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Fuel Specifications of Aqueous Ethanol-Butanol-Gasoline in Stable Emulsion

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This study investigates the fuel properties of ethanol-butanol-gasoline emulsions prepared with varying ethanol concentrations (80, 90, and 96%) to develop stable and efficient alternative fuels. Key parameters evaluated include the research octane number (RON), Reid vapor pressure (RVP), fuel density, specific gravity (SG), distillation characteristics, and copper strip corrosion resistance, with an emphasis on stability and performance at temperatures between 15 and 30 °C. The results indicate that these fuel blends exhibit high octane ratings, with RON values ranging from 91.8 to 94.1, demonstrating strong anti-knock characteristics suitable for high-performance engines. The RVP increases from 41 to 50 kPa as ethanol content rises, supporting stability under diverse environmental conditions. Fuel density decreases from 0.798 to 0.759 g cm^{-3}, while SG ranges from 0.770 to 0.715, reflecting the influence of ethanol content on fuel mass and volume. Copper strip corrosion tests conducted in accordance with American Society for Testing and Materials, ASTM D130 standards confirmed that all blends are non-corrosive, achieving a "Class 1" corrosion rating and ensuring compatibility with engines containing copper or other metallic components. Distillation tests revealed initial boiling points (IBP) between 41 and 45 °C and final boiling points (FBP) from 122 to 177 °C. Overall, these findings suggest that ethanol-butanol-gasoline emulsions offer notable benefits for enhancing engine performance, reducing emissions, and improving fuel stability.

Keywords: aqueous ethanol, butanol, gasoline, phase, stable emulsion

Introduction

The growing demand for sustainable and renewable energy sources has intensified research on alternative fuels, as fossil fuel reserves decline and environmental concerns associated with petroleum-based fuels continue to rise.[1,2] Developing biofuels is therefore essential to mitigate environmental impacts while ensuring an adequate energy supply for increasing global demand.[3]

Ethanol and butanol are among the most promising biofuels for blending with gasoline.[4] Ethanol, widely produced from biomass such as corn and sugarcane, has been used for decades as a fuel additive due to its high octane rating and improved combustion efficiency.[5,6] However, its hygroscopic nature and lower energy content compared with gasoline present challenges for fuel stability and overall efficiency.[7] Butanol, also derived from renewable biomass, offers complementary advantages, including higher energy density, lower vapor pressure, and reduced hygroscopicity, resulting in better compatibility and stability in gasoline blends.[8-10] Combining ethanol and

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butanol with gasoline, therefore, enables the benefits of each biofuel while mitigating their individual limitations.[11]

Recent studies[12,13] have focused on the development of stable aqueous ethanol-butanol-gasoline emulsions, motivated by the need to manage water contamination issues common in ethanol-based fuels. Several fuel properties are critical for evaluating these emulsions, including research octane number (RON),[14] Reid vapor pressure (RVP),[15] density, specific gravity, distillation profile, and corrosion resistance.[16,17] Ethanol and butanol blending can significantly affect octane performance,[18,19] volatility behavior,[20] mixture formation,[21,22] and combustion uniformity.[23] Corrosion resistance also remains an important factor, particularly because ethanol may induce corrosion in certain engine components; however, ethanol-butanol-gasoline blends have demonstrated excellent anti-corrosive properties.[24,25]

Stable aqueous emulsions of ethanol-gasoline and butanol-gasoline represent a promising advancement in biofuel technology.[26-28] These emulsions may improve tolerance to water and enhance overall fuel stability. Continued research aims to optimize fuel specifications and performance across a broad range of operating conditions. As global initiatives to reduce carbon emissions expand, ethanol-butanol-gasoline emulsions offer a pathway toward cleaner and more sustainable fuel options. Nevertheless, further refinement and evaluation are needed to ensure compatibility with existing engine technologies.

