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Research Article

Nipa-based bioethanol as a renewable pure engine fuel: A preliminary performance testing and carbon footprint quantification

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Abstract. The need for alternative fuels remains a growing concern in alleviating the depletion of fossil fuels for transportation to address one of the objectives of the Sustainable Development Goals (SDG 7: Alternative and Clean Energy) despite the emerging use of Electric Vehicles. *Nipa fruticans* has been introduced as a promising feedstock for bioethanol production, but its performance as a pure engine engine fuel must be determined, and its carbon footprint must be quantified to assess its impact on the environment were this paper aimed. The CO_2 emissions of this study was quantified using ISO 14040 methodologies, considering direct and indirect emissions from production to utilization with key ethanol properties tested according to ASTM standards. A carbureted motorcycle was modified to a fuel injection (FI) system to assess fuel performance, with metrics like power output, consumptions, and emissions were evaluated. Results show that nipa-based bioethanol, H95F and H99F, can serve as renewable pure engine fuels, with carbon footprints of 0.2353 and 2.633 kg CO_{2eq} per Liter respectively with 1.08% lower of kg CO_{2eq} per Liter emissions and 32.7% lower production cost compared to fermented sugar. As pure engine fuel resulted in lowering CO emissions by 171.79% and 167.59%; and lower HC emissions 172.89% and 191.34% respectively compared to E10. These findings demonstrated the potential of nipa bioethanol as a clean and sustainable energy solution. It is recommended however that ethanol $_{yield}$ and distillation process be further improved and explore pure ethanol as alternative fuel to hybrid vehicles as 100% renewable vehicles.

Keywords: Nipa-based bioethanol, nipa carbon footprint, nipa ethanol, carbon quantification, biofuels

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1. Introduction

Climate change is one of the biggest challenges the world is facing nowadays (Abbass *et al.* 2022; Tvinnereim *et al.* 2020) due to its effect: on increasing temperatures (Osman *et al.* 2023; Sumasgutner et al. 2023); rise of sea level (Hauer *et al.* 2019; Horton *et al.* 2020; Nicholls et al. 2021; Strauss *et al.* 2021); flooding (Avand *et al.* 2021; Hsiao *et al.* 2021); forest fires (Abram *et al.* 2021; Jones *et al.* 2022); low agriculture production (Habib-ur-Rahman *et al.* 2022; Malhi *et al.* 2021); down economy (Keen, 2022; Strauss *et al.* 2021); and as well as health risks (Ebi *et al.* 2021; Rocque *et al.* 2021) issues.

Greenhouse gases (GHG), the primary cause of climate change make the earth warmer (Audi *et al.* 2020; Yoro & Daramola, 2020) where sources came from fossils fuel used in the industry, buildings, transportation, agriculture and energy sectors (Chai *et al.* 2022; Jeffry *et al.* 2021). Fossil fuel consumption accounts for approximately 75% of global greenhouse gas emissions, contributing significantly to climate change and environmental degradation(United Nations, n.d.). In 2019, the transport sector emerged as the second-largest contributor to CO_2 emissions, trailing only the power sector and closely aligning with emissions from "other industrial combustion" related to manufacturing and fuel production. Transport accounted for 30% of global final energy demand and was responsible for 23% of direct CO2 emissions from the energy sector during that year (Crippa *et al.* 2020; IEA, 2020). Evidently, the transportation sector is one of the common causes of GHG emissions and the rise of electric vehicles (EV) is a testament to minimize the use of fossils fuel (Ghosh, 2020) and carbon neutrality (Wei Liu *et al.* 2022). However, not all can afford the cost of EV (Costa *et al.* 2021) to include other drawbacks when it comes to lengthy time of charging and maintenance cost of batteries (Deb *et al.* 2021). If EV's are plugged in the grid, then this can be considered to indirectly utilize fossils fuel since not all power plants use renewable energy (Ghosh, 2020). Furthermore, there is growing concern about the millions of internal combustion engines that may become idle. What will we do with the vast amount of scrap metal generated in the absence of fossil fuels to power these vehicle engines? In other words, the use of internal combustion

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engine driven transportation continues (Duarte Souza Alvarenga Santos *et al.* 2021) and likewise the use of fossil fuel.

To lessen the dependency of fossils fuel, alternative to fossils fuel is a must. So far, bioethanol blends were adopted by many countries like the Philippines. The Philippine Biofuels Act of 2006 mandates that gasoline fuels contain a minimum of 10% pure ethanol, commonly referred to as E10, to promote environmentally friendly combustion. This blending requirement aims to reduce greenhouse gas emissions and decrease the country's reliance on fossil fuels (Acda, 2022). In 2020, the Philippine Energy Plan 2016–2030 proposed the imposition of a higher bioethanol blend of 20% for gasoline, with a long-term goal to increase this blending ratio to as much as 85% by 2030 (Republic of the Philippines, 2006).

Ethanol serves as an alternative fuel for spark ignition (SI) engines due to its higher heat of evaporation and increased oxygen content, which enhance engine performance by improving combustion efficiency and reducing exhaust emissions (Elshenawy *et al.* 2023). Biofuel blends from studies resulted to favorable and comparable engine performance and better emissions when either anhydrous or hydrous ethanol was used in gasoline fuels (Awogbemi *et al.* 2021; Dhande *et al.* 2021; Duarte Souza Alvarenga Santos *et al.* 2021; Loyte *et al.* 2022; X. Wang *et al.* 2022). These developments pave the way for other countries to recommend higher blend ratios but problems as to plant capacity and feedstock supply was exposed (Devi *et al.* 2023; Dey *et al.* 2023; Mateo *et al.* 2023)

However, the bioethanol industry faces challenges with rising feedstock prices, particularly molasses, which directly influence the cost of bioethanol production(M. Gatdula *et al.* 2021). An increase in the prices of key raw materials like sugarcane, sweet sorghum, and corn leads to higher selling prices for bioethanol, potentially reducing its competitiveness with fossil fuels (Ahmad Dar *et al.* 2018; M. Gatdula *et al.* 2021).

