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Bioethanol Production from Sugarcane Bagasse and Pineapple Peel Waste and Its Combustion Characteristics

Diswanto[1*], Wawan Purwanto[1], M. Yasep Setiawan[1], Ahmad Arif[1], Irma Wirantina Kustanrika[2]

Abstract

Growing demand for renewable fuels has increased interest in converting agricultural and fruit-processing residues into bioethanol. This study evaluated sugarcane bagasse and pineapple peel waste as feedstocks for bioethanol production and compared the combustion characteristics of the resulting fuels. Bioethanol was produced through pretreatment, hydrolysis, fermentation using yeast, and distillation. The samples were then examined based on boiling-point range, flame color, flame height, flame area, and flame duration at fuel volumes of 1, 2, and 3 mL. The pineapple peel bioethanol showed a boiling-point range closer to ethanol and produced flame-height values closer to pure ethanol, particularly with 8 g yeast, whereas Pertamax generated the highest flame height and flame area overall. These results indicate that sugarcane bagasse and pineapple peel waste are promising feedstocks for preliminary bioethanol production, with pineapple peel showing better combustion-related characteristics among the waste-derived samples.

Keywords
Bioethanol production; sugarcane bagasse; pineapple peel waste; biomass waste fermentation; combustion characteristics.

[1]*Departemen Teknik Otomotif, Fakultas Teknik, Universitas Negeri Padang*
Jln.Prof.Dr.Hamka, AirTawar, PadangSumateraBarat, Indonesia
[2]*Department of Civil Engineering, Technology Institute of PLN, Jakarta, Indonesia*
Lingkar Luar Barat Duri Kosambi Street, Cengkareng, West Jakarta, Indonesia
* diswanto2002@gmail.com

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INTRODUCTION

The increasing demand for energy, together with the gradual depletion of fossil fuel resources, has strengthened the need for renewable liquid fuels that can be produced from locally available biomass. Bioethanol is one of the alternative fuels that has received considerable attention because it can be produced from sugar-, starch-, and lignocellulose-based materials through biological conversion. Recent studies have emphasized that lignocellulosic bioethanol is technically promising because it uses non-food biomass and agricultural residues, although its production is still challenged by feedstock variability, pretreatment efficiency, fermentation performance, and purification cost [1]–[3]. Therefore, experimental studies using readily available organic residues remain important, particularly when they provide preliminary information on the quality and combustion behavior of the resulting bioethanol.

Agricultural and fruit-processing wastes are potential feedstocks for bioethanol production because many of them still contain fermentable sugars, cellulose, and hemicellulose. Sugarcane bagasse is a lignocellulosic residue generated after juice extraction, and its cellulose-rich structure makes it suitable for conversion into fermentable sugars after appropriate pretreatment and hydrolysis. Previous studies on sugarcane bagasse have shown that alkaline pretreatment, delignification, and enzymatic hydrolysis can improve sugar accessibility and support bioethanol production from this agricultural waste [4], [5]. In addition, pineapple peel waste has been reported as a promising substrate because it contains soluble sugars and structural carbohydrates that can be converted into ethanol through fermentation using yeast, particularly Saccharomyces cerevisiae [6]–[8]. These two residues are relevant for further investigation because they are inexpensive, locally available, and often underutilized.

The production of bioethanol from biomass generally involves several main stages, including raw material preparation, pretreatment, hydrolysis, fermentation, and distillation. Pretreatment and hydrolysis are required to break down complex carbohydrates into simpler sugars, while fermentation converts these sugars into ethanol with the assistance of microorganisms. Distillation is then used to separate ethanol from the fermentation broth and increase its concentration. The quality of the produced bioethanol is influenced by several factors, including feedstock composition, yeast dosage, fermentation conditions, water content, and the effectiveness of the distillation process [2], [4], [7], [8]. These factors may also affect the physical and combustion-related properties of the fuel.

