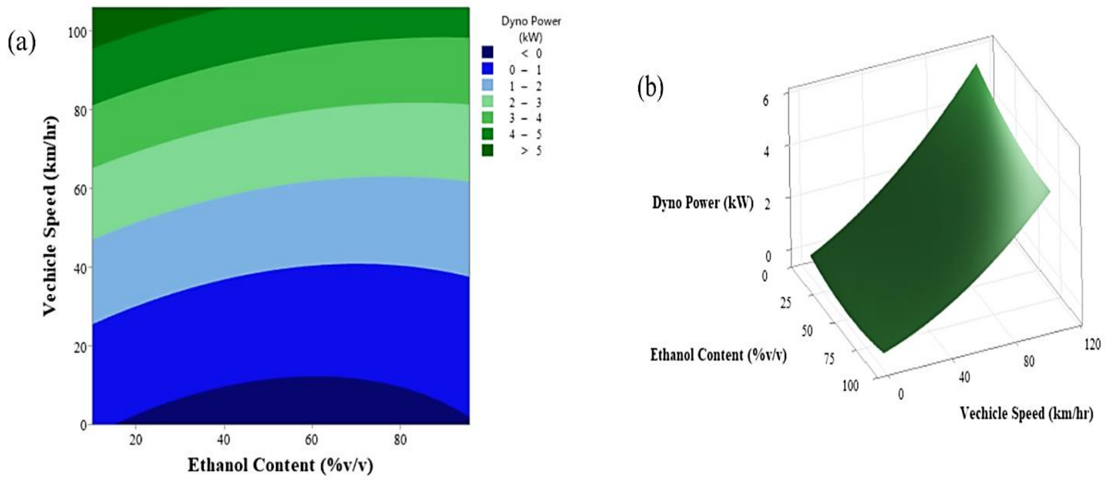

Fig. 5. (a) Contour and (b) surface plot for torque at different ethanol content and vehicle speed

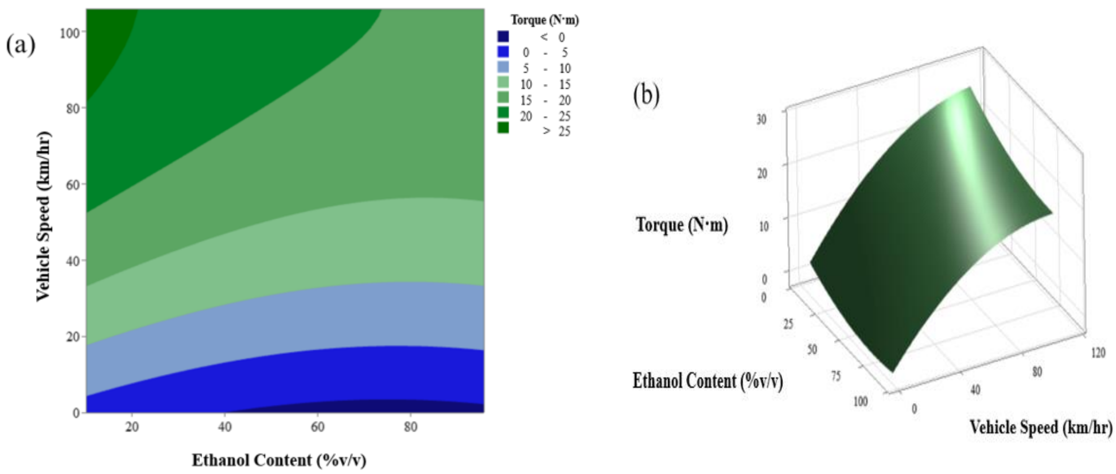

Fig. 6. (a) Contour and (b) surface plot for dyno power at different ethanol content and vehicle speed

Mode 1 of MBCE was found to have a better power performance, approximately 24.9% better than Mode 2 and 25.45% better than Mode 3. The power output performance refers to dynamometer power.

Figure 5a reveals that dyno power is significantly lower at lower vehicle speeds and higher ethanol content. Dyno power tends to reach 5 kW, which corresponds to approximately 61.49% efficiency, based on the 8.13 kW rated power of the test motorcycle with an ethanol content below 40% at around 100 km/h. This is indicated by the negative coefficient for ethanol content (–0.02160), which suggests that increasing ethanol content reduces dyno power. The surface plot in Fig. 5 shows the curve gradually decreasing in dyno power as ethanol content increases.

The trend of decreasing torque as the blend increases, as shown in Fig. 6, is also observed, indicating the adverse effect of ethanol on torque. The reduction in torque due to increasing ethanol content is more pronounced and stronger at lower vehicle speeds. This is indicated by the interaction of ethanol content and vehicle speed, where the negative coefficient (–0.000340) slightly reduces torque at high ethanol and high speed, making the ethanol effect more noticeable at lower speeds.

