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Catalytic Valorization of Organic Solid Waste: A Pilot-Scale Run of Sugarcane Bagasse

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Abstract: Organic solid waste treatment is crucial for enhancing environmental sustainability, promoting economic growth, and improving public health. Following our previous organic solid waste upgrading technique, a further two-step pilot-scale run, using sugarcane bagasse as the feedstock, has been successfully conducted with long-term stability. Firstly, the sugarcane bagasse was treated under mild conditions (400 °C and 1 bar of CH_4), and this catalytic Methanolysis treatment resulted in a bio-oil with a yield of 60.5 wt.%. Following that, it was subjected to a catalytic Methano-Refining process (400 °C and 50 bar of CH_4) to achieve high-quality renewable fuel with a liquid yield of 95.0 wt.%. Additionally, this renewable fuel can be regarded as an ideal diesel component with a high cetane number, high heating values, a low freezing point, low density and viscosity, and low oxygen, nitrogen, and sulfur contents. The successful pilot-scale catalytic upgrading of sugarcane bagasse further verified the effectiveness of this methane-assisted organic solid waste upgrading technique and confirmed the high flexibility of this innovative technology for processing a wide spectrum of agricultural and forestry residues. This study will shed light on the further valorization of organic solid waste and other carbonaceous materials.

Keywords: sugarcane bagasse; methane; catalytic upgrading; renewable biofuel

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Citation: Li, Z.; Omidkar, A.; Song, H. Catalytic Valorization of Organic Solid Waste: A Pilot-Scale Run of Sugarcane Bagasse. *Catalysts* **2024**, *14*, 568. https://doi.org/10.3390/catal14090568

Academic Editors: Hugo de Lasa and Carlos Omar Castillo Araiza

Received: 26 July 2024
Revised: 26 August 2024
Accepted: 27 August 2024
Published: 28 August 2024

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1. Introduction

The treatment and valorization of organic solid waste, including materials like wood chips, rice straw, corn stover, sugarcane bagasse, and other agricultural and forestry residues, is of significant importance and has attracted considerable interest globally due to the following reasons [1–6].

Firstly, the treatment of organic solid waste helps to reduce the volume of waste that would otherwise end up in landfills or incineration. This mitigates the associated environmental problems, such as methane emissions from anaerobic decomposition, emission of greenhouse gases, and the release of particulate matter of PM 2.5/PM 10, causing severe air pollution, like haze. Secondly, it helps minimize pollution and protect the environment. Untreated organic waste can lead to soil and water pollution through leachate and runoff. Treating these wastes prevents such contamination, protecting our ecosystems and water resources. Thirdly, it promotes the utilization of these valuable natural resources, with a better and more profitable approach. Organic solid wastes normally contain valuable carbon and hydrogen atoms and should be converted to valuable commodities to comply with the atomic economy. Converting organic solid waste into valuable products like bio-oil, biochar, and renewable fuels transforms waste materials into economic assets. This can provide additional income streams for farmers and industrial practitioners. Lastly, it helps to reduce greenhouse gas emissions and can enhance the production of biofuels and chemicals. Properly treated organic waste can be converted into renewable fuels, which emit much fewer greenhouse gases compared to conventional fossil fuels. This contributes to efforts to combat climate change. Utilizing agricultural residues as feedstock for biofuel

production can further promote sustainable farming practices by recycling nutrients and reducing the need for synthetic fertilizers [7–11].

Sugarcane bagasse is the fibrous byproduct that remains after the extraction of juice from sugarcane stalks. It is a lignocellulosic material composed mainly of cellulose (40–50 wt.%), hemicellulose (25–30 wt.%), and lignin (20–25 wt.%) [12]. In addition, sugarcane bagasse is abundantly available in regions where sugarcane is processed and is conventionally regarded as low-cost waste from sugar-producing factories. It is reported that the global production of sugarcane bagasse is around 0.8 billion tons annually, with the possibility of further increase due to the development of the sugar industry. Therefore, valorizing sugarcane bagasse, or converting it into valuable products, is crucial for economic benefits, since it will create additional revenue streams for sugarcane processors and farmers. Also, it will reduce the environmental impact of waste disposal. Further, the utilization of bagasse in bioenergy and bioproducts supports the transition to a circular economy and reduces dependence on fossil fuels. By developing innovative technologies and processes to treat and convert sugarcane bagasse, we can enhance its economic value and contribute to sustainable agricultural and industrial practices [12–14].