Previous studies[27] underscore the potential of ethanol-butanol-gasoline emulsions to enhance fuel stability, combustion efficiency, and emissions performance. A detailed understanding of their key physicochemical properties is essential to support future development and broader application of these alternative fuel systems.

Experimental

Ethanol was produced from the fermentation of *Arenga pinnata* sap and purified by reflux distillation.[29] Three ethanol concentrations (80, 90, and 96%) were prepared. Butanol (Merck KGaA, Darmstadt, Germany, 99.8% purity < 0.2% water) was used as received and blended with ethanol and gasoline. The gasoline (RON 90) was supplied by PERTAMINA and complied with national commercial fuel specifications, featuring low sulfur content, controlled aromatic hydrocarbon levels, and no intentionally added oxygenated components.

Volumetric blend compositions were selected following a previously reported methodology that optimized low-temperature phase stability of aqueous emulsions.[30] Phase stability was evaluated through visual inspection, thermal cycling, and time-based separation tests. After preparing blends at predetermined volumetric ratios, each emulsion was magnetically stirred for 10-15 min at room temperature to ensure homogenization, transferred to glass vials, and stored at 25 ± 2 °C. Stability was monitored for seven days for signs of separation, turbidity, or sedimentation.

No surfactants or emulsifiers were added; emulsification relied solely on mechanical stirring. Despite the presence of water in ethanol and the inherent immiscibility between water and hydrocarbons, all blends remained single-phase and visually stable throughout the observation period. This stability suggests that compositional interactions-particularly the amphiphilic character of butanol-support emulsion formation without additional stabilizing agents. Although previous studies[31] often employ surfactants, the present approach demonstrates a simpler formulation strategy without concerns related to combustion residues or additive regulations.

To simulate operational conditions, blends were subjected to thermal cycling between 15 and 30 °C for five days (two cycles *per* day). Emulsions were considered stable if no phase separation, droplet aggregation, or stratification was observed. Only formulations maintaining single-phase transparency were selected for ASTM-standard fuel property testing.

RON was measured according to ASTM D2699[32] using a Cooperative Fuel Research (CFR) engine. Each sample was tested in triplicate, and the compression ratio was adjusted until knock onset was detected. RON was calculated by comparison with reference fuels. Measurements were performed for all ethanol concentrations (80, 90, and 96%).

Vapor pressure was determined using the Reid vapor pressure (RVP) test (ASTM D323).[33] Fuel samples were placed in sealed chambers, heated to 37.8 °C (100 °F), and the resulting internal pressure was recorded. Average RVP values were calculated for each ethanol concentration.[34]

Density and specific gravity were measured using ASTM D1298.[35] A hydrometer reading was taken at 15.6 °C (60 °F) to determine specific gravity (SG), and density (ρ) was calculated by multiplying SG by the reference density of water at the same temperature. Triplicate measurements were conducted for all blends.[36]

Copper strip corrosion testing followed ASTM D130.[37,38] A polished copper strip was immersed in the fuel at 50 °C (122 °F) for three hours, removed, cleaned, and visually compared with the ASTM corrosion standards. Corrosion severity was assigned using the standard classification scale.

Distillation characteristics were measured according to ASTM D86.[39,40] The initial boiling point (IBP) was recorded

at the first drop of distillate, and the final boiling point (FBP) corresponded to 95% sample evaporation. Measurements were carried out for all ethanol concentrations to determine volatility profiles.

Long-term storage stability was assessed over 30 days at 25 ± 3 °C. Emulsions were visually inspected on days 0, 7, 14, and 30. No phase separation, sedimentation, or color change was observed.

