International Journal of Advances in Engineering and Management (IJAEM)
Volume 3, Issue 5 May 2021, pp: 972-981 www.ijaem.net ISSN: 2395-5252

Bioconverters for biogas production from bloomed water fern and duckweed biomass with swine manure co-digestion

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Submitted: 05-05-2021 Revised: 17-05-2021 Accepted: 20-05-2021

ABSTRACT: The pursuit for sustainable biomass resources has been driven by the need for bioenergy sources that are not dependent on proven oil or water supplies and the depletion of established fossil fuel reserves and the continued rise in greenhouse gas emissions. Another problem that has emerged from the food crisis is that their crops are now considered viable energy sources. Water fern and duckweed are very attractive and desirable biomass feed sources, so using them as a biomass feed source is more than a bonus. This study offers a vision for integrated aquatic and biogas development that decreases land use while also lowering fresh water and fertilizer requirements while also considering the treatment's demonstrated ability to stimulate phytates and bioenergy growth in planting and bioenergy systems. Also, animal manure on a huge available biomass source for biogas production.The biogas output from bloomed water fern and duckweed biomass combined with co-digestion of swine manure resulted that methane and carbon dioxide on 35 days was achieved to 64.6 and 34.2 %, respectively.This study suggested that the water fern and duckweed with swine manure could serve as a reliable biomass energy source to produce biogas.

KEYWORDS: Water Fern, Duckweed, Swine Manure, Bioconverter, Biogas Production

I. INTRODUCTION

Anaerobic digestion (AD) is a promising method for transforming biowaste into long-term energy, heating, drying, and cooling source [1, 2]. However, in order to generate bio-based energy efficiently, these factors must be extensively researched due to technical, political, social, and economic changes. Recent studies have focused on the current state of biowaste use, biowaste conversion processes, and process parameters to satisfy demand [3]. In addition, environmental changes and the decline of fossil fuels have generated a massive demand for technology that can substitute renewable energy sources for conventional oil.

According to a recent forecast, global demand for primary energy will rise by 48% between 2012 and 2040 [4]. As a result, 84 % of total electricity will be produced by liquid fuels, coal, natural gas, and nuclear power in 2040, down from 91 % in 1990. On the other hand, renewable energy sources will see a 9 % to 16 % rise in global energy demand in the coming years. As a result, by2040, nonrenewableresources would have decreased from 78 % to 71 %. As a result, energy sources are in high demand around the world.Biogas produced from anaerobic digestion of organic substances such as food wastes, cellulosic biomass, and animal waste can be used as fuel for cooking,operating engines, and generating electricity [5]. Thailand has set a new renewable energy target of 30% of total final energy consumption by 2036 in its Alternative Energy Development Plan (AEDP) and can achieve a high energy level from bio-power by 2036 [6].

These energy sources could be used to replace nonrenewable energy sources such as coal and petroleum, which are expected to become more expensive in the near future due to rising demand and scarcity [7]. Furthermore, the pollution emitted by such traditional fuels pollutes the environment and contributes to global warming. On the other hand, renewable energy sources emit very little carbon, assisting in the fight against climate change caused by fossil fuels. Furthermore, among the various renewable energy conversion technologies, biochemical conversion has proven to be one of the most effective methods for converting biowaste into a useful energy source (biogas) [8].

This technology can convert organic waste into biogas, which can be used for cooking, lighting, and power generation, among other things. However, because it is one of the most recent classifications, electricity from urban/rural waste ranks lowest in its renewable energy mix. Therefore, the main idea behind the biowaste utilization technique is to recycle energy from urban wastes in order to reduce emissions while also producing energy.

As a result, because it is one of the most recent classifications, electricity generated by the urban/rural waste strategy ranks slightly lower in its renewable energy mix [9]. Many countries rely on thermochemical (biomass gasification) and biochemical conversion (biogas) bio-power to supply energy for lighting, cooking, and power generation.