The development of efficient waste treatment technologies stimulates innovation and advancements in the bioengineering, catalysis, and renewable energy sectors. The biofuel derived from biomass feedstock normally suffers from high oxygen concentration with low heat value and a high TAN (total acidic number), which requires the deoxygenation process as the prerequisite [4,7,11]. The well-established and widely applied hydrotreating processes are employed to enhance the biofuel properties under high pressure of H_2 assisted by the costly catalysts which normally contain noble metals. These processes involve significant capital and operational costs mainly due to the severe hydrotreating conditions, pretreatment unit operations, and costly catalysts. Furthermore, H_2 is not naturally available and is often produced via unfavorable methane reforming with enormous energy and water consumption and CO_2 emission. Also, the hydrotreating of bio-oils always produces a large amount of water, which may significantly increase the pressure and cause corrosive issues and safety concerns to the unit [15,16].

Meanwhile, natural gas is another abundant natural resource worldwide with its main component of methane. Due to its chemical inertness (strong C-H bonds and highly symmetrical structure) and low volumetric energy density, natural gas is currently dominantly used for residential heating. Therefore, its value is thus often underestimated [17–21]. In this context, developing a technology that can utilize and convert biomass in the presence of natural gas/methane will attract the attention of both industry and academia [22].

It was discovered that catalytic methane conversion can be realized under mild conditions with the co-existence of organic molecules including both heavy crude oil and light hydrocarbons [23–26]. Following that, a methane-assisted conversion platform has been established [16,27–41]. Furthermore, our research group has verified that high-value-added commodities such as BTEX can be produced from various types of bio-derived feedstocks and oxygenated model compounds including ethanol, acetic acid, acetone, glycerol, phenol, cellulose, furfural, lignin, and especially sawdust and rice straw [4,16,20–22,30–40].

A small-scale pilot unit with a capacity of 50 kg/day has been designed and constructed, with three main catalytic reactors following our bench-scale studies [20,21]. The biomass feedstock was fully utilized and converted to liquid fuel and cleaned syngas through carefully designed reaction processes and specifically tailored catalysts. Several 30-day catalytic runs have been successfully conducted with three types of the most abundant agriculture and forestry waste materials (pelleted wood chip, crushed rice straw, and crushed corn stover) as feedstock. The feasibility, long-term stability, wide adaptability, and environmental friendliness of this novel process are confirmed by the detailed feedstock and product analysis, comprehensive TEA (techno-economic assessment), and LCA (life cycle analysis). This novel technique provides a new possibility for the co-utilization of biomass and natural gas, which is beneficial for both energy supply and environmental protection [4].

To expand the versatility and generality of this technique and also to address the issues identified in previous runs, another form of abundant agricultural waste, sugarcane bagasse, has been applied to this unit with slightly tuned operational conditions and catalysts. It was observed that the powdered-form catalyst used previously can not circulate well as required by the fluid-bed reactor. Also, the biochar regeneration process encountered occasionally poor performances due to the encapsulation of the too-fine catalyst particles, as well as the large demand for cyclone separation. Therefore, a new catalyst with a better abrasion index was manufactured and applied in this study.

2. Results and Discussion

2.1. Properties of Feedstock

Table 1 lists the crucial properties of the feedstock used in this study, which is the dried and crushed sugarcane bagasse. It is noted that the sugarcane bagasse has a high amount of volatile matter of 82.64 wt.%, which is higher than the other three types of organic solid waste materials reported before [4], implying a possible higher yield of valuable organic products. The ash amount is 3.79 wt.%, which is higher than the wood chips, yet considerably lower than the rice straw and corn stover, making it an outstanding feedstock in the herbaceous plants. The moisture content was controlled to be 5.22 wt.% to save energy for heating in pyrolysis and to ensure the right capacity for the following gas/liquid separation. Further, the low moisture concentration will have benefits: enabling a smooth operation and reducing the maintenance needed for the unit. The elemental analysis gives very consistent C and H contents with the raw materials reported before. A low atomic molar ratio of H/C (~1.5) is observed, which requires either a decarbonization process or a hydrotreating process to increase the H/C ratio for the final products. As CH_4 has the highest H/C molar ratio (4) among all naturally existing organic compounds, the co-conversion of CH_4 with the sugarcane bagasse could be a promising and profitable approach. It is further noted that the nitrogen and sulfur contents are much lower compared with other materials, making the sugarcane bagasse an excellent precursor to produce biofuel.