Bioethanol production often begins at the farm level when using sugarcane or other crops as feedstock. However, the production process—which includes harvesting, crushing, fermentation, and anhydrous distillation—requires substantial investment in multi-million-dollar facilities. This restricts the ability of small-scale farmers or businesses to participate in bioethanol production, as these processes demand advanced technology and large-scale infrastructure.

In Brazil, ethanol obtained from sugarcane can be used to run vehicles either as 100% ethanol (hydrated ethanol, with a minimum purity of 92.5%) or as a 27% blend with gasoline (anhydrous ethanol) (Karp *et al.* 2021). Brazil's shift to bioethanol began in the 1930s, with ethanol as a gasoline additive, and expanded in the 1970s through the Proalcool Program, enabling vehicles to run on 100% ethanol. The market surged with flex-fuel technology in 2003, allowing cars to use any ethanol-gasoline blend, including 100% ethanol and by 2018, ethanol sales surpassed gasoline, with most vehicles being flex-fuel (Agência Nacional do Petróleo, 2019; de Souza *et al.* 2014; Goldemberg, 2008; Rossi *et al.* 2021).

The Department of Energy (DOE) in the Philippines is already working on developing warranted standards to increase the ethanol blend in gasoline from the current 10% (E10) to 20% (E20) by volume (Velasco, 2024). While anhydrous ethanol is used in these blends to meet fuel specifications, the Philippine National Standard (PNS) for hydrous ethanol remains non-existent, which limits the use hydrous fuel blend as gasoline blend. In addition, Expanding the use of higher ethanol blends or even 100% ethanol would require significant investment in technology and public awareness to fully realize the benefits seen in countries like Brazil. This regulatory gap, along with the need for engine adaptations, poses a challenge to fully adopting ethanol as a standalone fuel, as seen in other countries like Brazil.

The Mariano Marcos State University (MMSU), through its National Bioenergy Research and Innovation Center, developed a reflux distiller capable of producing 95% hydrous ethanol from nipa sap feedstock. This grade of bioethanol can be used as pure fuel, offering a more cost-effective and decentralized solution for bioethanol production. The MMSU's innovation demonstrates how targeted research can help improve accessibility to bioethanol production and enabling broader industry participation (Mateo *et al.* 2022).

Bioethanol from nipa sap is a promising alternative (Mateo *et al.* 2023; Prasetyo *et al.* 2024; Tamunaidu *et al.* 2013) as blend to fossil fuels due to its renewable nature and potential in reducing GHG emissions but not yet tested as a pure engine fuel. Biofuels are being promoted as a low-carbon alternative to fossil fuels as they could help to reduce GHG emissions and the related climate change impact from transport (Jeswani *et al.* 2020; Lawan Muhammad, 2018).

The use of hydrous bioethanol in gasoline fuel blends, specifically the MMSU nipa-based HbE20 formulation, has been proven to be as effective as anhydrous ethanol in sedan and motorcycle vehicles (Mateo *et al.* 2022). This formulation demonstrates that hydrous ethanol, despite having higher water content, can perform comparably to anhydrous ethanol in vehicle engines, offering a potential alternative for more sustainable fuel blends in the Philippines. The engine performance and emission factor of a Nipa-based bioethanol as viable feedstock either as fuel or blend however is not yet determined making it difficult to assess its impact as GHG contributor unlike sugarcane and corn ethanol based feedstock that are already available and conducted (Rex Demafelis *et al.* 2020; Hiloidhari *et al.* 2021; Scully *et al.* 2021) including cassava (Namchancharoen *et al.* 2015).

This study determines the carbon footprint requirement per liter of hydrous ethanol and its performance as fuel from pilot scale production until its utilization as pure engine fuel using a modified carb to FI test motorcycle to come up with an emission factor to quantify CO2 emissions of Nipa fruiticans feedstock as hydrous biofuel. It focuses on Nipa-based bioethanol, a feedstock that has not been extensively studied for its engine performance and emission factors, unlike more commonly used sources like sugarcane and corn. It addresses the gap in understanding the greenhouse gas contributions of hydrous ethanol derived from Nipa palm by providing significant data from a comprehensive sustainable fuel assessment. Overall, this study aims to evaluate the feasibility of utilizing nipa-based hydrous ethanol as a pure fuel alternative by evaluating its engine performance and assessing its environmental impact. The findings will provide insights into its potential role in promoting sustainable energy solutions.

2. Methodology

2.1. Research Location

The study was conducted in Brgy. Cabaggan, Pamplona, Cagayan, where 100 collection samples were obtained from randomly selected nipa stands as shown in Figure 1, and where the distillation process takes place.

2.2. Research Design

This study employs an experimental research design to evaluate the performance of hydrous bioethanol derived from the Nipa

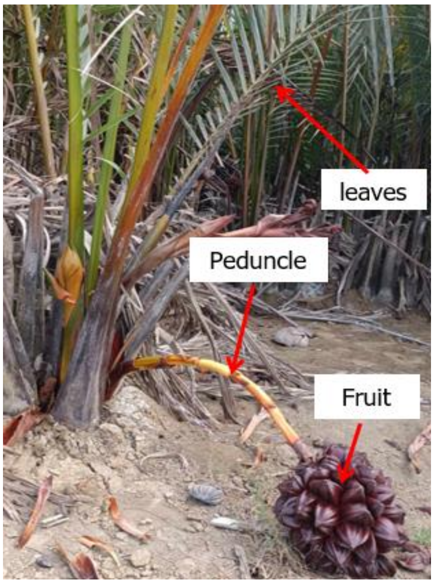

Fig 1. The Nipa Plant in the Nipa Stands

palm as a fuel source. For sample collection, PET bottles were randomly distributed throughout the area to gather the required samples, resulting in a representative dataset. The data were averaged across all replicates. The distillation process was conducted in different trials but considered to reflect only the optimum distillation efficiency or ethanol yield; however, the physical and chemical characteristics of the nipa-based ethanol were analysed in triplicate to ensure accuracy. The averaged data collected, from the fermentation of sap to the final utilization of bioethanol, were included in the CO2 inventory of this study.