There is much potential for using anaerobic digestion as waste management and energy production technology in Thailand and worldwide. However, before implementing proper digestion technology, it is observed that adequate feedstock/biowastes for the proposed biogas plant size must be ensured. Many countries have recently prioritized biogas technology due to its importance in waste management, power generation, reduced workload for women, improved sanitation, removal of chemical fertilizers, and replacement of traditional fuel cooking [10].

Educational institutions generate a significant amount of biowaste, which varies depending on the number of employees and students. In contrast to schools, biogas plants can be effectively introduced in universities and colleges through adequate knowledge and training programs [11]. Additionally, for the device to operate correctly, households must be appropriately trained to operate and manage it. Educational institutions generate a significant amount of biowaste, and individuals can easily be trained to manage waste disposal mechanisms following the digester's operational requirements.

However, due to unstable biowaste generation and a lack of knowledge about economic viability, many educational institutions have been unable to implement these programs successfully. Therefore, even though waste management systems generate energy for heating, lighting, refrigeration, and other purposes, a thorough examination of the current situation is necessary before implementing biochemical conversion of biowaste in a variety of areas, including the availability of biowastes, feeding biowastes to various types of biodigesters, applications, pretreatment, and co-digestion [12].

Additionally, economic factors and new policies must be considered when integrating emerging technology into existing applications. As a result, successful implementations require the convergence of several factors while also considering possible outcomes. Free-floating aquatic macrophytes include Azolla and duckweed, are available massive biowaste from the ricefield. Floating plants do not need soil or water depth to survive. Aquatic macrophytes enter holes and cause various problems due to their rapid growth, which is why many scientists consider them a pest [13].

However, they can produce huge biomass. Moreover, it has high nutritional value and several applications, including human food, animal feed, medicine, biogas production, hydrogen fuel production, water purification, weed control, ammonia volatilization reduction, and super plant due to its rapid development.It is high in protein and contains nearly all essential amino acids and minerals like iron, calcium, magnesium, potassium, phosphorus, manganese, and vitamin A precursor beta-carotene vitamin B12 [14, 15].

Figure 1: Bloomed water fern and duckweeds collection from the organic paddy field A-D).

This study also examines pretreatment and co-digestion methods for increasing AD efficacy. In this manner, biowaste sources of water fern and duckweed applied with the anaerobic co-digestion of swine manure were assessed. As a result, this research focuses on biowaste sources such as biogas to achieve a successful implementation.

II. MATERIALS AND METHODS

Biomass collection and preparation

Bloomed water fern (Azolla pinnata) and duckweed (Lemna minor) were collected from organic rice research fields near Energy Research Center, Maejo University, Chiang Mai, Thailand (Figure 1).Swine manure was obtained from the Faculty of Animal Science and Technology, Maejo University; manure available locally and stored under the same condition prior to anaerobic digestion. The biomass was blended using a mixer blender and stored at 4 °C for a maximum of 48 h prior to anaerobic digestion.

Physico-chemical analysis of biomass

Substrates (water fern, duckweed and Swine manure) were analyzed for total solids (TS), volatile solids (VS), ash content, pH, chemical oxygen demand (COD), carbohydrate, organic carbon and total nitrogen for determining various physico-chemical properties of biomass according to APHA et al. [16], and data not shown in this article.

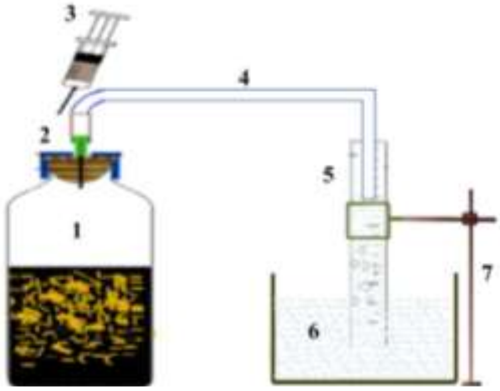

Figure 2: Fermentation system: 1) digester, 2) sealed head face, 3) sampling syringe, 4) gas transfer tube, 5) gas holder, and 6) water bath

Anaerobic digestion

The anaerobic digestion of substrates (water fern, duckweed and swine manure) was carried out using a 1 L Duran bottle (working volume 700 ml), the same substrate of swine manure used as an inoculum as well. The substrate ratios are used at the same level (1:1:1). The substrates are mixed them and the pH was set to 8.5 for all triplicate fermenters [17].