In preliminary fuel evaluation, it is not sufficient to observe only whether bioethanol can be produced; the combustion behavior of the resulting fuel also needs to be described. Parameters such as flame color, flame height, flame area, and flame duration can provide basic information on evaporation behavior, burning intensity, flame spread, and burning time. Studies on pineapple-peel bioethanol blended with commercial gasoline-type fuel have shown that the physical properties of bioethanol blends, including flash point, density, viscosity, and octane number, vary with blending composition [9]. Other experimental studies on ethanol–gasoline combustion have also reported that ethanol content can influence flame temperature and burning duration because ethanol has different physical and chemical properties from gasoline [10]. In the automotive-engineering context, ethanol-based fuels may require attention to fuel properties and combustion characteristics before broader application in engines [11].

Although previous studies have investigated bioethanol production from sugarcane bagasse or pineapple waste separately, comparative information on the combustion characteristics of bioethanol derived from these two waste materials remains limited, especially when assessed using simple flame parameters and compared with ethanol and commercial fuel. This study addresses that gap by producing bioethanol from sugarcane bagasse and pineapple peel waste through pretreatment, hydrolysis, fermentation, and distillation, and then comparing the combustion characteristics of the resulting fuels. The evaluation focuses on boiling-point range, flame color, flame height, flame area, and flame duration. The results are expected to provide preliminary evidence of the potential use of sugarcane bagasse and pineapple peel waste as feedstocks for bioethanol production and as part of biomass-based alternative fuel development.

METHOD

This study employed a descriptive experimental method to produce bioethanol from sugarcane bagasse and pineapple peel waste and to evaluate the physical and combustion characteristics of the resulting fuels. The experimental stages consisted of raw material preparation, hydrolysis, fermentation, distillation, physical characterization, flame-characteristic testing, and descriptive data analysis. This sequence was adapted to the general procedure of lignocellulosic bioethanol production, in which biomass must be prepared and converted into fermentable sugars before fermentation and purification [4], [6], [12], [13]. The main parameters observed in this study were boiling-point range, flame color, flame height, flame area, and flame duration.

The production process began with raw material preparation. Sugarcane bagasse and pineapple peel waste were first cleaned to remove adhering dirt and unwanted residues. The cleaned materials were then cut or crushed into smaller pieces to facilitate further processing. Size reduction was carried out to increase the contact area between the biomass and water during the hydrolysis stage. After preparation, each biomass material was mixed with water before being subjected to hydrolysis.

Hydrolysis was conducted to break down complex carbohydrate structures, particularly cellulose and hemicellulose, into simpler sugars that could be utilized by microorganisms during fermentation. The hydrolysis process was performed by heating the biomass–water mixture so that the fibrous structure of the material became easier to degrade. This stage is important because the conversion of lignocellulosic biomass into bioethanol depends on the availability of fermentable sugars released from the raw material [4], [12], [13].

After hydrolysis, the resulting liquid was cooled before fermentation. Fermentation was carried out by adding yeast containing Saccharomyces cerevisiae to the hydrolyzed substrate. The fermentation process was performed in a closed container for the predetermined fermentation period to allow the microorganisms to convert available sugars into ethanol. The use of Saccharomyces cerevisiae is common in bioethanol production because this yeast can convert fermentable sugars into ethanol under suitable fermentation conditions [6], [12], [13]. The fermentation scheme is presented in Figure 1, which illustrates the closed-system principle used to support gas release and maintain the fermentation environment.