Results and Discussion

The RON values of the ethanol-butanol-gasoline emulsions at 80, 90, and 96% ethanol are summarized in Table 1. A clear increase from 91.8 to 94.1 was observed as ethanol concentration rose from 80 to 96%, indicating that higher ethanol content improves knock resistance and enhances suitability for engines requiring higher octane fuels.[41]

At 80% ethanol, the RON was 91.8, placing the blend at the lower end of the standard range (91-95) and indicating moderate anti-knock performance suitable for conventional engines. Increasing the ethanol concentration to 90% raised the RON to 93.5, reflecting improved combustion efficiency and greater resistance to pre-ignition, which benefits engines operating at higher compression ratios. The highest RON value, 94.1, was obtained at 96% ethanol, indicating strong anti-knock capability and suitability for higher-performance applications.[42]

The RON measurements showed excellent repeatability across triplicate tests. For the 80 and 96% ethanol blends, identical values were obtained in all three trials, resulting in a standard deviation of ± 0.0. For the 90% blend, only slight variation was observed (93.6, 93.5, 93.6), giving a low standard deviation of ± 0.06, well within the acceptable limits of ASTM D2699. These small deviations likely reflect minor fluctuations in knock detection or emulsion uniformity. The consistently low standard deviations confirm both the reliability of the RON testing procedure and the phase stability of the emulsions, indicating that the differences in RON are primarily due to ethanol concentration rather than experimental error. Similar repeatability was observed for other measurements, such as density (e.g., ± 0.00012 at 80% ethanol), further demonstrating the robustness of the methodology.

The RVP results at ethanol concentrations of 80, 90, and 96% are summarized in Table 2. The 80% ethanol blend exhibited an average RVP of 41.6 kPa, below the standard reference range of 45-60 kPa. Increasing the ethanol content to 90% elevated the RVP to 46.75 kPa, within the standard limits. At 96% ethanol, the RVP reached 50 kPa, approaching the upper end of the reference range.

The increase in RVP with higher ethanol concentrations reflects strong influence of ethanol on blend volatility. As ethanol content rises, overall volatility increases, consistent with higher vapor pressure of ethanol relative to butanol and gasoline.[34] At 80% ethanol, however, the RVP falls slightly below the standard reference range, indicating that further formulation adjustments may be required to ensure adequate volatility at lower ethanol levels.

For the 90 and 96% ethanol blends, the RVP values fall within the acceptable limits, indicating sufficient volatility to support efficient fuel evaporation and combustion across a range of operating temperatures.[43] The 96% ethanol blend, with an RVP of 50 kPa, demonstrates stable and reliable volatility characteristics suitable for diverse environmental conditions.

Table 1. Research octane number (RON) specifications (ASTM D2699) for ethanol-butanol-gasoline blends stabilized at 15-30 °C, prepared with ethanol concentrations of 80, 90, and 96% (triplicate measurements)

Ethanol / %	Composition / (%, v/v)			RON	Reference (standard value)
	Ethanol	Butanol	Gasoline		
80	20.62	41.09	38.29	91.8 91.8 91.8 average = 91.8	91-95
90	26.47	24.39	49.15	93.6 93.5 93.6 average = 93.5	
96	33.13	5.34	61.53	94.1 94.1 94.1 average = 94.1	

Table 2. Reid vapor pressure (RVP) specifications (ASTM D323) for aqueous ethanol-butanol-gasoline (RON 90) stable emulsions at 15-30 °C, prepared with ethanol concentrations of 80, 90, and 96% (based on 3-4 measurements).

Ethanol / %	Composition / (%, v/v)			RVP / kPa	Reference (standard value) / kPa
	Ethanol	Butanol	Gasoline		
80	20.62	41.09	38.29	41	45-60
				42	
				42	
				average = 41.6	
90	26.47	24.39	49.15	45	
				46	
				48	
				48	
				average = 46.75	
96	33.13	5.34	61.53	50	
				50	
				50	
				average = 50	

RVP measurements were conducted in triplicate or quadruplicate to ensure accuracy and repeatability. For the 80% ethanol blend, the values (41, 42, 42 kPa) produced an average of 41.6 kPa with a standard deviation of ±0.58, indicating good consistency. The 90% blend displayed slightly greater variation (45, 46, 48, 48 kPa), resulting in an average of 46.75 kPa and a standard deviation of ±1.50, while the 96% blend showed complete repeatability (50 kPa; ±0.0). These deviations remain within the acceptable precision limits of ASTM D323, confirming both emulsion stability and the reproducibility of the measurement technique. The standard deviation of ±1.50 kPa for the 90% blend represents acceptable variability for RVP testing.