The digester was then sealed airtight, and nitrogen gas was flushed for 5 min to create an anaerobic condition inside the digester. Finally, the digesters were maintained in a room temperature-water bath during anaerobic digestion. A demonstration of the experimental setup is shown in Figure 2. All experiments were carried out in triplicate. The volume of biogas produced by the digesters was calculated by measuring the pressure of the bottle's headspace. The incubation time was approximately 45 days [1, 3]. The primary biogas composition of methane and carbon dioxide data were analyzed.

Statistical analysis

All analytical results were conducted at least in triplicate. Therefore, the data is presented as the mean ± SD of triplicate experiments.

III. RESULTS AND DISCUSSION

Biowaste use and technical solution

Biowastes are typically classified into six categories in solid waste management (paper, glass, organic, synthetic, metals, and others). Approximately 80% of this waste is used as feed in pig farms. As a result, waste disposal in the region has become increasingly important [18]. Researchers discovered an anaerobic digestion process using a single-stage bioreactor that could successfully co-digest the 164 million tons of municipal solid waste produced in China to select an effective waste management technology.

Studies on the potential of five biowastes for biogas production in Kenya show that biowastes can produce 3916 GWh of electricity and 5887 GWh of thermal energy, with a maximum methane generation 1313 million cubic meters. Kenya's annual power output of 73% equals the total electrical capacity of the country. In Iran, biogas from livestock manure has been described as a low-cost alternative to fossil fuels [19].

Based on the number of cows, the amount of manure produced, and the amount of biogas produced, this conclusion was reached. According to experimental and theoretical studies, biogas produced from livestock manure can replace approximately 3% of natural gas consumption in each Iranian province. The potential of human excreta as a biogas production in Indonesia confirms that it can produce 106.85 m^3 of biogas per day or 652.91 kWh per day. Because of the country's large population and unequal energy distribution, biogas output from human excreta has also been significant [20]. According to studies on many renewable energy sources such as solar, wind, hydro, and biomass, biogas plants and biomass briquetting are more valuable.

This technology was demonstrated in Bangladesh, where a population of 24 million cattle and 75 million poultry produced three billion cubic meters of biogas. Compared to two-stage digesters, supermarket waste could be successfully anaerobically digested, yielding 40L CH_4/g of methane. Thus, instead of being disposed of in landfills, supermarket waste could be used to generate renewable energy for heating and electricity, lowering GHG emissions and improving solid waste management [21].

Biowaste conversion method and technologies on biogas production through the anaerobic digestion system

Any organic waste can be used as biowaste in biogas processing. The most common biowaste conversion processes are described in detail (Figure 3). Numerous studies have shown that new technologies and processes have increased biogas capacity and that, depending on the biowaste, a combination of processes can increase biogas production and quality. The temperature has a significant impact on the production of biogas from food waste. Biogas production is typically higher under thermophilic conditions, defined as temperatures between 55°C and 65°C, than under mesophilic conditions, defined as temperatures between 35°C and 45°C [10]. By varying storage time and temperature, the effects of anaerobic digestion on slurry growth were investigated. It was discovered that keeping the slurry at 9°C for 26 hours had no significant effect on biogas output.

After 8 weeks, however, the slurry kept at 20°C harmed biogas output. Under mesophilic conditions, the co-digestion substrate has a greater effect on biodegradability and methane yield. Furthermore, substrate co-digestion and anaerobic digestion can work well together. Several studies have found that the influencing parameters in biogas production can impact the overall performance of biogas digesters. This problem could be solved if biowaste was pretreated to boost the digestion process. The effect of biogas production with different feedstocks co-digested with rice straw at different mixing ratios in a labscale with continuously stirred digesters shows that several straws (30%) co-digested different feedstocks have a disadvantage in energy balance. Using 10% less rice straw, on the other hand, resulted in a 16 % increase in methane production [22]. The energy obtained is also greater than that needed for extrusion. Therefore, the extrusion method was used as a pretreatment to increase the biodegradability of biomass.