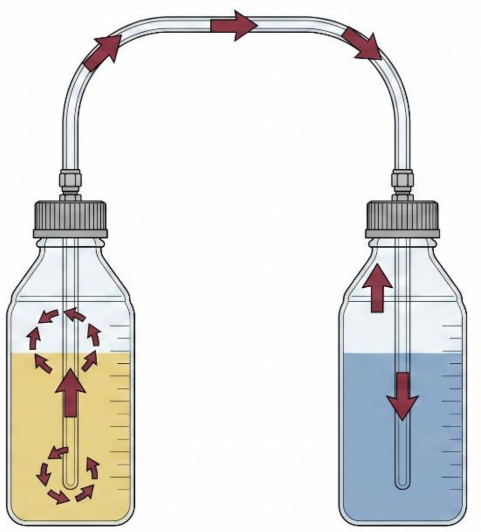

Figure 1. Schematic of the bioethanol fermentation process

The fermented liquid was then processed through distillation to separate ethanol from the fermentation broth. Distillation was performed based on the difference in boiling points between ethanol and water. During heating, ethanol-rich vapor was generated at approximately 78°C and then passed through the condenser. The condensed vapor was collected as liquid bioethanol with a higher ethanol concentration than the initial fermentation broth. The distillation apparatus is shown in Figure 2, which illustrates the heating, vapor transfer, condensation, and collection stages of the distillation process.

The obtained bioethanol samples were then used for physical and combustion-characteristic testing. Physical characterization was conducted by observing the boiling-point range as an indication of the relative quality of the produced bioethanol. Combustion testing was conducted by burning the fuel samples and observing the resulting flame characteristics. The tested parameters included flame color, flame height, flame area, and flame duration. These parameters were selected because they can describe the visible combustion behavior of bioethanol, including burning intensity, flame spread, and burning time [14], [15].

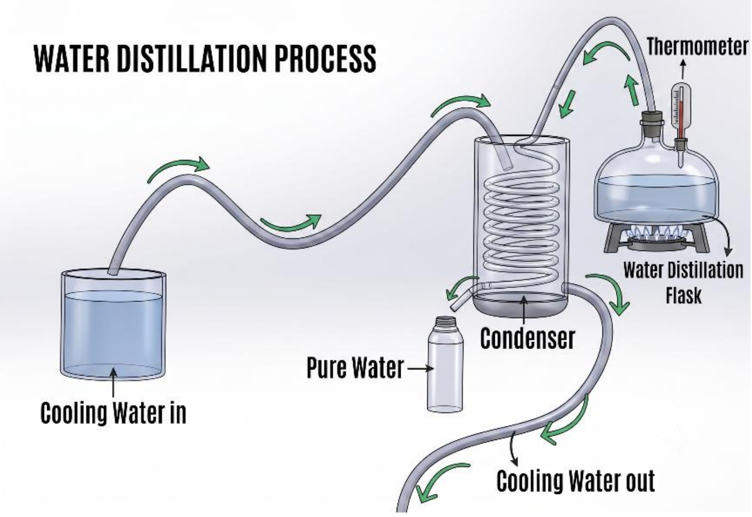

Figure 2. Schematic of the bioethanol distillation apparatus

The combustion test was conducted using several fuel-volume variations, namely 1 mL, 2 mL, and 3 mL. Each fuel sample was ignited under the same testing conditions to maintain consistency among observations. Flame height was measured in millimeters, flame area was expressed in square millimeters, and flame duration was measured in seconds using a stopwatch. The flame image was used to support the visual observation of flame color and flame spread. The overall research workflow is shown in Figure 3, which summarizes the sequence from material preparation, bioethanol production, physical characterization, combustion testing, and data analysis.

The data obtained from physical and combustion-characteristic testing were analyzed descriptively. The results were organized in tables and graphs to compare the combustion behavior of bioethanol produced from sugarcane bagasse and pineapple peel waste with ethanol and Pertamax. The descriptive analysis focused on identifying differences in boiling-point range, flame color, flame height, flame area, and flame duration among the tested fuel samples.