Table 1. Physicochemical properties of the sugarcane bagasse.

Proximate Analysis (wt.%)				Heating Value (MJ/kg)	Ultimate Analysis (wt.%)				
Moisture	Volatile Matter	Fixed Carbon	Ash		C	H	N	S	O
5.22	82.64	8.35	3.79	24.5	46.55	5.92	0.12	0.09	47.32

However, its oxygen content is rather high, which means that severe conditions are required for deoxygenation to qualify it as an excellent biofuel precursor.

2.2. Overall Reaction Performance

Table 2 lists the overall performance of the mass balance in the ML process. It can be seen that a good overall mass balance is achieved, proving the excellent operation and reliability of this methane-assisted pyrolysis process. Compared with the other woody plants/herbaceous plants studied previously [4], sugarcane bagasse is shown to produce the lowest amount of char and the highest amount of liquid product, which is more desirable and more profitable.

Table 2. Mass balance of the Methanolysis process.

Overall Mass Balance (%)	Char Yield (%)	Gas Yield (%)	Liquid Yield (%)
94.5	12.5	21.5	60.5

Figure 1a shows a photo of the liquid product (noted as the upgraded bio-oil) achieved from the metanalysis process. This brownish liquid is then subject to the following Methano-Refining process. The Methano-Refining process, operating at 400 °C and 725 Psi, leads to a light-colored, renewable biofuel with a liquid yield of 95.0%, as shown in Figure 1b. This long-term Methano-Refining process is highly stable for 30 days; no clogging of the deactivation aspect was observed, implying that the catalyst has an excellent performance and good process stability.

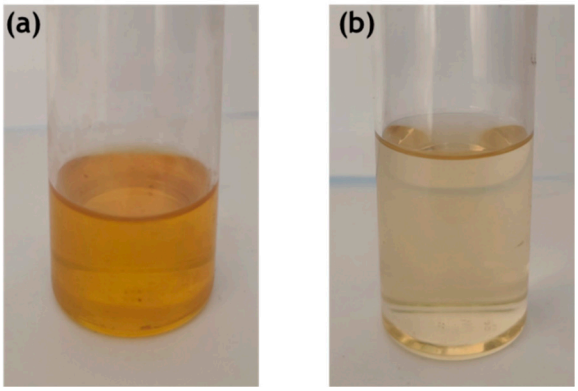


Figure 1. Photos of the upgraded bio-oil (**a**) and renewable biofuel (**b**).

2.3. Comprehensive Analysis of the Upgraded Bio-Oil and Renewable Biofuel

A comprehensive analysis of the two liquid products collected in the one-month run has been conducted at the Chinese National Petroleum and Petrochemical Products Quality Supervision and Inspection Center; the detailed results are listed in Table 3. It can be seen that Methanolysis is highly effective in ensuring property enhancement, since this one-step treatment results in much-improved and satisfactory properties. Yet, continued Methano-Refining treatment significantly enhances the properties further, making it an ideal candidate for renewable diesel.

The heating value is one of the most important factors for a fuel, which is highly related to its structures and chemical composition. The sugarcane bagasse has quite a low heating value of 24.5 MJ/kg, which is largely attributed to its high oxygen content of 47.32 wt.%, moisture, and ash amounts. Therefore, deoxygenation, together with the removal of moisture and other impurities, should be able to lead to higher heating values. As expected, the upgraded biofuel has a heating value of 29.85 MJ/kg, and the Methano-Refining process further increases its heating value to 44.57 MJ/kg by lowering the moisture and oxygen contents.

The viscosity index is another important index for evaluating the stability of viscosity over temperature changes, and a higher viscosity index is more desirable for a fuel. It can be seen that the upgraded bio-oil has a viscosity of 50; yet, the renewable biofuel has a high viscosity index of 134, confirming its excellent viscosity–temperature relationship.