An investigation of alkali, thermal, and combined thermo-alkaline pretreatment of straw and forage biomass at 110°C for 2 hours, 100°C for 30 minutes, and 160°C for 30 minutes found that the thermal treatment has no positive effects, but the thermo-alkaline treatment has positive results in methane production with 10% NaOH/TS]. The lignin content of lignocellulosic biomass is high [25, 26]. As a result, because wheat straw contains many lignin, the authors decided to use it as a feedstock for anaerobic digestion. Five different types of pretreatment were used to study methane extraction from wheat straw. Pretreatments with alkali and calcium hydroxide-sodium carbonate increased biogas and methane yields by 94 % and 99 %, respectively, according to the findings.

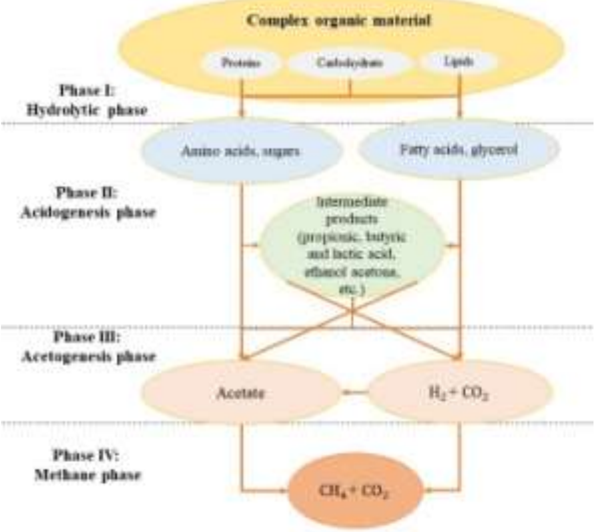

Figure: 3. Schematic of 4 phases of biogas production.

An alkaline pretreatment study with NaOH solution for a wheat plant at temperatures ranging from 0°C to 150°C is observed. It generates 47.5 % more methane, 40.8 % more methane, and 54.5 % more methane than the untreated wheat plant at 25°C, 50°C, and 75°C. Methane production did not increase at 0°C or 100°C. Scanning electron microscopy and fourier transform infrared were also used to investigate the removal of surface layers of hemicellulose and lignin and reduce crystallinity [28]. The experimental study of these pretreated particles has a positive impact on methane production and energy balance. According to the bio-methanation process with highly liquified biomass, agricultural residues are used to generate producer gas. Through proper pretreatments, such as alkali pretreatment, thermochemical pretreatment, milling, additives or nutrients, and selecting the appropriate digester type, lignified biomass could be used bio-methanation. Corn straw can increase biogas productivity when pretreated with fungus (biological treatment) and chemically treated with NaOH, ammonia, and urea [28].

Among the two pretreatments, chemical treatment increased biogas production by 207.07 % and 16.58 % more than untreated and biological treatment, respectively. Although fresh maize and maize silage have a high degradation rate in the anaerobic digestion process without pretreatment, mechanical pretreatment increases methane yield by 10%. It has also been discovered that the energy yield from fresh maize increases with the length of harvest time—the best time to harvest brown seaweeds with a beating pretreatment to generate biogas via anaerobic digestion [27]. Furthermore, biogas production can continue as usual without affecting both quantity and quality. As a result, a 2 % NaOH solution was used with Napeigrass in this study. Moreover, biogas production can be achieved as usual without affecting the quantity as well as the quality. Therefore, in this study, 2 % NaOH solution was applied with Napeigrass [29].

Co-digestion for improved biogas production

Another method for increasing biogas efficiency is co-digestion; the application system was presented in Figure 4. Under cold climatic (Psychrophilic) conditions, biogas processing using cow manure, llama manure, and sheep manure was carried out in four low-cost tubular digesters using cow manure combined cow-sheep manure and llama-sheep manure. In addition, it has been discovered that llama-sheep manure produces 50% less biogas than llama manure substrate. However, after 100 days, the co-digestion reached a stable state regarding biogas output, methane content, and pH level. Furthermore, the authors conclude that more research into llama-sheep manure is required to improve biogas generation.