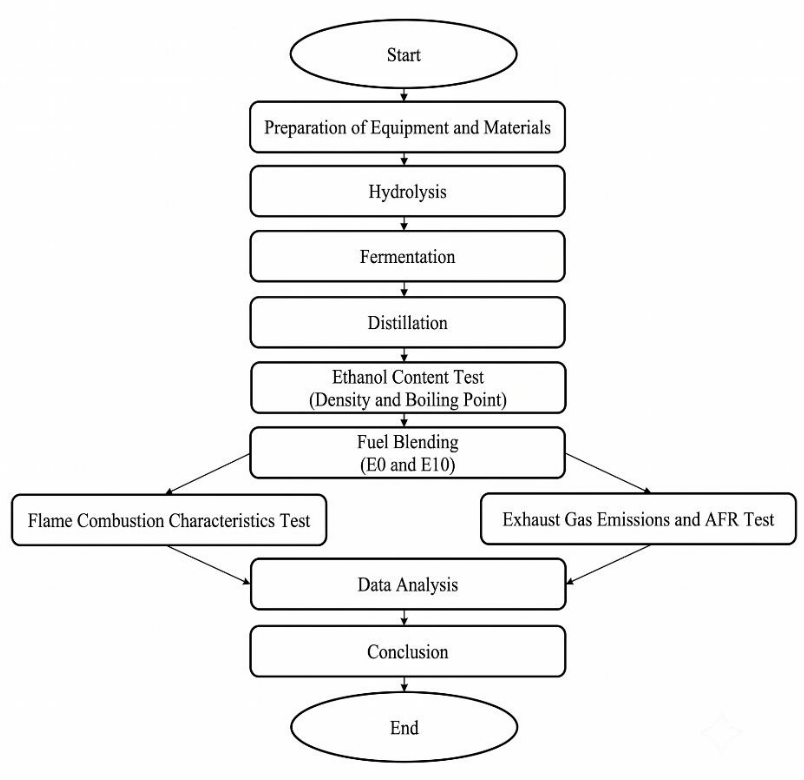

Figure 3. Research workflow for bioethanol production and combustion-characteristic evaluation

RESULT AND DISCUSSION

Results

Before the combustion-characteristic test was conducted, the bioethanol produced from sugarcane bagasse and pineapple peel waste through fermentation and distillation was first evaluated based on its physical characteristics. This preliminary observation was intended to identify the initial quality of the produced bioethanol before it was used in the flame test. The observed parameters included boiling-point range, relative purity indication, and estimated water-content indication. The physical characteristics of the produced bioethanol are presented in Table 1.

Table 1. Physical characteristics of bioethanol produced from sugarcane bagasse and pineapple peel waste

Parameter	Sugarcane Bagasse Bioethanol	Pineapple Peel Bioethanol
Boiling-point range	85–90°C	80–85°C
Relative purity indication	Lower	Higher
Estimated water-content indication	Higher	Lower

Table 1 shows that pineapple peel bioethanol had a boiling-point range of 80–85°C, whereas sugarcane bagasse bioethanol had a boiling-point range of 85–90°C. Based on this observation, the pineapple peel bioethanol showed a boiling-point range closer to that of ethanol than the sugarcane bagasse bioethanol. The table also indicates that pineapple peel bioethanol had a higher relative purity indication and a lower estimated water-content indication than sugarcane bagasse bioethanol.

After the physical observation, flame-characteristic testing was conducted to compare the combustion behavior of each tested fuel. The observed parameters included flame color, flame height, flame area, and flame duration. The test was carried out using three fuel-volume variations, namely 1 mL, 2 mL, and 3 mL. The visual flame profiles of the tested fuels are shown in Figure 4.