Table 3 summarizes the density (ρ) and SG results for the emulsions at 80, 90, and 96% ethanol. Measurements were recorded at temperatures between 15 and 30 °C. The 80% ethanol blend exhibited a density of 0.79805 g cm^{-3} and an SG of 0.79877. Increasing the ethanol concentration to 90% reduced the density to 0.78402 g cm^{-3} (SG = 0.78472), while the 96% ethanol blend showed the lowest values (ρ = 0.75905 g cm^{-3}; SG = 0.75973), falling within the standard reference range of 0.715-0.770 g cm^{-3}.

The results show that increasing ethanol concentration decreases the density and specific gravity of the ethanol-butanol-gasoline emulsions, consistent with lower density of ethanol relative to gasoline and butanol.[44] The 80% ethanol blend exhibited the highest density and SG, while

Table 3. Fuel parameters for density and specific gravity (SG) of aqueous ethanol-butanol-gasoline (RON 90) stable emulsions at 15-30 °C, prepared with ethanol concentrations of 80, 90, and 96% (triplicate measurements)

Ethanol / %	Composition / %			Density (ρ) / (g cm^{-3})	Specific gravity (SG) 60/60	Reference (standard value)
	Ethanol	Butanol	Gasoline			
80	20.62	41.09	38.29	0.79801	0.79873	0.715-0.770
				0.79796	0.79868	
				0.79819	0.79891	
				average = 0.79805	0.79877	
90	26.47	24.39	49.15	0.78317	0.78387	
				0.78434	0.78504	
				0.78456	0.78527	
				average = 0.78402	0.78472	
96	33.13	5.34	61.53	0.75151	0.75583	
				0.76542	0.76521	
				0.75747	0.75815	
				average = 0.75905	0.75973	

the 90 and 96% blends showed progressively lower values, approaching the mid and lower bounds of the reference standard range.

Lower density may promote a more uniform air-fuel mixture and enhance combustion efficiency; however, it also corresponds to reduced energy density, which can decrease mileage or energy output.[45] Understanding this relationship is essential for evaluating blend performance, as the inherently lower energy content of ethanol introduces a trade-off between improved combustion characteristics and overall energy efficiency.[46]

At 80% ethanol, the blend remains closer in density to gasoline and therefore offers higher energy content, though it may be more susceptible to instability due to the hygroscopic nature of ethanol. The 90% ethanol blend represents a balance between stability and energy content, providing good combustion performance while maintaining reasonable efficiency. At 96% ethanol, the density is the lowest, which may reduce fuel economy but offers optimal combustion behavior for engines designed to operate with high-ethanol mixtures.[47] Overall, the results indicate that ethanol-butanol-gasoline blends can be tailored to meet specific engine requirements, though increasing ethanol content may negatively impact energy density and fuel economy in engines originally designed for gasoline.[48]

Density and SG were measured in triplicate to assess repeatability. The 80% ethanol blend demonstrated excellent consistency, with density and SG standard deviations of ± 0.00012. The 90% blend also showed tight clustering (density ± 0.00072; SG ± 0.00070), confirming stable formulation. The 96% blend exhibited slightly higher variability (density ± 0.00700; SG ± 0.00430), likely due to reduced butanol content affecting homogeneity. Nonetheless, all measurements remained within acceptable limits, confirming the stability of the emulsions and the reliability of the physical property data.

Table 4 summarizes the copper strip corrosion test (ASTM D130) results. All blends achieved a class 1 rating, indicating minimal corrosivity and full compliance with the standard specification.