Food waste and cattle manure co-digestion increased biogas yield by 41.1 % and 55.2 %, respectively, in batch and semi-continuous experiments. Improved biodegradability and C/N ratio may contribute to increased biogas yield. The co-digestion of cattle manure with C5 molasses under thermophilic and mesophilic conditions with varying Organic Loading Rates results in a strong methane yield of 31316 l/kg VS under thermophilic conditions, which is greater than the same obtained under mesophilic conditions. It is also suggested that co-digestion, particularly cow/pig manure, is an important factor in increasing biogas generation via anaerobic digestion [1, 3, 29].

In a series of studies, researchers experimented with co-digesting food waste with cow manure and sewage sludge. The experiments were conducted in both mesophilic and thermophilic environments. Pretreatment with ultrasound was used to evaluate the performance of co-digestion in both conditions. The result shows a positive methane output with an OLR of 1.2g VS/l day. Methane output falls by approximately 28%, while the OLR rises to 1.5 grams per liter per day [5]. Even under thermophilic conditions, the methane yield is found to be lower. Althoughpretreatment increased methane yield, the cost of implementing the process is not offset by biogas output.

The 17-day HRT of co-digestion of organic municipal solid wastes with animal or vegetable fat is an excellent biogas processing combination. According to the findings, animal/vegetable fat with a content of about 28% is preferable for co-digestion. When Korean food waste and piggery wastewater were co-digested, the results revealed that, while food waste produces a high methane yield, trace elements from piggery wastewater produced a high methane yield of 0.396 m^3/kg VS and 75.6 % VS destruction with no significant Volatile Fatty Acid (VFA) accumulation [7]. The anaerobic co-digestion of algal sludge with 50% of wastepaper produced 1170 75 ml/l days of methane, which was higher than the production observed when algal sludge was digested alone. Co-digestion can achieve a healthy Carbon Nitrogen (C/N) ratio of 20-25/l.

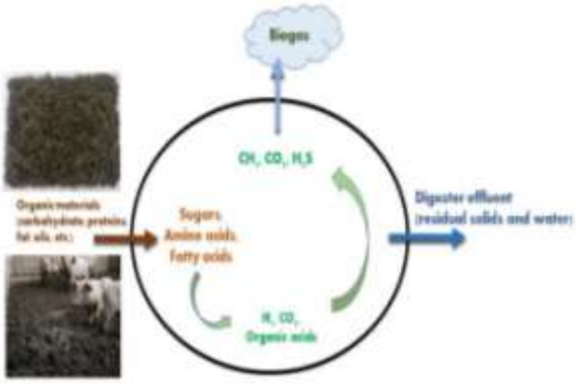

Figure: 3. Anaerobic digester process

The anaerobic co-digestion of pig slurry with four agricultural substrates (tomato, pepper, persimmon, and peach) revealed that vegetable substrates (tomato and pepper) have higher levels of lipid, protein, cellulose, and lignin than fruit substrates (peach and persimmon), which have higher levels of carbohydrates [10]. Furthermore, when co-digested with pig slurry, each substrate produced varying amounts of methane depending on the chemical combinations.

When 50% of the VS from pig slurry was co-digested, BMP increased by 41% and 44% for tomato and pepper, respectively. The genes of bacteria and archaea involved in the metabolism process of converting organic matter to methane remained unaltered during the experiment. This suggests that the degree of inclusion and substrate form may be important factors to consider when selecting agricultural byproducts and handling pig slurry [11]. According to the findings, anaerobic digestion of apple waste and swine manure in a batch process for co-digestion of apple waste and swine manure provided a stronger mixing ratio of 33:67 volatile solids.