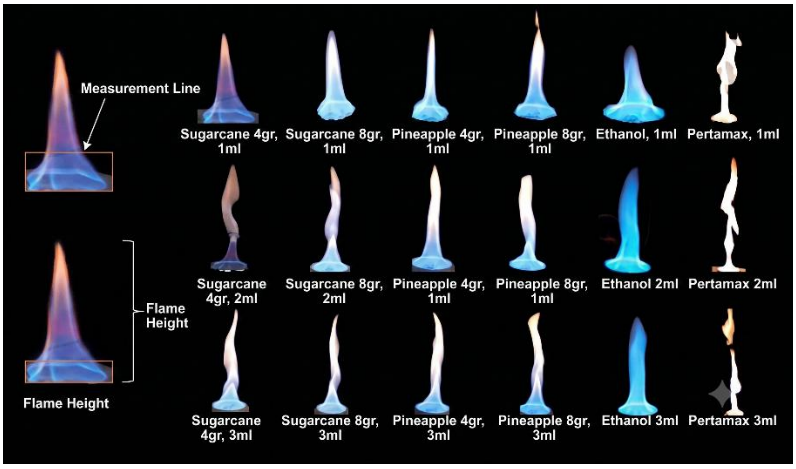

Figure 4. Visual observation of flame characteristics for each fuel sample and volume variation

Figure 4 presents the visual differences in flame shape and color among the tested fuels. The bioethanol and ethanol samples generally produced flames dominated by bluish tones, while Pertamax showed a taller flame with a brighter yellow-white region. These visual observations were used to support the quantitative evaluation of flame height, flame area, and flame duration.

The flame-height test was conducted to observe the vertical flame response of each fuel sample at different fuel volumes. The flame-height data are presented in Table 2 and visualized in Figure 5.

Table 2. Flame height of each tested fuel at different fuel volumes

Fuel type	**Volume 1 mL**	**Volume 2 mL**	**Volume 3 mL**
Sugarcane bagasse bioethanol, 4 g yeast	133	159	135
Sugarcane bagasse bioethanol, 8 g yeast	145	165	171
Pineapple peel bioethanol, 4 g yeast	146	170	193
Pineapple peel bioethanol, 8 g yeast	187	203	210
Ethanol	170	191	201
Pertamax	270	300	310

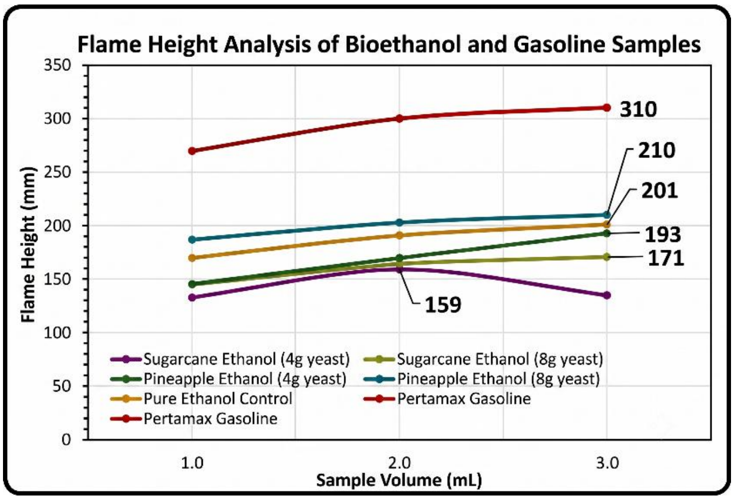

Figure 5. Flame-height comparison of each tested fuel at different fuel volumes

As shown in Table 2 and Figure 5, Pertamax produced the highest flame height at all fuel volumes, with values of 270 mm, 300 mm, and 310 mm for 1 mL, 2 mL, and 3 mL, respectively. Among the bioethanol samples, pineapple peel bioethanol with 8 g yeast produced the highest flame-height values, namely 187 mm, 203 mm, and 210 mm. These values were slightly higher than those of ethanol at the same volumes, which were 170 mm, 191 mm, and 201 mm. Most samples showed an increase in flame height as fuel volume increased; however, sugarcane bagasse bioethanol with 4 g yeast decreased from 159 mm at 2 mL to 135 mm at 3 mL.

The next parameter was flame area, which was used to describe the spread of the flame during combustion. The flame-area data are presented in Table 3 and illustrated in Figure 6.

