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EFFICIENT BIOMASS CONVERSION PROCESS TO SUSTAINABLE ENERGY

Samuel Oludayo ALAMU[1], Marc J Louise Orque CABALLES[2], Xuejun QIAN[3] Seong W. LEE[4] and James G. HUNTER Jr.[5]

[1,2,3,4&5] Morgan State University, Department of Industrial and Systems Engineering, 1700 E Cold Spring Ln, Baltimore, Maryland 21251 U.S.A.

Email: Olala22@morgan.edu[1]; Macab1@morgan.edu[2]; Xuqia1@morgan.edu[3]; Seong.lee@morgan.edu[4]; James.hunter@morgan.edu [5]

ABSTRACT

A greener approach to sustainable energy production is by processing and burning biomass. Readily abundant across the globe, biomass can be obtained largely from agricultural, domestic and industrial processes. The growing concern for an energy source that is environmentally friendly, socially acceptable, and economically feasible, prompts researchers to explore the conversion of everyday biomass wastes in the form of municipal solid waste (MSW) and agricultural wastes (such as poultry litters, wood pellets) to useful energy(i.e., heat or electricity). This research work studied the two broad biomass conversion processes-thermochemical and biochemical. A comparative study was performed using poultry litter as the biomass feedstock in both conversion processes. The obtained data was justified considering the environmental, economic and social impacts of the biomass-to-energy source. At an industrial scale, biochemical processes are capital intensive as pre-treatment and post-treatment of both feedstocks and products are required. In addition, more reaction time is required for product formation and high volume of secondary wastes (sludge) are generated during the process. On the other hand, burning of biomass waste has been largely considered as a better approach due to the fact that the CO2 generated during the process is being balanced by an equivalent amount that plants capture through photosynthesis while they are growing, thus making biomass a carbon-neutral energy source. However, raw biomass possesses low density (30–50 kg/m3) and high moisture content that limits its usage for thermochemical processes. Therefore, the inclusion of a pelletizing process which allows easier economic storage, transportation, and energy conversion characteristics, is considered as an efficient and sustainable approach to biomass-to-energy conversion.

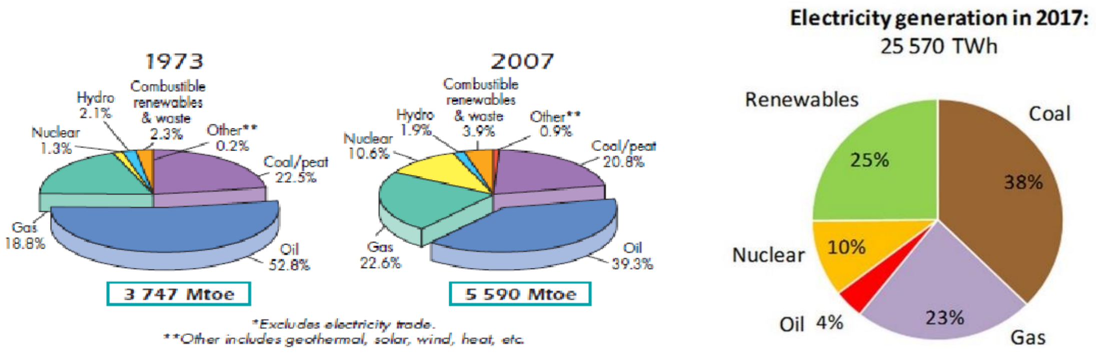
Keywords: Biomass, Biochemical, Thermochemical, Poultry litter, Municipal Solid Waste (MSW), Greenhouse gases (GHG).

1. INTRODUCTION

Owing to the ever-increasing release of gaseous pollutants that impacted the atmosphere greatly, there have been continuous efforts by researchers to provide lasting solutions through biomass conversion to energy. Biomass is made up of plant and animal materials-wood, animal dungs, solid waste, poultry litters, sawdust among others. Biomass has been proven to be a good alternative to energy production and a source of heat energy since the discovery of fire by the first man. More than 3 billion people in the world today are still burning wood as their primary source of cooking and heating because it is relatively cheap and affordable for low-income earners (WHO, 2015). Biofuels (i.e., bioethanol, biodiesel, and biogas) made from biomass are alternative energy sources to fossil fuels (e.g. coal, petroleum, and natural gas). The use of biofuels, such as ethanol, has been around for some time as well. It was used as lamp fuel in the United States in the 1800s as well as the first Model-T Fords until 1908 (Solomon et al., 2007).