The density of the bio-oil is 915.6 kg/m^3, which is slightly higher than that of regular diesel. Yet, the Methano-Refining process can lower the density to 855.4 kg/m^3 (API = 33.4), which aligns well with the density of conventional diesel.

The open flash point is measured by placing the oil sample in an open vessel and gradually raising the temperature. The oil will flash and ignite once it reaches a certain critical temperature, which is the flash point. The high flash points of upgraded bio-oil (168 °C) and renewable fuel (94 °C) indicate their limited flammability and good stability, which is important for fuel transportation and storage. A low freezing point and a low pour point normally confirm the versatility and adaptability of the oils used in low-temperature regions. It can be seen that this renewable fuel has good low-temperature mobility and can be widely used in most Arctic countries, even in harsh winters.

Table 3. Properties of upgraded bio-oil and renewable fuel.

Properties	Upgraded Bio-Oil	Renewable Fuel
Basic Kinematic viscosity (mm^2/s, 40 °C)	22.23	7.126
Kinematic viscosity (mm^2/s, 100 °C)	3.98	2.256
Viscosity index	50	134
Density (kg/m^3, 20 °C)	915.6	855.4
API (°)	22.6	33.4
Flashpoint (open cup, °C)	168	94
Freezing point (°C)	−2	−23
Pour point (°C)	3	−18
Cetane number	26	51
Heating value (MJ/kg)	29.85	44.57
	Compositional	
Saturated (wt.%)	80.25	75.48
Aromatics (wt.%)	18.5	24.51
Polar (Resin + Asphaltene, wt.%)	0.8	0.01
TAN (mg KOH/g)	8.2	0.01
Water content (wt.%)	1.17	Trace amount
Carbon residue (wt.%)	0.25	0.10
Ash content (wt.%)	0.15	0.001
Organochlorine content (ppm)	<1.0	<1.0
	Elemental analysis	
N (wt.%)	0.25	0.0036
O (wt.%)	9.7	0.02
S (wt.%)	0.17	0.06
Ca (ppm)	10.5	3.2
K (ppm)	41.2	5.7
Na (ppm)	6.5	0.5
Mg (ppm)	15.2	0.3
P (ppm)	1.5	1.0

For both oils, the major components are saturates, with a certain proportion of aromatics. The olefins are quite low, verifying their good stability and compatibility. Also, this observation is consistent with our finding for methane-assisted partial upgrading [21,22]. In addition, the concentrations of the polar components (resins and asphaltenes) are fairly low, indicating a favorable combustion behavior. The TAN for the upgraded bio-oil is rather high (8.2 mg KOH/g), with a high amount of oxygen content (9.7 wt.%). However, the Methano-Refining process removes most of the acidic groups in the molecules, realizing the TAN of 0.01 mg KOH/g with a low oxygen content of 0.02 wt.%. Not surprisingly, the water content is also significantly lowered after the Methano-Refining process and only a trace amount of water is detected, implying the favorable long-term stability of the renewable fuel.

The carbon residue of both products is controlled at very low levels, which can be regarded as an indication of the increased H/C ratio and is also consistent with the compositional analysis results. Ash content is another indicator representing the amount of non-combustible solids after full combustion. A high ash content will cause potential hazards to the engines as well as the release of PM 2.5 and PM 10 into the atmosphere. A very low ash content in the derived renewable fuel increases the relevance of certain concerns.

The cetane number is a measure of the combustion quality of diesel fuel during compression ignition. It indicates how quickly and efficiently the fuel will ignite in a diesel engine. Higher cetane numbers represent fuels that ignite more readily when injected into a high-temperature, high-pressure environment inside the engine. And a higher cetane number normally means the diesel is of better quality and higher profitability. It is noted that the cetane number for the upgraded bio-oil is only 26, which is rather low and does not meet the requirement (minimum 40) for typical diesel engines. However, the Methano-Refining process remarkably increases the cetane number to 51, making it an ideal diesel or diesel component for blending.

The Methano-Refining process also greatly decreases the nitrogen and sulfur contents, increasing concerns surrounding the NO_x and SO_x emissions after combustion in the engine. Additionally, the contents of commonly seen impurities including Na, Ca, K,

Mg, and P are all maintained at low levels and continue to decrease further with the Methano-Refining process, which is consistent with the low ash content. The low impurity concentrations, together with all the other features, further confirm that this process can lead to the production of a high-quality renewable fuel.