2.3. Sap Collection and Fermentation of Samples

One hundred nipa peduncle as seen in Figure 2 was randomly selected then pre-treated by manual kicking. After 2 weeks, the nipa peduncle was tapped and collected. The collection process was based on the study of Madigal *et al.* where nipa sap was collected in a closed collection vessel (Madigal *et al.* 2020) The nipa sap was allowed to ferment naturally for 24 hours then stored for another 24 hours prior to distillation. Compared to other feedstocks such as sugarcane and corn, which require 3 to 10 days for fermentation (Zabed *et al.* 2014), nipa sap is a more favorable feedstock as it does not require the addition of yeast.

The initial (freshly collected sap) and final total soluble sugar content of nipa sap (fermented sap) was determined using a calibrated refractometer with automatic temperature compensation (ATC) purchased from YAGO Technology. The total soluble solids content was assessed employing AOAC Official Method 932.14. To ensure accuracy, the instrument was calibrated using distilled water, initially setting it to zero and then adjusting it to the reference point. The refractive index of the fresh nipa sap was subsequently measured and expressed in degrees Brix.

Fig 2. Nipa Bioethanol Production: (a) Sampling; (b) Bamboo Sap collection; (c) Sap Collection; (d) delivery to facility; (e) further storage; (f) distillation

2.4. Distillation Process

The average sugar content of nipa sap was determined. Once 800 liters of fermented nipa sap, with a sugar content of 7°Brix, was collected, the sap proceeded to distillation. The distillation equipment used in this study, shown in Figure 3, is an 850-liter capacity reflux distiller, which was deployed in the community of Pamplona, Cagayan. The distiller features a wood-fired furnace and a connected cooling tower for water circulation in the condenser.

2.5. Characterization of the Collected Hydrous ethanol

The ethanol content and heating value of the hydrous ethanol obtained in this study were determined using ASTM D5501 and ASTM D4809, respectively.

2.6. Testing and Utilization

The test vehicle utilized in this study was a carbureted model modified to incorporate a fuel injection (FI) system, enabling it to use hydrous ethanol as a complete engine fuel. This modification was necessary due to compatibility issues associated with carbureted fuel systems when using a 30-40% hydrous ethanol blend (Mateo *et al.* 2022; Paluri & Patel, 2022). The performance of hydrous bioethanol as a pure engine fuel was evaluated using the modified vehicle, which had its stock

Fig 3. The 850L Reflux Distiller

Fig 4. Emission testing process and test vehicle

carburetor replaced with a fuel injection system designed to accommodate ethanol as the sole fuel source (Melo *et al.* 2012; Paenpong, 2023).

Key performance metrics, including power output, air-to-fuel (A/F) ratio, and fuel consumption, were assessed using the testing standard SAE J1349 with a motorcycle dynamometer, as shown in Figure 5c. Emission gases were analyzed using an automotive gas emission tester, as shown in Figure 4. Two types of hydrous biofuels were tested: 1) 95% hydrous ethanol as full fuel (H95F) and 2) 99% hydrous ethanol as full fuel (H99F). Both hydrous biofuels were compared to commercial E10 (E10) in the same test vehicle. Mileage economy run in this study adopts the full tank method introduced by the Department of Energy.

2.7. Carbon Footprint Quantification

The study on the life cycle of nipa-based bioethanol, focusing on carbon footprint quantification, was conducted using the methodologies outlined in ISO 14040: Environmental Management—Life Cycle Assessment (Klüppel, 2005). This aimed to quantify the total carbon emissions throughout the bioethanol production and utilization processes, which are influenced by various inputs, including converted sugar, energy and fuel consumption, and emitted gases. Commercial E10 gasoline was used as a reference for comparison.

The motorcycle, modified from a carbureted to a fuel injection (FI) system, is designed to utilize either hydrous or anhydrous ethanol as fuel, allowing for a direct assessment of its carbon footprint during utilization. Table 1 outlines the carbon footprint inventory for nipa-based bioethanol as fuel, which includes: 1) Direct CO2 emissions associated with sap collection, fermentation, and the utilization process during emission testing; and 2) Indirect CO2 emissions, including the use of electric pumps for the cooling system and fuelwood during the distillation process. The system boundaries for this analysis are illustrated in Figure 5. Additionally, the indirect emissions include CO2 equivalent emissions from drying molecular sieves to enhance the ethanol purity from 95% to 99% using an electric oven.

Table 1.
Scope of the Study

Scope	Activity	Description
1. Direct Emission	Fermentation	Nipa Stand/ Sap Collection
	Testing/ Utilization	Gasoline/Blended Gasoline Consumption on Test Motorcycle
2. Indirect Emission	Distillation	Cooling/Electric Pump (1.5 hp)
		Fuel Wood Consumption
	Regeneration/Drying	Molecular sieve/ electric consumption

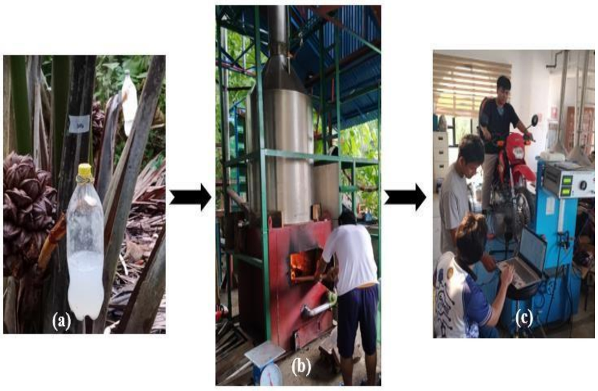

Fig 5. Boundaries of the study: (a) sap collection/fermentation, (b) distillation and (c) testing