Table 3. Flame area of each tested fuel at different fuel volumes

Fuel type	Volume 1 mL	Volume 2 mL	Volume 3 mL
Sugarcane bagasse bioethanol, 4 g yeast	142	504	752
Sugarcane bagasse bioethanol, 8 g yeast	210	741	800
Pineapple peel bioethanol, 4 g yeast	287	536	676.7
Pineapple peel bioethanol, 8 g yeast	300	639	646
Ethanol	228	567	714
Pertamax	707	1056	1278

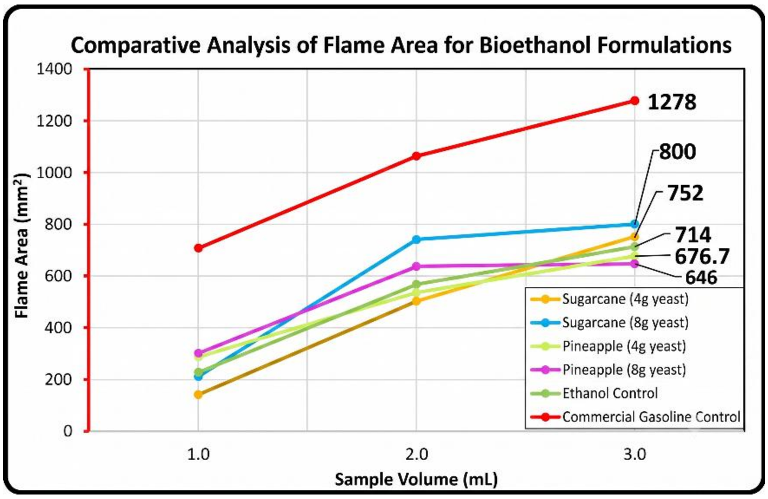

Figure 6. Flame-area comparison of each tested fuel at different fuel volumes

Table 3 and Figure 6 show that Pertamax produced the largest flame area at all volume variations, with values of 707 mm^2, 1056 mm^2, and 1278 mm^2. The flame area of the bioethanol samples was lower than that of Pertamax but generally increased as fuel volume increased. At 3 mL, sugarcane bagasse bioethanol with 8 g yeast produced the largest flame area among the waste-derived bioethanol samples, reaching 800 mm^2. This was followed by sugarcane bagasse bioethanol with 4 g yeast at 752 mm^2, pineapple peel bioethanol with 4 g yeast at 676.7 mm^2, and pineapple peel bioethanol with 8 g yeast at 646 mm^2.

Flame duration was then measured to determine the burning time of each tested fuel from ignition until the flame was completely extinguished. The flame-duration results are presented in Table 4 and visualized in Figure 7.

Table 4. Flame duration of each tested fuel at different fuel volumes

Fuel type	**Volume 1 mL**	**Volume 2 mL**	**Volume 3 mL**
Sugarcane bagasse bioethanol, 4 g yeast	30	60	80
Sugarcane bagasse bioethanol, 8 g yeast	36	58	70
Pineapple peel bioethanol, 4 g yeast	37	64	74
Pineapple peel bioethanol, 8 g yeast	29	51	69
Ethanol	31	48	71
Pertamax	32	51	72