Real distillation curve, also known as the true boiling point curve, represents the relationship between the temperature at which different fractions of crude oil evaporate and the volume of liquid that has distilled. This curve is crucial in characterizing crude oil because it provides detailed information on the boiling range distribution of its components. Figure 2. shows the real distillation curves of the upgraded bio-oil and the renewable biofuel derived from this long-term pilot run. For the upgraded bio-oil, the distillation spans from 191 to 525 °C, while the methane-refining process lowers the range to 114–419 °C. Therefore, a remarkable left shift to the low-temperature end is seen from the bio-oil to the renewable fuel, confirming the lightening effect of the Methano-Refining process. It is also noted that the liquid yield of this process is as high as 95.0%, which means that only small amounts of gas and coke products formed in this treatment. Moreover, the oxygen content decreases remarkably after the treatment, and the removal of heteroatoms in the molecules significantly lowers the polarity of the molecules, leading to much lower boiling points.

Also, the mass recovery of the major distillates is detailed in Table 4. It can be seen that the upgraded bio-oil has a large amount of heavy residues (b.p. > 425 °C), while this residue is fully converted to lighter components. After the Methano-Refining process, the product contains 33 wt.% medium distillate, which can be directly blended into the diesel pool. Around 61 wt.% of gas oil is confirmed, which can treated as an excellent feedstock for the FCC or hydro-cracking units in refineries. The lightening effect as well as the conversion of heavy residues to the light ends affect the oil properties greatly, which is consistent with the treads in the other physiochemical properties such as viscosity, density, freezing point, pour point, etc.

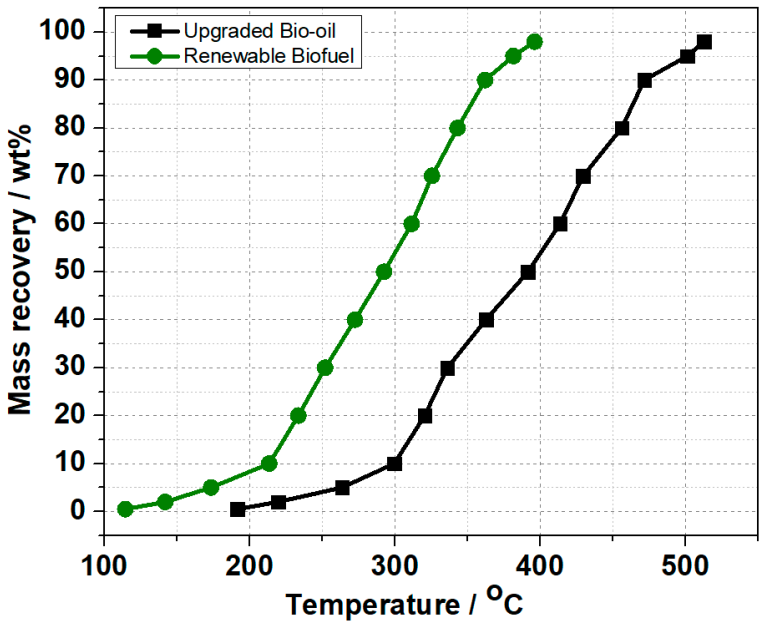


Figure 2. Real distillation curve of the upgraded bio-oil and renewable biofuel.

Table 4. Recovery of several typical distillates of upgraded bio-oil and renewable biofuel.

Distillates	Upgraded Bio-Oil	Renewable Biofuel
Naphtha (wt.%) (<180 °C)	0	6
Medium distillate (wt.%) (180–270 °C)	6	33
Gas oil (wt.%) (270–425 °C)	61	61
Heavy residue (wt.%) (>425 °C)	33	0

Overall, the properties of the renewable biofuel are close to those of biofuels derived from other organic solid waste [4], confirming the versatility of this valorization technique. This technique can be further generalized to other agricultural or forestry waste.