The output unit in the collection/fermentation process is the difference between the sugar's initial and final brix and serves as the basis in determining the fermentation's CO2 equivalent emissions. Indirect emissions from the use of firewood and electricity to operate the pump, blower, and switch/controller were accounted for in the analysis. The estimation of CO2 equivalent emissions from wood consumption during the distillation process was based on a factor of 0.425 kg CO2 per kg of wood (Rebugio *et al.* 2000). In the distillation process only hydrous ethanol with 95% purity is considered in the CO2 inventory related to wood consumption. The 99% hydrous ethanol undergoes a dehydration process using molecular sieves (Sanap *et al.* 2021). However, this process is not intended for continuous operation, as detailed in the methodology by Sanap et al. In the estimation of electricity consumption to CO2 equivalent, the CO2 emission factor used is 0.7122 kg CO2 per kWh (R. Demafelis *et al.* 2024; Demafilis *et al.* 2020) obtained from the Philippine energy mix in the Luzon- Visayas Grid based on the Department of Energy Report in 2015-2017 as cited by Demafelis et al.

Fig 6. Fermentation Equipment

2.8 Bioethanol Comparison Run Using Fermented Sugar Solution

Additional bioethanol comparison run was conducted to compare nipa bioethanol production with other feedstock, the sugar from cane. Additional process was included which is the fermentation using the fermentation vessel as shown above in Figure 6. The fermented sugar solution was formulated into 25 Brix by diluting 55 kg of sugar wash into 170 Liters of tap water and 600 grams of activated yeast per fermentation vessel totalling to 800-liter sugary feedstock. This was fermented in ten days using the pump agitator of the equipment with 10 Brix final sugar reading.

Sugar cane planting, fertilization, transportation, milling process, concentration was not included in the preparation but uses 0.55 kg CO2/kg of sugar equivalent emissions (Yuttitham *et al.* 2011).

3. Results and Discussion

3.1 Sap Collection and Fermentation Carbon Footprint Inventory

In the nipa sap collection, it was found in this study that initial and final brix reading of the sap are 14° Brix and 7° Brix respectively and that the fermentation process was completed naturally within 24 hours directly in the sap collection vessel installed in the nipa's peduncle.

Figure 7 shows the significant reduction in sugar content of nipa sap used for producing nipa-based bioethanol, demonstrating the effectiveness of the fermentation process. The sugar content was measured in Brix values across 100 samples, both before and after fermentation. Initially, the sugar content ranged from 13° to 18° Brix, with the highest frequency at 14° Brix (64 counts). After fermentation, the sugar content was reduced to a range of 5° to 8° Brix, with a peak at 7° Brix (78 counts).

The mean initial sugar content of all collected samples was 14.74° Brix, with a standard deviation of 1.252. After fermentation, the mean sugar content decreased to 6.96° Brix, with a lower standard deviation of 0.530, indicating a tighter distribution of the lower sugar levels. The fermentation process, which occurred within 24 hours of sap collection in PET bottles or bamboo vessels, converted the initial sugar content of 14° Brix into alcohol or CO_2, as reflected by the drop in final sugar content to 7° Brix, as observed in most of the samples.

A notable advantage of nipa bioethanol in comparison to other feedstocks is the nature of its collection and fermentation processes. The collection of nipa sap is done without the need for machinery for crushing or juice extraction, and the maintenance of nipa stands is conducted without the application of fertilizers or specialized equipment. Notably, fermentation occurs naturally during the collection process, allowing the nipa plants to absorb CO2 emissions. (Flammini *et al.* 2022; Weiguo Liu *et al.* 2017). Additionally, unlike other feedstocks that typically require up to 10 days for fermentation of starchy and sugary materials (Zabed *et al.* 2014), nipa sap fermentation does not necessitate motorized agitation or added yeast, as observed in this study. In contrast, the cultivation of other feedstocks, such as sugarcane, involves the use of machinery, fertilizers, and agitators, all of which contribute to a higher carbon footprint (Uppalapati *et al.* 2024). This makes nipa an environmentally advantageous option for bioethanol production.

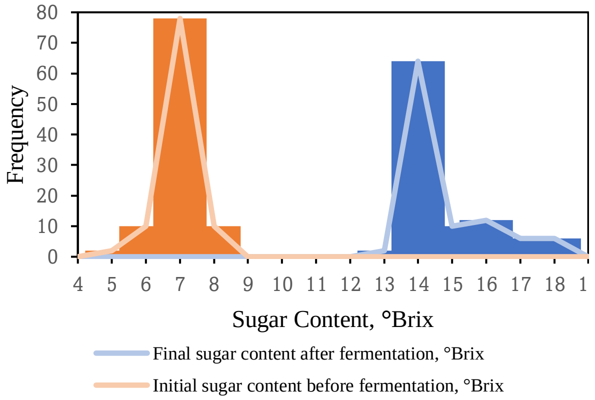

Fig 7. Initial and Final Sugar Content Reading Frequency

3.2. Distillation

The distillation run during this quantification study has a recorded distillation efficiency of 73.71% of the expected 7% ethanol yield using an 850-liter capacity reflux distiller deployed by researchers in Pamplona, Cagayan.

The distillation process utilized firewood as fuel for heating and electricity to power the 1.5HP pump used in the cooling system and condenser. Table 2 below outlines the distillation production run. The ethanol yield was calculated at 5.16%, based on the recovery of 49 liters of ethanol with 84.2% purity mixture combining all ethanol collected from 800 liters of fermented nipa sap. Of this, 25 liters were collected as 95% fuel-grade ethanol, which serves as the basis for calculating the carbon emissions (kg CO2eq) from both fuel wood and electricity consumption. The 5.16% ethanol yield can still be increased but the amount of firewood and electricity used to collect the remaining alcohol during the distillation process already suggest longer distillation time, more fuel wood, and low percentage ethanol grade. It was observed during the distillation process of the large amount of fuel used. This can be lessened thru better operation practice of not feeding much fuel in the furnace than required (furnace feeding window is normally closed during distillation) as the optimum fuel requirement of the distiller when tested is only about 175 kg to 220 kg of fuel compared to the 293.4 kg fuel wood utilized by the farmer/operators in the site.