3.4. MCBE mileage efficiency

Figure 7, as shown below, reflects the performance of the alternative fuel on the MBCE as to mileage economy in kilometres of distance travelled per liter (km/L) of fuel consumed. The MBCE average fuel efficiency in terms of km/lit was measured using a 5 km complete tank method. Trials included two minutes of idling per trial to simulate traffic and city driving, conducted inside the MMSU campus.

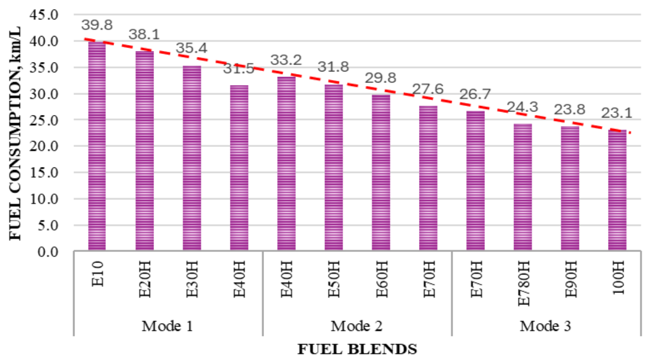

Fig. 7. MTBCE fuel consumption at different modes and fuel blends

The Honda XR125 MBCE's mileage of approximately 40 km/hr, observed using E10 under Mode 1, was close to the mileage of motorcycles in the Philippines. However, the figure implies that as the blend increases with ethanol percentages, its fuel economy decreases, as indicated by the sloping red line trend. The fuel efficiency, in terms of mileage, decreases by approximately 7.76%, 6.15%, and 4.86% for Modes 1, 2, and 3, respectively, for every 10% increase in ethanol content. The said decrease in mileage efficiency was expected due to the lower heating value of the resulting blends [59] as observed in Table 4 above.

3.5. MCBE tailpipe emission using the alternative fuel

In compliance with SDG 7, clean and affordable energy, biofuel offers clean emissions, as implied in Fig. 8, through the decrease in emissions of hydrocarbons (HC) and carbon monoxide (CO), gases known to cause respiratory problems and carcinogens when released into the surroundings [35].

The decreasing amounts of HC and CO, but with increasing CO_2 emissions, as shown in Figs. 8a to 8c, are signs of better combustion in higher fuel blends [48]. Although E10 already has a very low HC emission of 867 ppm, the emission of every blend continues to decrease, reaching 154 ppm from E10 to E100H, as shown in Fig. 8a. The same observation was noted in Fig. 8b regarding CO emissions, which continuously decrease from 6.46% to 0.98% as E10 to E100H is used, respectively. The HC emissions are very low compared to the Euro 4 standard of 1000 ppm and the 4500 ppm limit [34] on all fuel blends. For CO% emissions, only blends from E80H to E100H passed the CO allowed emission of 2.5% set by the government [34, 44]. Figure 8 shows emission characteristics of MBCE using different fuel blends.

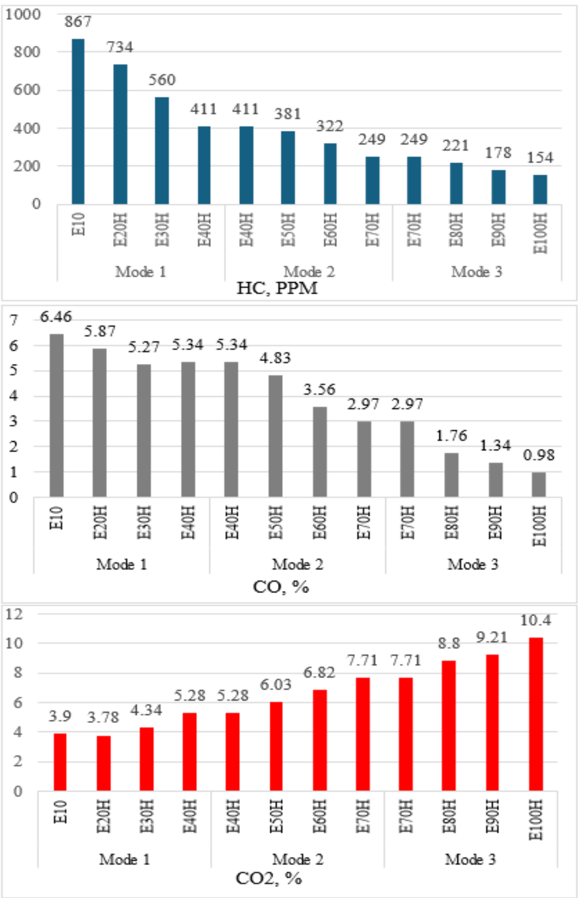

Fig. 8. Emission characteristics of MBCE using different fuel blends

This CO_2 emission can be neutralized by planting trees, as suggested in urban and roadside areas [2]. This can also be adopted in cities in the Philippines. The CO emission can be improved through adjustment of the A/F ratio [33]. The A/F during MBCE testing is more compatible with 11–13 than with the ideal A/F of 14.7.