2.4. Techno-Economic Analysis and Energy Assessment

To show the competitiveness of the proposed process with commercial petro-diesel, an analysis of the material and energy balance around the control volume has been carried out on an industrial scale. Aspen Plus v 12.1, has been utilized for the material and energy balance. Based on the energy balance and operational cost, the break-even price of the produced renewable diesel is 3.5 USD/gal. The energy balance over control volume is also depicted in Figure 3. As can be seen from Figure 3, the heat value of the product is higher compared to that of raw material. Thus, the upgrading has not only been carried out in the economical aspect; the calorific value of the products has also been valorized.

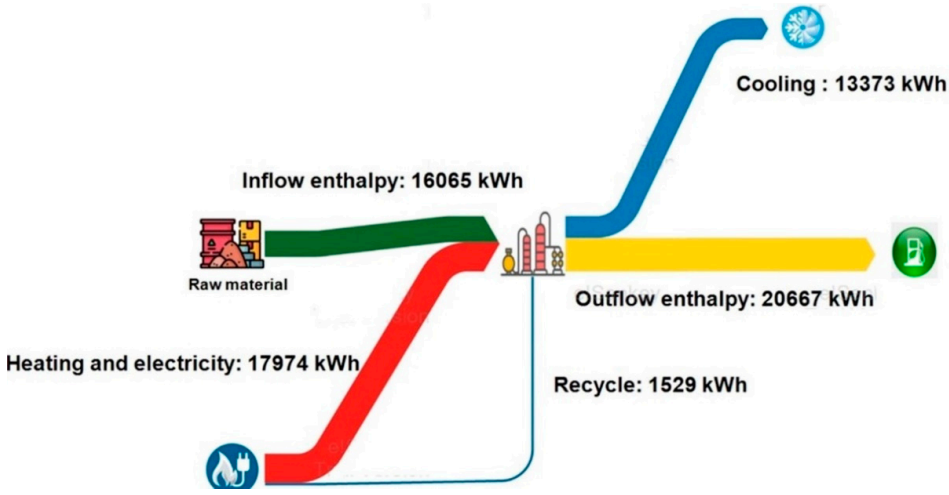


Figure 3. Energy balance of upgrading plant.

3. Experimental Process

3.1. Process Unit

Detailed information on the pilot-scale unit, reaction process, operational parameters, catalysts, and product analysis can be found in our previous studies [4,20], with some minor modifications.

Figure 4 presents the schematic diagram of the system for the sugarcane bagasse conversion process, which includes three major sections.

The first section is the Methanolysis (ML) process, with a fluidized bed reactor and regenerator, which is similar to a typical FCC riser. This process has been modified considerably from the previous unit. Previously, a powdered form catalyst was used in this reactor and some circulation issues were observed. Also, a relatively large amount of fine powder was collected after the cyclone separation. The particle size and moisture content of the feedstock need to be tuned more carefully for smooth run. Here, natural gas was heated to a certain temperature and introduced into the fluid-bed reactor together with the catalyst circulated from the regenerator. Meanwhile, the crushed sugarcane bagasse was simultaneously injected into the system as the feedstock. The products exited from the top of the reactor and were separated by two cyclones. The products underwent cooling for heat exchange and the gas and liquid products were separated using a typical two-phase separator. The liquid phase was noted as the upgraded bio-oil, which was sent to the 2nd reactor for methane-assisted upgrading. Meanwhile, the gas product was used as the feedstock for the 3rd reactor.