The copper strip corrosion test (ASTM D130) showed that all ethanol-butanol-gasoline blends, regardless of ethanol content (80, 90, or 96%), produced a class 1 rating, indicating no significant corrosive effects on copper

Table 4. Copper strip corrosion specifications (ASTM D130) for aqueous ethanol-butanol-gasoline (RON 90) stable emulsions at 15-30 °C, prepared with ethanol concentrations of 80, 90, and 96%, compared against stainless steel

Ethanol / %	Composition / %			Copper strip	Standard specs
	Ethanol	Butanol	Gasoline		
80	20.62	41.09	38.29	 1A	class 1
90	26.47	24.39	49.15	 1 A	class 1
96	33.13	5.34	61.53	 1 A	class 1

components. A class 1 classification reflects the highest level of corrosion resistance and confirms that these blends are safe for use in engines containing copper or other metallic parts. This result is noteworthy given the known tendency of ethanol to promote corrosion in fuel systems; the presence of butanol in the mixture may contribute to mitigating these effects by enhancing overall blend stability.

The distillation characteristics of the blends were analyzed at ethanol concentrations of 80, 90, and 96%. Key parameters-including the initial boiling point (IBP), final boiling point (FBP), total recovery, and distillation losses-are summarized in Table 5.[49]

For the 80% ethanol blend, the IBP was 45 °C and the FBP was 122 °C, with a total recovery of 969 mL and losses of 1.3 mL, indicating moderate volatility comparable to standard gasoline. At 90% ethanol, the IBP decreased to 41 °C and the FBP increased to 165 °C, with a total recovery of 965 mL and higher losses of 2.8 mL, reflecting increased volatility associated with the higher ethanol content. The 96% ethanol blend maintained an IBP of 41 °C but exhibited the highest FBP (177 °C) and markedly lower total recovery (95 mL), with losses of 3.1 mL, demonstrating the broadest distillation range and most aggressive evaporation behavior. The influence of ethanol on boiling characteristics and evaporative losses aligns with its higher volatility relative to butanol and gasoline.[50] The elevated IBP observed for the 80% blend suggests a stabilizing contribution from butanol, which moderates initial evaporation and delays the onset of boiling.[51]

The FBP values for the 90 and 96% blends show a clear upward trend with increasing ethanol concentration, resulting in wider distillation ranges characteristic of more volatile emulsions. The high FBP of the 96% blend (177 °C) suggests prolonged evaporation, which may hinder complete vaporization under certain engine conditions. Higher distillation losses in the 90 and 96% blends further highlight the strong volatility of ethanol, potentially affecting fuel efficiency due to increased evaporative loss. In contrast, the smaller losses in the 80% blend indicate more controlled evaporation and better stability during distillation.

The increase in RON with higher ethanol content is primarily linked to the chemical structure of ethanol. Its high oxygen content promotes more complete combustion and reduces carbon deposits, enhancing knock resistance.[52] Additionally, the ability of ethanol to form hydrogen bonds increases the energy required for ignition, further elevating RON.[53] Although butanol is less volatile, its higher energy density contributes to blend stability and compensates for the lower energy content of ethanol, resulting in a more balanced fuel mixture.[54] The improved RON across the blends supports their effectiveness in reducing engine knocking, particularly in modern engines designed for high compression ratios.[55] Nevertheless, the trade-offs associated with high ethanol content-such as increased volatility and hygroscopic tendency of ethanol-must be carefully managed to ensure performance reliability.[56]

The RVP data reinforce these trade-offs. While high ethanol concentrations enhance cold-start performance due

Table 5. Distillation specifications (ASTM D86) for blended fuels of aqueous ethanol-butanol-gasoline (RON 90) stable emulsions prepared with ethanol concentrations of 80, 90, and 96%