An average methane yield and methane content were discovered when using potato waste for methane production via anaerobic digestion. When potato waste was co-digested with sugar beet, the methane yield and content increased by about 62 %. Starch-rich substrates can be co-digested with nitrogen-rich substrates for proper digestion. This industrial waste from Karanja biodiesel factories was mixed with cow dung in various proportions, and the best mixing ratio for a 73 % methane yield and an environmentally friendly fertilizer was discovered to be 25:75. The co-digestion method aids in the proper operation of the digester and the production of additional biogas. Understanding the various compositions of biowaste may aid in achieving a high methane yield [8].

The daily biogas production by the co-digestion of Mixed water fern and duckweed and swine manure for 45 days anaerobic digestion was calculated: control samples and co-digestion ratios. Table 2 confirms the main composition of the biogas produced in term of methane and carbon dioxide (%). Biogas production was first observed within initial seven days from incubation in case of the digester containing only swine manure alone (control), mixed water fern and duckweed (control), and mixed water fern and duckweed with swine manure as the feedstock. This may be due to the presence of higher amount of easily degradable organic carbon fractions in the fresh swine manure. Presence of labile carbon sources in swine manure could be easily hydrolyzed by acedogenic and acetogenic bacteria, which provide nutrient substrate to methanogenic bacteria for methanogensis [13].

On the other hand, mixed water fern and duckweed being a lignocellulosic biomass contains lignin and cellulose, which needed more time to break down into more labile carbon moieties and thus gets converted into precursor for methanogenesis. Hence, biogas production in the rest of the digester containing a mixture of mixed water fern and duckweed and cattle dung started after 14 days after incubation. In case of the digester with swine manure alone, the gas production decreased rapidly after 35 days while with the other combinations [20]. Moreover, others, the gas production sustained till 42 days. It has been observed that the log phase was higher for the mixed feedstock compared to control samples. The highest methane content was reached 64.6% by a Co-digestion fermenter.

Table 1: biogas production from Mixed water fern and duckweed and swine manure

Days	**Methane content (%)**			**Carbon dioxide content (%)**		
	Mixedwater fern and duckweed (control)	**Swine manure (control)**	**Co-digestion (1:1)***	**Mixedwater fern and duckweed (control)**	**Swine manure (control)**	**Co-digestion (1:1)***
Day 01	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0
Day 07	0 ± 0.1	0 ± 0.1	0 ± 0.2	11 ± 0.1	24 ± 0.2	13 ± 0.12
Day 14	39.2 ± 0.11	31 ± 0.13	41 ± 0.12	58.5 ± 0.1	60 ± 0.11	54 ± 0.3
Day 21	58.1 ± 0.13	37 ± 0.11	61.3 ± 0.13	40.1 ± 0.3	34.7 ± 0.3	34.7 ± 1.03
Day 28	59.3 ± 0.21	38.4 ± 1.2	63.5 ± 0.1	38.3 ± 0.2	59.1 ± 0.21	33.8 ± 1.14
Day 35	44.1 ± 0.17	32± 0.32	64.6 ± 0.21	54.9 ± 0.12	65.7 ± 0.11	34.2 ± 1.11
Day 42	33.2 ± 1.15	27 ± 0.52	62.1 ± 0.2	61.4 ± 2.11	59.7 ± 0.1	33.5 ± 0.21

Note:- ∗1:1 = Mixed water fern and duckweed and swine manure.

Anaerobic digestion system: Applications

Overall anaerobic digestion system and application approaches were presented in Figure 4. By dual-fuel running on biogas fuel, the test results that only ran for the first half of the time showed a similar number of hours. Over time, the dual-fuel engine caused significant engine wear and tear. However, the overall dual-fuel engine operated without penalty and could utilize biomethane as fuel when the biogas was very low in hydrogen, at about 0.1 ppm. The vapor-compression air conditioning with a biogas power unit using a single-cylinder, four-stroke gasoline engine (125 cm^3/rev) had significant loads and speeds that could be used as controls were measured. COP of 6.7 and 1000 rpms would be required to generate

3.5 watts of cooling capacity. Engine performance decreases above 1000 rpm [1, 2].