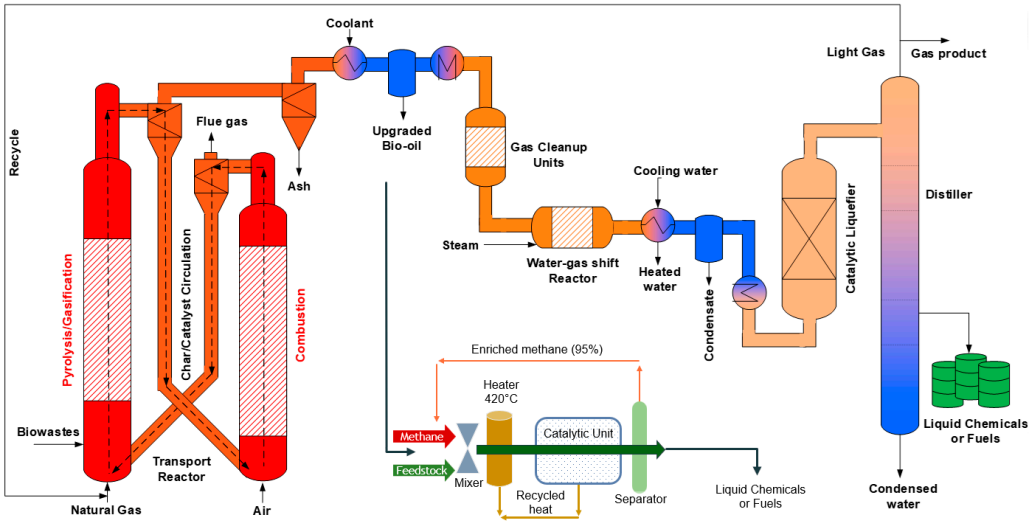


Figure 4. Schematic illustration of the methane-assisted organic solid waste valorization process.

The second section is called the Methano-Refining (MR) process; its purpose is to improve the quality of the upgraded bio-oil, which can be performed by enhancing the cetane number and heating value, lowering the oxygen content and freezing point, etc. This bio-oil was then reheated and co-fed into the MR fixed-bed reactor along with natural gas. The products from this reactor were cooled and separated again in another gas–liquid separator to achieve a high-quality liquid product, which was noted to be a renewable biofuel in this study.

The third section is the Catalytic Liquefaction (CL) process, which focuses on the further utilization of the gas product derived from the ML process. The gas product was first treated in a three-stage purification unit to remove H_2S, NH_3, HCl, and other possible toxic gas species that may cause adverse impacts on the following catalysts, followed by a water–gas shift reactor to adjust the H_2/CO ratio. Following that, the cleaned syngas was subjected to the Fischer–Tropsch (F-T) process to produce liquid fuel and other valuable chemicals. In this work, special attention is given to detailing the first two processes, since the F-T process is well known.

3.2. Catalysts Preparation

In total, 3 types of tailored catalysts were used to realize the conversion of sugarcane bagasse under mild conditions. They are noted as Cat-ML, Cat-MR, and Cat-CL, and were used in these three aforementioned processes, respectively.

The catalyst was developed and optimized during the lab-scale studies and verified by using three other biomasses (pelleted wood chips, crushed rice straw, and crushed corn stover), as reported in our previous research [4]. In this study, the catalyst was the same with slight differences in the manufacturing process. The role of Cat-ML is to facilitate the pyrolysis of biomass in the presence of methane. Cat-ML needs to realize the activation of methane at mild conditions, while helping the pyrolysis of sugarcane bagasse to achieve a high amount of gas and liquid products. Therefore, two components were designed and prepared to fulfil their desired functions. As for the Cat-MR, the major function is to partially upgrade the bio-oil into a renewable fuel in the presence of methane. The catalyst was developed based on previous studies of methane-assisted heavy oil upgrading and methane-assisted deoxygenation studies. Ag and Ga were doped to ZSM-5-activated methane; co-doping of Co and Mo will enhance methane activation and eliminate heteroatoms; meanwhile, the introduction of Ce will help in prohibiting the coke yield, resulting in a higher liquid yield and contributing to a stable long-term run.

In contrast to our previous report, the Cat-ML was prepared via a spray-drying method instead of through the incipient-wetness impregnation method that was reported previously to comply with the requirements of a fluid-bed reactor, with better mobility

and a smaller abrasion index. On the other hand, Cat-MR and Cat-CL were extruded from the precursors, with a pellet shape, enabling them to fit the fixed-bed reactor, as described previously [4].