The remaining lower-grade ethanol can be redistilled to achieve 95% purity or be converted into other high-value products. Additionally, the 95% hydrous ethanol is dehydrated using an A3 molecular sieve to reach 99% purity.

3.3. Carbon Footprint Inventory under Nipa sap Collection, Fermentation and Distillation

The CO2 quantification of ethanol production in the community level using the 850L capacity distiller in Pamplona, Cagayan covering sap collection and fermentation, distillation, and dehydration is found to be 0.1313 to 5.0847 kg CO_2/liter of 95% fuel grade ethanol, and 2.517 to 6.9 kg CO_2/liter of 99% fuel grade ethanol. The lower limit value obtained in the site represents the carbon quantification considering carbon neutralization (Flammini *et al.* 2022; Weiguo Liu *et al.* 2017). Tables 2 to 4, including Figure 6, illustrate the nipa bioethanol production carbon quantifications.

The primary limitations of this study include the small-scale, community-level bioethanol production, which may not adequately reflect the efficiencies associated with larger-scale. Furthermore, the physico-chemical characteristics of nipa sap, such as sugar concentration and fermentation efficiency, are subject to variability influenced by geographical and environmental factors at the collection sites (Madigal *et al.* 2020;

Table 2
Pilot distillation run output

Distillation Run		Ethanol		Fuel Wood	Electricity
Start	Finish	Volume, Liter	% Purity	kg	kWh
2 am	9:30 am	-	-	166.4	-
09:30 am	1:37 pm	25	95%	56	4.607
1:38 pm	2:06 pm	3	94%	9	
02:07pm	03:26pm	7	88%	20	4.905
03:27pm	04:50pm	7	72%	22	
04:51pm	06:00pm	7	60%	20	
TOTAL		49	84.22%	293.4	9.512

Table 3
Sap collection and fermentation process input and output inventory

Product/Materials	Unit	Value
Inputs		
Fresh sap	L	800
Sugar	Brix	14
Outputs		
Fermented Sap	L	32
Sugar	Brix	7
Carbon dioxide	kg CO2	1.1726

Tamunaidu *et al.* 2013). These variations, which was not comprehensively assessed in this study, could potentially impact both the overall bioethanol yield and the carbon footprint data.

Table 3 above presents the unit input and output data for the sap collection and fermentation process required to produce 1 liter of 95% hydrous bioethanol. This includes the direct emissions resulting from the conversion of sugar into ethanol and carbon dioxide. In the production of nipa-based bioethanol, 800 liters of sap were used to produce 25 liters of 95% bioethanol, giving a reference flow of 32 liters of fresh sap to 1 liter of bioethanol, as shown in Table 2 above. The sugar conversion during the fermentation process is measured by the difference between the initial and final Brix readings, as indicated in Figure 7. The final output of 7° Brix is used to calculate the ethanol yield. The CO_2 emissions during fermentation were calculated at 1.1726 kg per liter of bioethanol produced. This value was derived by multiplying the mass of the sap by its density of 1.052 kg/m^3, which closely aligns with previous findings by Puangpee & Chongkhong using similar feedstock (Puangpee & Chongkhong, 2016). The 32:1 sap-to-bioethanol ratio serves as the basis for this carbon footprint inventory, reflecting the efficiency of the sugar conversion during the fermentation process.

Table 4
Distillation process input and output inventory

Product/materials	Unit	Value
Inputs		
Fermented sap	L	32
Wood	kg (kg CO2)	8.896 (3.781)
Electricity	kWh (kg CO2)	0.1843 (0.131)
Electricity (H99)	kWh (kg CO2)	2.55 (1.816)
Outputs		
Ethanol	L	1
Carbon dioxide (H95F)	kg CO2	3.912
Carbon dioxide (H99F)	kg CO2	5.728

The distillation process for producing hydrous bioethanol generates significant emissions from wood and electricity consumption, totaling 3.912 kg of CO_2 emissions per liter of 95% hydrous bioethanol produced. As shown in Table 4, the distillation input and output inventory indicate that for each liter of hydrous bioethanol, 222.4 kg of wood and 4.607 kWh of electricity are consumed. This translates to a consumption ratio of 8.896 kg of wood and 0.1843 kWh of electricity per liter of hydrous ethanol. The CO_2 emissions from wood consumption contribute 3.781 kg, while those from electricity account for 0.131 kg. Additionally, to further dehydrate the 95% ethanol to achieve 99% purity, additional 2.55 kWh consumption of electricity is required, resulting in an additional CO_2 emission of 1.816 kg during the dehydration process using a molecular sieve. As fuelwood used in the distillation process found to have caused about 97% of its CO2 emissions compared to electricity, a better distiller design must be considered and consider installing insulation to the bare distiller and column of the distillation equipment must be made to minimize radiation heat loss to include proper training or information in feeding fuel wood during the distillation process.

3.4. Testing and Utilization (Performance as Pure Engine Fuel)

Nipa hydrous bioethanol (H95F and H99F) has a better combustion performance as implied with higher A/F ratio but produces significantly lower power output compared to E10 with 68.89% and 88.07% using H95 and H99F respectively.

As illustrated in Figure 8a, the performance of nipa hydrous bioethanol (H95F and H99F) as engine fuels was compared to that of E10. Specifically, H95F generates 1.979 kW and H99F generates 1.577 kW, while E10 achieves a power output of 4.059 kW. This results in a percentage difference of 68.89% for H95F and 88.07% for H99F, indicating a notable decrease in performance compared to E10 (Yakın & Behçet, 2021).