Biogas digesters have the potential to be viable in rural areas. The biogas replacing biomasses were as straw, and additionally, it can be used as fertilizer in the home [30]. Overall, biogas in rural areas would help the environment, cut down on chemical fertilizers, and use fossil fuels; power generation increased with varying from 60% biogas and 73% in various air/methane gas concentrations.

The comparison of biogas-enriched CNG and base-normal CNG on a dynamometer revealed that CO, HC, and NOx emissions were greater for biogas-enriched operation. Those results showed that the emission standards. It was concluded that the biogas's fuel economy was nearly equal to 24.kg/24.5 km, suggesting it could be used as a diesel fuel [4, 5]. The system was built with 3-cylinder 1.6-liter with an electric valve control for any mixture of biogas and city gas. Everything met the NOx emission standards, from various ratios and loads. This system is anticipated to reduce the costs and doable at any time, aside from improving biomass energy usage [18].

Figure 5: Biogas applications

Based on the statistics, it was estimated that the waste products in Kirkuk (north of Iraq) would rise to 1200 tonnes a day. Due to the correct treatment of solid waste, the authors predicted that the total electricity generation could be reduced to 175 MW. The Landfill biogas (LB) has poor performance, and both can be used for cooking. According to the researchers, the jet size should be altered to 1.9 mm for BB. for biogases, the ideal pressure is 10mb Butane and propane must be blended together to be interchangeable, with the Wobbe Index reading 34% indicates. The observations can be used for converting from liquefied petroleum gas (L) to biogas. It was found that the injection was effective for natural gas (or bio-fuel) fired engines that use about 95cc per spark plug (single-cylinder, four strokes S.I. engine). Absolute power from exclusive use of biomethane engines.

When coupling anaerobic digestion with the devolution, the system generates enough heat to dry the solid digestate. It can be concluded that when compared to stand-alone plants, this system will yield 42% more electricity. A study on microturbine biomethane gas generation showed that the NoX emission reduction was successful. Acceptable CO levels and less than 15 percent, and three different designs produced 13.57 MJ/m^3, 0.029 m^3 and 0.031 MJ/m^3 for each design, as a result. It was found that the optimum design between WI 21 to WI 26 MJ/m3 is in the working range [19].

The greatest amount of biogas is produced using bioelectrochemical systems (BES) in different compositions [20]. During the 20 days, an anaerobic was provided. Dairy and chicken litter from farms was used as the base. In the different production scenarios, the biogas production was found to be at 35, 45, and 65 cm3/day. The 65-centimeter-per-per-day process was found to produce the greatest COD removal [20].As a result, the amount of heat produced in the anaerobic and anoxic digestion is enough to fulfill the energy requirements for solid drying. Additionally, when compared to a standalone plants, this system could increase electricity generation by 42%.

The experimental biogas combustion and emission study results with microturbines showed that the nitrogen oxide (NOx) emissions were successfully reduced. The three different designs used WI 17.57 MJ/3, which produced less than 7.3% NOx and CO, and even when utilizing 3MJ/m^3 MJ, to CO. It was found that WI 22 MJ/m^3 was the best for the engine operating range. The greatest amount of biogas is produced using bioelectrochemical systems (BES) in different compositions. An anaerobic was kept at 35°C for 20 days. Dairy and chicken litter from farms was used as the base. The biogas production was found to be at 35, 45, and 65 cm^3/day [18-20].

IV. CONCLUSIONS

Water fern and duckweed biomass, invasive aquatic weeds,are found to be complex worldwide. Chemical and biological treatments can be applied for its growth retardation, but it may affect water quality, ultimately affecting aquatic lives. Previously reported studies proposed that the aquatic weeds can be managed and utilized using advanced techniques that changed the approach from nuisance to useful resources. It has been proved to be protein-rich and hence can be used as fodder for cattle. Exploring the feasibility of weeds has become of prime importance in any of the applications of it. However, there is a need to research large-scale management and utilization of aquatic weeds to benefit the agriculture field.This paper summarizes growth, harvest and recent development for the management and use of aquatic weeds for biogas production and potential for sustainable applications.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the School of Renewable Energy, Energy Research Centerand, Program in Biotechnology, Maejo University, for providing facilities.

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