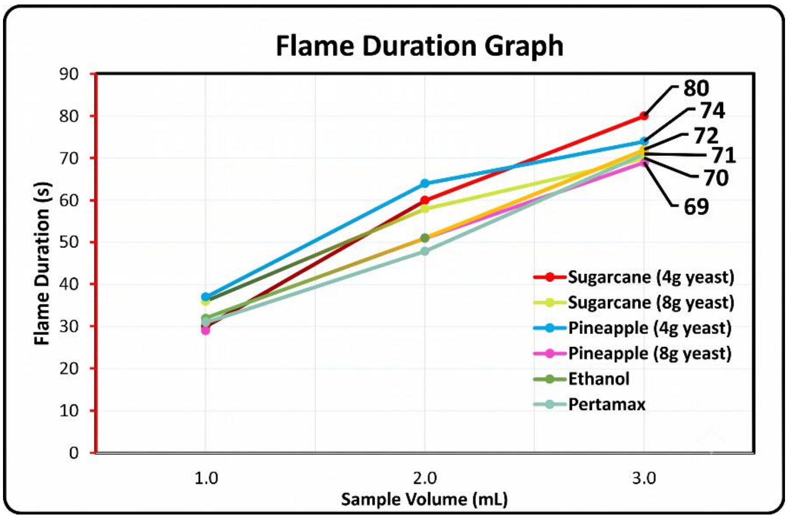

Figure 7. Flame-duration comparison of each tested fuel at different fuel volumes

Based on Table 4 and Figure 7, the flame duration of all tested fuels increased as the fuel volume increased. At 1 mL, pineapple peel bioethanol with 4 g yeast showed the longest flame duration, at 37 s. At 2 mL, the same sample also produced the longest duration, at 64 s. At 3 mL, sugarcane bagasse bioethanol with 4 g yeast showed the longest flame duration, reaching 80 s. The flame-duration values of pineapple peel bioethanol were relatively close to those of ethanol and Pertamax, particularly at the 3 mL volume.

Discussion

The results indicate that bioethanol produced from sugarcane bagasse and pineapple peel waste showed different physical and combustion characteristics. Based on Table 1, pineapple peel bioethanol had a boiling-point range of 80–85°C, which was closer to the boiling point of ethanol than sugarcane bagasse bioethanol, which ranged from 85–90°C. This difference suggests that the pineapple peel sample may have contained a higher ethanol fraction or lower residual water content than the sugarcane bagasse sample. However, this interpretation should be treated as an indication rather than a direct purity measurement because ethanol concentration and water content were not quantified using analytical instruments. In bioethanol production, purification quality is strongly related to the efficiency of fermentation and distillation, while ethanol yield can also be affected by substrate composition, microbial activity, fermentation conditions, and water content in the final product [16], [17]. The role of water is also important because a higher water fraction in ethanol-based fuels can reduce burning velocity and modify combustion behavior [18].

The visual flame patterns in Figure 4 support the physical-characteristic results by showing observable differences in flame color, height, and shape among the tested fuels. The bioethanol and ethanol samples generally produced bluish flames, whereas Pertamax showed a taller flame with a brighter yellow-white region. This visual difference can be associated with differences in fuel composition, volatility, oxygen content, and energy density. Studies on multicomponent pool fires have shown that flame height, flame temperature, and burning rate are influenced by fuel composition and vapor–liquid behavior during combustion [19]. Similarly, ethanol–gasoline combustion studies indicate that variations in ethanol fraction and ambient combustion conditions can change flame morphology, flame height, and heat-release behavior [20]. Therefore, the flame differences observed in this study should not be interpreted only as a result of the raw material source, but also as a combined outcome of fuel composition, evaporation behavior, and the remaining water fraction in each bioethanol sample [21].

Based on Table 2 and Figure 5, Pertamax produced the highest flame height at all fuel volumes. This pattern is reasonable because commercial gasoline-type fuels generally have higher energy density and different volatility characteristics than ethanol-based fuels. Among the waste-derived bioethanol samples, pineapple peel bioethanol with 8 g yeast produced the highest flame-height values and was closest to ethanol. This finding suggests that the pineapple peel substrate, particularly under the 8 g yeast condition, produced a fuel sample with combustion behavior closer to ethanol than the sugarcane bagasse samples. However, the result should not be interpreted as proof that a higher yeast dose always improves bioethanol quality. Ethanol yield depends not only on yeast quantity but also on available fermentable sugars, nutrient balance, fermentation time, pH, temperature, and possible substrate inhibition [17]. Previous ethanol-combustion studies also show that alcohol-based fuels can behave differently from gasoline because of their oxygen content, lower heating value, and higher latent heat of vaporization [22], [23].