Cat-ML: A fine powder (Cat-ML-A) with the chemical composition of 10 wt.%K-10 wt.%Mg/38 wt.%SnO_2-29 wt.%Fe_2O_3-33 wt.%Al_2O_3 was prepared. Then, another powdered form catalyst (Cat-ML-B) with the formula of 1 wt.%Ag-1 wt.%Ga-2 wt.%Co-6 wt.%Mo-10 wt.%Ce/HZSM-5 (Silica to Alumina ratio of 23) was prepared. The detailed preparation method is listed in the previous report [4]. Following that, a composite slurry was prepared by admixing 40 wt.% of Cat-ML-A, 40 wt. % Cat-ML-B, and another 20% of inorganic binder, which is Ludox HS 40 (40 wt % SiO_2 dispersed in aqueous media). Additional water was added to maintain the slurry at a concentration of 20 wt.% based on the solid content. Then, the slurry was homogenized with a ball mill for 1 h followed by the spray-drying process. The collected powder was subjected to calcination in a static oven at 500 °C for 4 h. Finally, the sieved portion of the catalyst within the particle size of 20–90 µm was used as the Cat-ML catalyst. Its abrasion index was determined to be 2.1%, which is due to the relatively large amount of silica gel that was used as the binder. Further, this low abrasion index helps to maintain the stable long-term run with a low catalyst compensation rate. The surface area and pore volume of this catalyst are 85.3 m^2/g and 0.12 mL/g; these values are slightly smaller than those of the typical FCC additives. However, the pyrolysis process will not generate heavy crudes and there is no need for large porosities.

3.3. Reaction Process

It is found that the particle size and moisture of the feedstock can significantly influence the stability of the Methanolysis; this is based on the previous runs using pelleted wood chips, crushed rice straw, and crushed corn stover. In this experiment, the sugarcane bagasse was used after a careful crushing and drying process, with a feeding rate of 70 g/min into the reactor. The fresh catalyst loading amount was 35 kg, with a daily compensation of around 200 g to maintain the required inventory, while the temperature was controlled to be 400 °C. Natural gas with a pressure of 15 Psi was used as the atmosphere with a flow rate of 2 m^2/min to facilitate the pyrolysis of sugarcane bagasse. The produced gas and liquid were subjected to the Catalytic Liquefaction and Methano-Refining processes, respectively. The char yield was calculated based on the coke deposition on the spent catalyst.

The operating parameters were mild in the Methano-Refining process. The reaction temperature was kept at 400 °C yet the pressure was 725 Psi. The liquid hourly space velocity (LHSV) was 1 h^{-1}, and the gas flow rate was 500 sccm.

The operating parameters for the Catalytic Liquefaction (CL) process were also mild. The temperature was 450 °C, the pressure was 50 Psi, and the gas hourly space velocity (GHSV) was set to be 1200 h^{-1}.

The experiment continued for 30 days without noticeable deactivation.

3.4. Feedstock and Products Characterizations

In this experiment, both the feedstock and the products are subject to comprehensive characterizations complying with the ASTM (American Society for Testing and Materials) methods or Chinese national standards. The properties of the liquid products including viscosity, density, flash point, freezing point, pour point, compositional analysis, TAN, water content, carbon residue, ash content, cetane number, heating value, elemental analysis, and real distillation are carefully characterized. The detailed analysis methods can be found in the previous report [4].

4. Conclusions

This study utilizes a novel two-step catalytic process to transform sugarcane bagasse into high-quality renewable fuel under mild conditions, achieving an impressive overall liquid yield of 57.0 wt.%. The renewable fuel produced through this innovative process exhibits characteristics that make it an ideal diesel component: high cetane number, high

heating values, low freezing point, low density and viscosity, and minimal oxygen, nitrogen, and sulfur content. In addition, its profitability has been confirmed by a TEA analysis. The successful pilot-scale implementation of this innovative, methane-assisted organic solid waste upgrading technique confirms its efficacy and versatility in processing a wide range of agricultural and forestry residues. This study highlights the potential of this groundbreaking technology in enhancing the valorization of organic solid waste and other carbonaceous materials, paving the way for a more sustainable and efficient biofuel production method.

Author Contributions: Z.L. conducted the original draft, data curation, formal analysis, investigation and methodology. A.O. conducted the review & editing, validation, software. H.S. conducted review & editing, validation, funding acquisition, project administration, resources, and supervision. All authors have read and agreed to the published version of the manuscript.

Funding: Natural Sciences and Engineering Research Council of Canada (NSERC) through Alliance Grant program (ALLRP/560812-2020) and Alberta Innovates (G2020000355).

Data Availability Statement: Date will be made available on request.

Acknowledgments: The authors gratefully acknowledge the financial supports from Kara Technologies Inc.

Conflicts of Interest: The authors declare no conflicts of interest.

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