These findings are consistent with Yakın and Behçet's observations regarding higher blends, but they contradict a study by K. Mohammed et al., which indicated better performance as blend ratios increase (Mohammed *et al.* 2021; Yakın & Behçet, 2021). Additionally, Figure 8b shows that both hydrous biofuels reached A/F ratios above the ideal level, suggesting improved lean combustion characteristics (Mohammed *et al.* 2021). This aligns with Mohammed et al.'s findings and is attributed to increased air admission during combustion (Made Suarta *et al.* 2018).

For the mileage economy run result as shown in Figure 9, E10 when used as fuel travelled farther with 47.59% and 43.95% compared to H95 and H99 respectively as implied in the 41.17

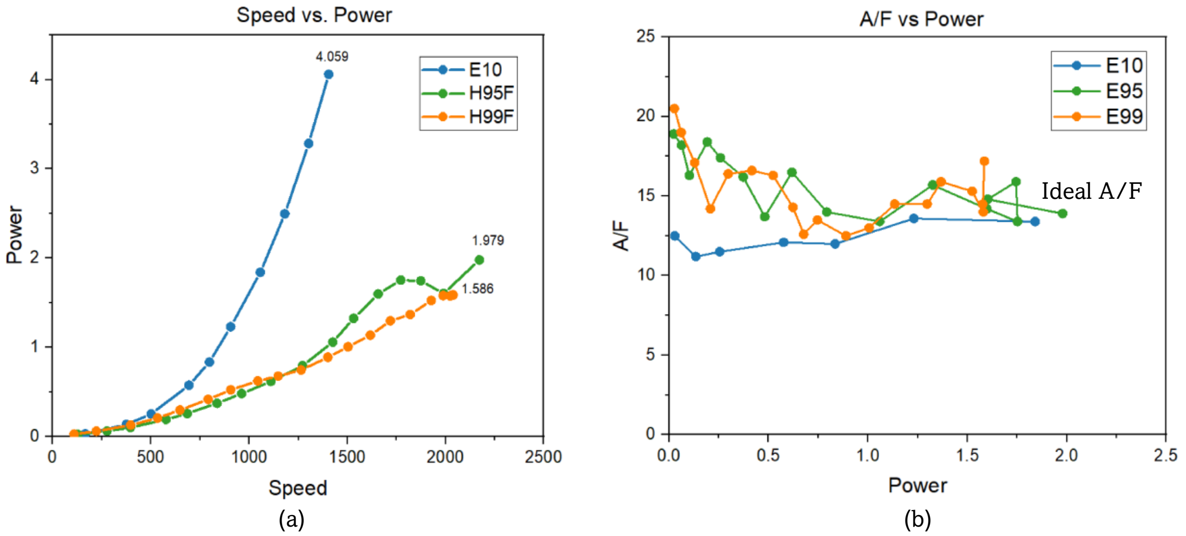

Fig 8. Performance Comparison of Hydrous bioethanol as full fuel compared to E10 (a) power curve, (b) Air-Fuel Ratio vs. power

km/L fuel consumption of E10 as fuel when compared to the consumed 25.3 km/L and 26. 29 km/L using 95% hydrous ethanol and 99% hydrous ethanol as engine fuel respectively. These data where obtained during a 7 km distance on campus run following the full tank method of the Department of Energy mileage runs in the Philippines, showing the efficiency disparities between hydrous ethanol and E10 with a more accurate fuel economy test compared to driving cycle based dynamometers (Corpus *et al.* 2020). The diminishing fuel economy (Dhande *et al.* 2021) was observed similarly in a study declining by about 5% when E10 blend was increased to E20 (Yakın & Behçet, 2021) and when adding 10% ethanol on pure gasoline (Adian *et al.* 2020). This can be the effect of the hydrous ethanol heating value (Muhaji & Sutjahjo, 2018; Sutarna *et al.* 2020).

The heating value of 95% and 99% ethanol in this study (H95F and H99F) was found to be 11,707 and 12,261 BTU/lb and ethanol purity of 95.63% and 99.3%, respectively. The heating value was lower compared to the commercial E10 of 19,024 BTU/lb (Jaramilla *et al.* 2015) found in the study of Jaramilla et.al in the Philippines. This supports the claim that bioethanol as pure engine fuel produces less power output and diminishing fuel economy with constant or unadjusted fuel supply in the combustion chamber due to lower heating value (Zhang *et al.* 2019). To increase the power output, the fuel supplied in the combustion chamber must be increased either carb jet adjustments or fuel remapping.

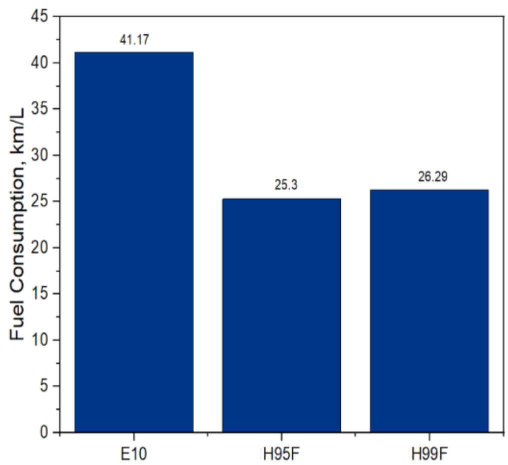

Fig 9. Fuel Consumption

3.5. Gas Emissions and CO_2 Inventory

Using hydrous ethanol as a pure engine fuel results in lower CO emissions compared to E10 by 171.79% and 167.59%; and 172.89% and 191.34% lower HC emissions using 95% hydrous ethanol, and 99% hydrous ethanol respectively based on percentage difference suggesting less harmful emissions to the environment, despite an increase in CO2 emissions.