Ethanol / %	Composition / %			Volume / mL	Temperature / ºC	Residue / mL	Recovery / mL	Losses / mL
	Ethanol	Butanol	Gasoline					
80	20.62	41.09	38.29	IBP	45	1.8	96.9	1.3
				10	58			
				50	88			
				90	117			
				FBP	122			
90	26.47	24.39	49.15	IBP	41	1.7	96.5	2.8
				10	52			
				50	75			
				90	119			
				FBP	165			
96	33.13	5.34	61.53	IBP	41	1.9	95	3.1
				10	50			
				50	65			
				90	133			
				FBP	177			

IBP: initial boiling point; FBP: final boiling point.

to rapid vaporization, they also heighten the risk of vapor lock in warm climates.[57] The relatively low RVP of the 80% blend suggests that butanol moderates volatility, improving emulsion stability. Achieving an optimal ethanol-butanol ratio is therefore crucial for maintaining appropriate vapor pressure across temperature conditions.

Overall, ethanol-butanol-gasoline emulsions can meet performance standards when properly formulated, with the 90 and 96% blends showing strong volatility control and stability across operational conditions. The 80% blend may require optimization-such as adjusting alcohol ratios or adding stabilizers-to maintain suitable RVP values. These emulsions thus present a promising alternative to conventional gasoline, offering adaptability across engine types and environmental conditions.[56]

At 80% ethanol, the blend provides a favorable balance between fuel density and energy output for conventional engines, though attention to hygroscopic nature of ethanol remains necessary. The 90 and 96% blends are better suited for engines optimized for high-ethanol fuels, leveraging the higher octane of ethanol rating and cleaner combustion characteristics.[58] Corrosion results further confirm that all blends are safe for use in standard fuel systems. Butanol likely plays a stabilizing role by mitigating the corrosive tendencies of ethanol, resulting in class 1 ratings across all concentrations. These outcomes indicate high compatibility with copper-containing components and metal fuel-system parts.

Accordingly, these emulsions can be used directly in conventional and modified gasoline engines without significant risk of corrosion, while engines designed for higher ethanol operation may benefit from improved emissions and combustion efficiency. Copper strip ASTM D130 results confirm no significant corrosion risk, reinforcing the potential of these blends as viable alternatives to conventional fuels.[59]

The distillation data further highlight the relationship between ethanol concentration, volatility, and fuel behavior. Higher ethanol levels produce more volatile mixtures, improving cold-start capability but raising concerns about efficiency losses and incomplete combustion if not properly managed. Lower ethanol blends (80%) offer more controlled distillation and reduced losses, aligning better with the requirements of standard internal combustion engines.[60]

The benchmark RON and RVP standards adopted in this study are based on Indonesian fuel specifications (Peraturan Dirjen Migas No. 3674 K/24/DJM.S/2016),[61] which require RON values of 90-95 and RVP values of 45-60 kPa, with copper strip corrosion meeting class 1 criteria.

Fuel property trends in Table 6 show that increasing ethanol from Et80 to Et96 raises RON from 91.8 to 94.1, consistent with the role of ethanol as a high-octane oxygenate.[62] These values are comparable to E20 fuels and fall within Indonesian regulatory limits. RVP rises from 41.6 to 50.0 kPa across the blends, remaining within the 45-60 kPa standard and demonstrating stability enhanced by the lower volatility of butanol.[63] Density and SG decline with higher ethanol content, consistent with known alcohol properties.[64] All blends achieve class 1 copper corrosion ratings, indicating excellent material compatibility.[65]

Overall, the Et90 blend offers the most balanced performance-high RON, moderate RVP, good stability, and excellent corrosion resistance. Compared with conventional E1-E20 fuels, these emulsions deliver competitive or superior performance while incorporating water without compromising stability, highlighting strong potential for flexible-fuel vehicles and distributed energy systems.