3.6. Total carbon footprint of fuel blends

Reflected below in Table 6 is the total quantification of CO_2 emissions when used as fuel in the MBCE. The gCO_2e/L increases as the blend increases by 6% of the emission for every 10% increase in the blend. The fuel blend's CO_2 quantification used in this study was estimated using the Life Cycle Analysis (LCA) emission of gasoline equal to 2.735 $kgCO_2e/L$ from well to wheel [31] obtained from 85 gCO_2e/MJ, 43.2 MJ/kg HV, and 745 kg/m^3 petrol density, which is slightly higher than the study considering 2.4 $kgCO_2e/L$ [13]; and the hydrous nipa-based bioethanol emission of 0.2353 $kgCO_2e/L$ to 5.1887 $kgCO_2e/L$ from nipa sap collection to utilization [29]. It is important to note that nipa-based total carbon quantification is lower than that of petrol, referring to the minimum value of nipa hydrous bioethanol. Still, it results in greater emissions due to its higher limit compared to petrol emissions (0.2353 < 2.735 > 5.1887 $kgCO_2e/L$).

As to emissions in terms of gCO_2/km, Table 6 also implies a comparable emission factor 76 gCO_2e/km based on the testing conducted on the MBCE when compared to the 82.2 gCO_2e/km used to estimate the Global Warming Potential (GWP) of CO_2 on motorcycles in Turkey using petrol [8], and in Taiwan at variable mileage at 1838–2098 gCO_2/km [50]. Using pure hydrous ethanol as fuel with 225 gCO_2e/km is still low considering the MBCE in this study.

4. Conclusions

In this study, an MBCE motorcycle was evaluated to determine the potential problems associated with the use of higher fuel blends in gasoline engines, particularly in terms of engine drivability and compatibility issues in motorcycles equipped with carburetor and EFI systems.

Table 6. Total CO_2e of MCCE on various fuel blends

CO_2e	Fuel blend									
	E10	E20H	E30H	E40H	E50H	E60H	E70H	E80H	E90H	E100H
gCO_2/L	3012	3231	3597	3844	4114	4342	4531	4757	4944	5189
gCO_2/km	76	85	102	122	129	146	164	178	208	225

It was found that the MBCE in its stock carb is only compatible up to E30H without adjustments, while the EFI based on the MBCE is compatible up to E40H. It suggests that to utilize higher fuel blends that include ethanol as a pure engine fuel in EFI, the remapping procedure must be performed on the ECU to make it compatible. In contrast, this study used three different mode switches. The carb type can be compatible only up to 40% blend after carb setting adjustments. Regarding the performance of the MBCE, its power curve showed a decrease of 24.9% and a 25.45% difference in Mode 2 and Mode 3, respectively, compared to Mode 1. The fuel efficiency in terms of mileage was also found to decrease by about 7.76%, 6.15%, and 4.86% for Mode 1, Mode 2, and Mode 3, respectively, using the percentage difference among the blends for every 10% increase in ethanol fuel blends. The exhaust gas emissions are found to be more environmentally friendly, with HC reducing its emissions from 867 ppm to 154 ppm, and its %CO emission decreasing from 6.49% to 0.98%, meeting the Euro standards of 1000 ppm and 2.5%, respectively. The emission factors of 76 gCO2e/km to 225 gCO2e/km for different blends found in this study can be used to estimate GWP. Based on the results, it is recommended that the country can safely proceed to implement fuel blends up to E30H and E40H after the carburetor type motorcycle's system is adjusted or modified to MBCE. Further testing must be conducted on cars and other petrol vehicles.

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Nomenclature

Carb	carburetor/carbureted
E	anhydrous ethanol
EFI	electronic fuel injection
E10-E100	ethanol-gasoline blend using anhydrous ethanol, number =% ethanol
E10H-100H	ethanol-gasoline blend using hydrous ethanol, number =% ethanol
Fcritical	critical F-value for comparison
F-value	calculated F-statistic from ANOVA
H	hydrous ethanol
MBCE	multi-blend capable engine
P-value	probability value

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