As shown in Figure 10, the products of combustion gases were obtained using an automobile gas tester that measures the gases CO, HC, and CO_2. It was observed that H95F and H99F produced significantly higher CO_2 emissions of 0.104 and 0.116 kg CO_2 per Liter, respectively compared to E10 with 0.036 kg CO_2 per Liter emissions. This supports the claim that bioethanol enhances combustion efficiency that higher CO_2 emissions have better combustion (Dahman *et al.* 2019; Li *et al.* 2021; Made Suarta *et al.* 2018). Additionally, the reduction in hydrocarbon (HC) emissions was notable, with E10 showing the highest HC

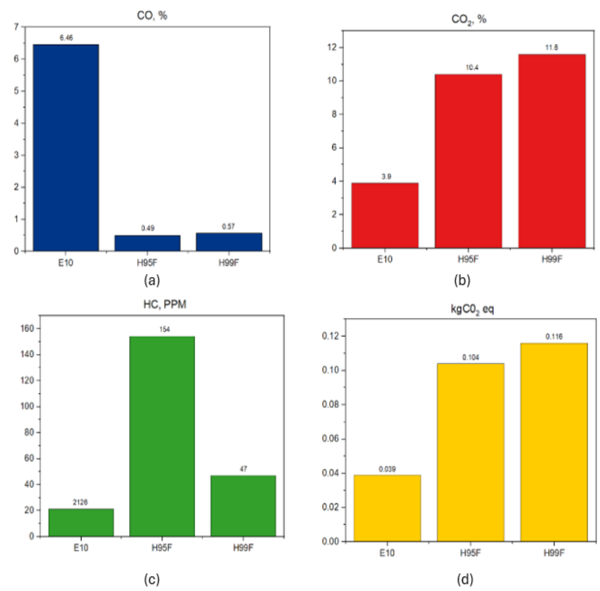

Fig 10. Emission Test Process Output Inventory: (a) %CO; (b) HC (c) % CO2; and (d) kgCO2 emissions

emissions at 2126 ppm, compared to 154 ppm for H95F and 47 ppm for H99F. E10 also produced more carbon monoxide (CO) at 6.46%, while H95F and H99F emitted significantly lower amounts at 0.49% and 0.57%, respectively. The increase in CO2 emissions with H95F and H99F is attributed to more complete combustion (Made Suarta *et al.* 2018). As a result of improved combustion, both CO and HC emissions were significantly reduced, making nipa-based hydrous bioethanol a safer and cleaner alternative, reducing airborne pollutants and carcinogenic risks (Mueller *et al.* 2021).

3.6. Full Carbon Footprint Inventory of a Nipa-based Hydrous Bioethanol

Result of the study using nipa-based bioethanol carbon footprint as fuel appeared to be 0.2353 to 5.1887 and 2.633 to 7.0167 kg of CO_2 per L of ethanol emissions using H95F and H99F respectively when compared to E10. The CO_2 emissions of H99F in this study is higher compared to the CO_2 emissions of H95F due to the electricity consumptions utilized during the dehydration process as shown in Table 5.

The carbon footprint of nipa as bioethanol feedstock appeared to be lower by 25% to 120% compared to corn as bioethanol feedstock in China at 9.171 (L. Wang *et al.* 2014; Yang & Chen, 2013), higher than sugarcane in Brazil at 0.436 (L. Wang *et al.* 2014), and comparable to Cassava in Thailand at 0.552 to 1.058 (Namchancharoen *et al.* 2015).

The minimum emissions per Liter for both hydrous fuels in this study were observed when excluding fuel wood and fermentation, which were considered carbon neutral. This is because the fermentation process occurs naturally in nipa stands, and the distillation is conducted within the community, where CO2 emissions are likely absorbed by surrounding plants and trees area (Flammini *et al.* 2022; Weiguo Liu *et al.* 2017).

The carbon footprint of bioethanol production using fermented sugar using the 850L capacity distiller was also conducted to compare with nipa-base bioethanol as shown in Tables 6. The total carbon footprint of nipa bioethanol is nearly identical to that of fermented sugar, with only a 1.08% difference in favor of nipa. To formulate 800 liters of fermented sugar feedstock solution, 1020 kg of sugar wash was required to achieve 25 Brix, along with the addition of 2400 grams of yeast. The fermentation process lasted for 10 days, with 30 minutes of agitation per day using a pump.

The significant difference in carbon emissions between sugar-based and nipa-based feedstocks, as highlighted in the table, arises from the additional steps involved in ethanol production from sugar. These steps, including cultivation and milling, contribute an additional 0.55 kg CO_2 per kilogram of sugar produced (Yuttitham *et al.* 2011).

Nipa-based bioethanol feedstock is cheaper to produce by about 32.7% compared to fermented sugar. However, it appears that the energy efficiency in MJ to produce one Liter of bioethanol using nipa sap is less efficient by about 38% compared to fermented sugar as feedstock as shown in Table 7. The cost of feedstock played a key factor as per Liter of sap ranges to Php2.5 to Php5.0 per Liter or Php2000 to 4000 for the needed 800 Liters volume compared to the Php6380 to Php11,000 cost of 220 kg sugar alone. Also, due to the voluminous fuel wood used in the bioethanol production affects the energy efficiency with 20% less efficient compared to fermented sugar. Nipa bioethanol production used 293kg compared to 330 kg for the fermented sugar but because the yield of nipa compared to fermented sugar is lesser with ethanol yield of about 6% and 10% respectively.