Although no external emulsifiers or surfactants were used in formulating the aqueous ethanol-butanol-gasoline blends, the emulsions exhibited strong phase stability over time. This stability arises from the intrinsic amphiphilic

Table 6. Comparison of ethanol-butanol-gasoline emulsions with commercial blends and literature-reported formulations

Blend type	Composition			RON	RVP / kPa	Density (15 °C) / (g cm^{-3})	Copper strip corrosion	Reference
	Ethanol (volume) / %	Butanol (volume) / %	Gasoline (volume) / %					
E10	10	0	90	92.5	57	0.753	class 1	66
E20	20	0	80	94.3	60	0.749	class 1	67
E85	85	0	15	100+	80+	0.745	corrosive	60
Bu16	0	16	84	99.5	38	0.780	class 1	67
Bu20	0	20	80	100.2	36	0.790	class 1	67
This study (Et.80%)	20.6	41.1	38.3	91.8	41.6	0.798	class 1	–
This study (Et.90%)	26.5	24.4	49.1	93.5	46.8	0.784	class 1	–
This study (Et.96%)	33.1	5.3	61.5	94.1	50.0	0.759	class 1	–

RVP: Reid vapor pressure; RON: research octane number.

properties of ethanol and butanol, which contain both a polar hydroxyl (–OH) group and a nonpolar alkyl chain.[68] The –OH group interacts with the aqueous ethanol-water phase, while the hydrocarbon chain is compatible with gasoline, allowing both alcohols to reduce interfacial tension and act as self-emulsifying agents.[69,70] Butanol, with its longer alkyl chain, enhances interaction with gasoline and contributes additional steric stabilization, consistent with reports identifying butanol as an effective co-surfactant in fuel emulsions.[58] These molecular interactions explain the observed stability under both ambient storage and thermal cycling conditions.

The increase in RON from 91.8 to 94.1 across the 80-96% ethanol blends aligns with well-established anti-knock behavior of ethanol. Comparison with commercial ethanol-gasoline blends shows similar trends: Turner *et al*.[60] reported RON values of 92.5 and 94.3 for E10 and E15, respectively, while higher-ethanol blends such as E30-E40 can exceed RON 98. Despite containing water and lacking octane-boosting additives, our emulsions-containing only 20-33 vol% ethanol-achieve comparable octane levels. Butanol also contributes to the octane performance. Foong *et al*.[67] reported RON values approaching 100 for B15-B20 blends, indicating that even the modest butanol content in the 96% ethanol blend (5.34%) likely provides synergistic enhancement. Together, these findings show that the emulsions offer competitive octane quality suitable for high-compression engines.

Although direct emission measurements were not performed, the environmental implications can be inferred from fuel composition. Ethanol and butanol are oxygenated biofuels that promote more complete combustion, reducing CO and particulate emissions through improved oxidation efficiency. The high oxygen content of ethanol (ca. 35 wt.%) enhances this effect, while lower vapor pressure of butanol helps reduce evaporative emissions compared with high-ethanol blends such as E85. The water present in the emulsions may further reduce NO_x emissions by lowering combustion temperatures, consistent with literature reporting 10-30% NO_x reductions for water-containing fuels. Renewable ethanol derived from *Arenga pinnata* sap also offers potential reductions in lifecycle carbon emissions. However, higher ethanol levels may increase aldehyde emissions-particularly formaldehyde and acetaldehyde-highlighting the need for further investigation.[58]

With respect to volatility, the RVP values of the emulsions ranged from 41.6 to 50.0 kPa. The 90 and 96% ethanol blends fall within the ASTM D4814 and SNI 06-6414-2020 warm-weather range of 45-60 kPa, indicating good suitability for tropical climates. The 80% blend, with an RVP of 41.6 kPa, falls slightly below this range and may face cold-start limitations. The presence of water, while not detrimental to stability, raises certification challenges because conventional fuel standards require water-free formulations to prevent phase separation and corrosion. Although the emulsions remained stable without surfactants, further evaluation is required for cold-climate performance and long-term durability. Nevertheless, the consistency of blends under ASTM testing suggests strong potential for tropical flex-fuel applications.