The flame-area results in Table 3 and Figure 6 provide a complementary view of flame spread. Pertamax again produced the largest flame area at all tested volumes, confirming that its visible flame spread was greater than that of the bioethanol samples. Among the waste-derived samples, sugarcane bagasse bioethanol with 8 g yeast showed the largest flame area at 3 mL, although pineapple peel bioethanol with 8 g yeast showed the highest flame height among the bioethanol samples. This indicates that flame height and flame area did not always follow the same pattern. A fuel may generate a taller flame without necessarily producing the widest flame spread. Such differences are plausible because flame geometry is affected by evaporation rate, local fuel vapor concentration, air entrainment, and heat-release distribution. Studies on ethanol–gasoline and alcohol-containing blends also show that changes in fuel composition can affect combustion behavior in different ways, depending on the observed parameter [24].

The flame-duration data in Table 4 and Figure 7 show that all samples burned longer as the fuel volume increased. This trend is expected because a larger fuel volume provides more combustible material and therefore extends burning time. At 3 mL, sugarcane bagasse bioethanol with 4 g yeast produced the longest flame duration, reaching 80 s, while pineapple peel bioethanol showed values closer to ethanol and Pertamax. This result indicates that longer flame duration does not necessarily mean better fuel quality. A longer burning time may be related to slower evaporation, higher water content, or lower combustion intensity. Therefore, flame duration should be interpreted together with flame height, flame area, and the physical characteristics in Table 1. Studies on ethanol-based fuels in spark-ignition engines also show that the effect of ethanol depends on several interacting fuel properties, including lower heating value, oxygen content, vaporization behavior, and combustion temperature [25].

Overall, the present findings show that sugarcane bagasse and pineapple peel waste can be converted into bioethanol with observable combustion characteristics, but the two feedstocks produced different flame responses. Pineapple peel bioethanol showed a boiling-point range closer to ethanol and relatively high flame-height values, especially with 8 g yeast. Sugarcane bagasse bioethanol, particularly with 8 g yeast, showed a relatively large flame area at higher fuel volume, while sugarcane bagasse bioethanol with 4 g yeast produced the longest flame duration at 3 mL. These results extend previous work on ethanol-based fuels by providing a simple comparative observation of waste-derived bioethanol using flame height, flame area, and flame duration as preliminary combustion indicators. However, the findings should be positioned as preliminary fuel-characteristic evidence rather than direct evidence of engine performance or emission reduction. Engine-based studies show that the behavior of ethanol-containing fuels depends strongly on engine setting, fuel blending ratio, ignition timing, load, and control strategy [26]. Therefore, further testing using direct ethanol-content measurement, water-content analysis, repeated trials, and controlled engine experiments would be needed before stronger claims about fuel performance can be made.

CONCLUSION

Conclusion

This study demonstrates that sugarcane bagasse and pineapple peel waste can be processed into bioethanol through hydrolysis, fermentation, and distillation. The bioethanol produced from both waste materials showed different physical and combustion characteristics, indicating that the type of biomass feedstock and fermentation condition may influence the quality of the resulting fuel. Pineapple peel bioethanol showed a boiling-point range closer to ethanol than sugarcane bagasse bioethanol, suggesting a better initial quality indication. In the flame-characteristic test, pineapple peel bioethanol with 8 g yeast produced flame-height values closer to ethanol, while Pertamax still produced the highest flame height and flame area overall. Sugarcane bagasse bioethanol also showed measurable combustion potential, particularly in flame area and flame duration at certain fuel-volume variations. Overall, the findings indicate that sugarcane bagasse and pineapple peel waste have potential as alternative biomass feedstocks for preliminary bioethanol production. However, the results should be interpreted as an initial assessment of physical and flame characteristics rather than direct evidence of engine performance or emission reduction. Further studies are needed to measure ethanol concentration, water content, calorific value, and combustion performance under more controlled conditions, including direct testing in internal combustion engines with defined fuel-blend variations.

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