Figure 11 shows the overall estimation of CO_2 emissions from nipa-based bioethanol production and utilization, indicating that the distillation process contributes the highest CO2 emissions due to the energy-intensive nature of operating a heat-integrated system (Gadalla *et al.* 2006). Fermentation, on

Table 5
Carbon emission inventory of a nipa-based bioethanol

Activity	Input/Output	CO2 Emission (kg CO2)
1. Fermentation	1.1 Sugar conversion	1.1726
2. Distillation	2.1 Fuel Wood Used	3.7808
	2.2 Electricity consumption	0.1313
3. Dehydration (H99F)	3.1 Electricity consumption	1.816
4. Fuel/Utilization	4.1 E10	0.039
	4.2 H95F	0.104
	4.3 H99F	0.116
Total CO2 Emissions (kg CO2/Liter)	H95F as engine fuel H99F as engine fuel	**0.2353 to 5.1887** **2.633 to 7.0167**

Table 6
Nipa vs Fermented Sugar Carbon Footprint

Inventory	kg CO2/liter	
	Nipa	**Fermented Sugar**
1. Fermentation		
Sugar Conversion	1.176	0.7715
Agitation (Electricity)	Not Required	0.851
2. Distillation		
Wood	3.7808	1.845
Electricity	0.1313	0.0839
3. Others (Cultivation, Fertilizer, Milling, Sugar concentration, etc.)	Not Required	1.592105263
Total	**5.0881**	**5.143505263**

Table 7
Energy and Cost Effectiveness of Nipa Bioethanol

Bioethanol Feedstock	Energy Efficiency, MJ/l	Cost Effectiveness, Php/liter of hydrous ethanol production
Nipa	45.7	56.9 to 89.9 (@ 7% v/v yield and Php 2.5 to Php5.0/liter sap)
Fermented Sugar Solution	30.85	Php79.16 to Php 125 (@ 29 to 50 per kg sugar wash and or molasses)

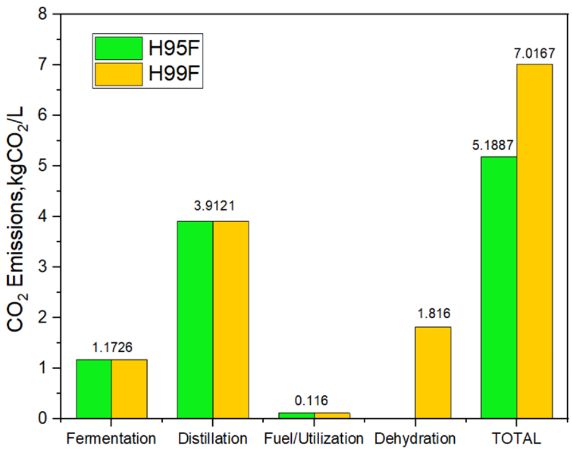

Fig 11. Overall Total CO2 Emission

the other hand, is the second highest contributor in CO_2 emission. This is due to the natural fermentation of nipa sap by Saccharomyces cerevisiae, releasing CO_2 as by-product (Mannan *et al.* 2017). However, fermentation is often considered to have a low or zero carbon footprint, resulting in products that are either carbon neutral or carbon negative (Agrawal *et al.* 2023) so the minimum kg of CO_2 emission per Liter value of both hydrous fuels used in this study considered the fuel wood and fermentation neglected due to carbon neutralization. Moreover, it can be noted that additional purification process such as dehydration of the 95% to 99% bioethanol increases CO_2 emission on the overall production and utilization due to electricity in regenerating the molecular sieves as enumerated in Table 6. Lastly, the utilization of H95F and H99F as fuel contributed least to the overall total CO_2 emission of the overall nipa-based bioethanol production and utilization.

The production and use of nipa-based bioethanol can lower carbon emissions in comparison to other bioethanol feedstocks such as corn (L. Wang *et al.* 2014; Yang & Chen, 2013), cassava (Namchancharoen *et al.* 2015) and sugarcane. This study addresses fossil fuel depletion and contributes to the Sustainable Development Goals Objectives (SDG 7) which aims for affordable and sustainable energy thereby aligning Nipa-based bioethanol as renewable energy alternative to fossils fuel. Utilizing locally sourced nipa sap, especially in rural areas, reduces dependence on imported fossil fuels and enhances energy security, as this feedstock does not compete with food resources (Tamunaidu *et al.* 2013).

Moreover, nipa stands contribute to carbon sequestration (Rahman *et al.* 2024) and protection as wind barriers in the coastlines mitigating the effects strong typhoons as a result of climate change contributing primarily to the objectives of SDG 13 (Nazari *et al.* 2021).

4. Conclusion

Nipa-based hydrous bioethanol produced in the community level was found in this study an alternative to fossils fuel as pure engine fuel for gasoline engines with comparable engine performance, better combustion and A/F ratio as implied by the higher CO_2 emissions, lower HC and O_2. The GWP of a nipa-based hydrous bioethanol was also found lower to other ethanol-based feedstock with 0.2353 kg CO_2 per L of H95F and 2.633 kg CO_2 per L of H99F considering carbon neutrality claims. Although pure ethanol as engine fuel for SI engines was found as an alternative to fossils fuel, hydrous bioethanol is better recommended by this time to become a fuel blend instead of utilizing it as a pure engine fuel due to an observable decrease in fuel economy by about 45% based on the result of this study. Studies on how to mechanize the sap collection process to improve the nipa-based bioethanol process as to volume required, increasing ethanol yield, and increasing distillation efficiency must be conducted to maximize the full potential of *Nipa fruticans* as a bioethanol feedstock. Additionally, nipa bioethanol's cost-effectiveness and lower carbon footprint compared to fermented sugar bioethanol reinforce its promise as a sustainable and eco-friendly biofuel alternative. It is further recommended to improve the distillation process to improve ethanol yield and consider ethanol as fuel to hybrid electric vehicles as 100% renewable vehicles.

Nomenclature

GHG	Greenhouse Gases
GWP	Global Warming Potential
PET	Polyethylene Terephthalate
CO2	Carbon Dioxide
FI	Fuel Injected
A/F	Air-Fuel Ratio
Ethanol	Ethyl Alcohol
E10	10% ethanol fuel blend gasoline
E20	20% ethanol fuel blend gasoline
H95F	Hydrous ethanol as pure engine fuel (95% ethanol)
H99F	Hydrous ethanol as pure engine fuel (99% ethanol)
CO	Carbon Monoxide
HC	Hydrocarbon
O2	Oxygen gas
L	Liter

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