All fuel property measurements adhered strictly to ASTM standards to ensure accuracy and international comparability. RON was measured using ASTM D2699 with a CFR engine, which rates fuel knock propensity based on standardized knock intensity measurements, as discussed by Hoth *et al*.[71] RVP was determined following ASTM D323, widely used for ethanol-blended fuels.[34] Density and SG were measured using ASTM D1298, a hydrometer method shown to be reliable for petroleum and bio-derived fuels.[72] Corrosive potential was assessed using ASTM D130, consistent with findings by previous work.[73] All emulsions achieved class 1 ratings, confirming excellent compatibility with metallic components. Distillation characteristics were evaluated using ASTM D86, a standard method proven effective for multi-component fuels such as ethanol-gasoline blends.[74]

Together, the ASTM methods employed, provide a rigorous and internationally recognized basis for characterizing the emulsions. Their consistent performance across these tests validates both the scientific integrity and the practical relevance of the ethanol-butanol-gasoline formulations.

Conclusions

This study evaluated the key physicochemical properties of ethanol-butanol-gasoline emulsions at ethanol concentrations of 80, 90, and 96%. The results show that increasing ethanol content enhances the RON with values ranging from 91.8 to 94.1, indicating improved resistance to engine knocking and suitability for higher-octane fuel applications. The RVP also increased with ethanol concentration, reaching 50 kPa for the 96% blend, reflecting higher volatility. While this can support improved cold-start behavior, it may require careful handling under warm conditions to avoid vapor lock. Density and specific gravity decreased progressively as ethanol content rose, consistent with the lower density of ethanol relative to gasoline and butanol. This reduction can improve mixture formation but may also lower overall energy density. All blends achieved a class 1 rating in the copper strip corrosion

test (ASTM D130), confirming their non-corrosive behavior and compatibility with metallic fuel system components. Distillation analysis using standard ASTM cut points showed that higher ethanol concentrations broadened the distillation range, with decreases in IBP and increases in FBP. The 80% ethanol blend exhibited the most controlled volatility profile, whereas the 96% blend demonstrated the widest range and greatest evaporative tendency. Overall, the results indicate that ethanol-butanol-gasoline emulsions possess fuel properties within acceptable ranges for spark-ignition engine use, with the 90% ethanol formulation offering the most balanced combination of octane quality, volatility, stability, and material compatibility.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author Contributions

H.F.S. designed the experimental methodology, supervised all ASTM-based testing procedures, and led the overall execution and coordination of the project. L. R. B. performed RON measurements using the CFR engine in accordance with ASTM D2699 and assisted in ASTM D323. G.H.T. conducted hydrometer-based measurements of fuel density and specific gravity following ASTM D1298. G.P. carried out distillation testing using ASTM D86, including IBP and FBP determinations across ethanol concentrations. M.C.S. developed and monitored emulsion formulation protocols, including ethanol-butanol-gasoline mixing ratios and stability evaluations. H F.A. oversaw ethanol fermentation and purification from *Arenga pinnata* sap and verified concentration levels for experimental use. S.Y.A. performed the ASTM D130 and visually assessed metal degradation. T.S. assisted in fuel sample preparation and maintained quality control during heating, mixing, and storage. R.A.S. provided technical support for instrumentation calibration, particularly for pressure and temperature control. N.M.K. managed laboratory logistics and ensured proper handling and measurement of volatile fuel samples. A.W.: advised on blending ratios and reviewed consistency across experimental runs and data reproducibility. B.A.S. processed and analyzed raw experimental data, conducted error estimations, and generated tabular and graphical outputs. T.O.R. managed project funding logistics, ensured compliance with research ethics and laboratory standards, and contributed to manuscript revisions.

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