The fast advance in biomass conversion technologies for energy production arises from the need to meet the growing energy demand worldwide as a result of dwindling in petroleum supplies. Figure 1 shows the proportional ratios of different sources of world electricity generation for over 40 years (1973-2017) according to the International Energy Agency (IEA). Renewable Energy has gained more popularity as the world seeks an energy sources that are environmentally friendly, easily accessible and less expensive. Renewable energy sources include solar, hydropower, wind, geothermal and biomass. Biomass contributes about 68 % of the total energy generated from renewable resources in the European Union (EU) in 2009 (Tomasz and Zenonin, 2012). In 2016, IEA recorded total primary energy supply of 13.7Mtoe of which slightly above 80% came from fossil fuels (in the form- 31.3% from oil, followed by coal (28.6%) and 21.2% from natural gas), 14.1% renewable energies (14.1%), and lastly nuclear power (4.8%). Of this total production, only 18% was in the form of electricity while the remaining 82% was used for heating and transportation. This means that larger percent of energy impacts on the climatic condition in terms of pollutants is from both industrial and transportation activities.

Burning either fossil fuels or biomass releases carbon dioxide (CO2), a greenhouse gas (GHG). However, the plants that are the source of biomass capture a nearly equivalent amount of CO2 through photosynthesis while they are growing, which can make biomass a carbon-neutral energy source. Using wood, wood pellets, and charcoal for heating and electricity generation can replace fossil fuels and may result in lower CO2 emissions overall.



A] Source: IEA 2008 B] Source: IEA 2017

Figure 1. World Electricity Generation (IEA 2008 and2017)

A large amount of agricultural and MSW are produced annually across the globe. In 2015, a total of 262.4 million tons of MSW was generated in USA, among which 52.5% was used in landfill, 25.8% recycled, 12.8% burnt for energy recovery, and the rest 8.9% was composted (EPA, 2015). MSW materials can be broadly categorized into three as: biomass (such as paper, food waste, grass clippings, leaves, wood, and leather products); Non-biomass combustible materials (plastics, petroleum-based); and Non-combustibles materials (glass, metals). Burning MSW produces gas emissions (that is, releases chemicals and substances into the air). Some of these chemicals can be hazardous to people and the environment if they are not properly controlled. The U.S. Environmental Protection Agency (EPA) applies strict environmental rules to waste-to-energy plants, which require thermal plants to use pollution control devices such as scrubbers, fabric filters, and electrostatic precipitators to capture air pollutants. Direct industrial CO2 emissions rose 0.3% to reach 8.5 GtCO2 in 2017 (24% of global emissions), a rebound from the 1.5% annual decline during 2014 16 (IEA, 2019).

Agricultural wastes, on the other hand, can be segmented into several categories: crop waste (such as wood waste, corn hubs, bagasse, paddy husks); animal wastes (e.g., animal excreta such as poultry litters, cow dungs; and animal carcasses); processing waste (e.g., packaging materials); and environmental harmful wastes (such as pesticides, herbicides, insecticides, and fertilizers). Out of the total global primary energy (230 exajoules), about 56 exajoules (one-fourth of the global primary energy) are utilized for agricultural purposes (WEC 1994). Suitable for energy production among these wastes are the crop and animal wastes. These wastes have been widely used in the production of biofuels through biochemical processes and heat energy through thermochemical processes.

This research paper seeks to increase societal perspectives of huge investment in renewable energies as a means to mitigate pollutions from largely used energy sources, by comparing the thermochemical and biochemical conversion processes of biomass for sustainable energy production in terms of environmental, economic and social impacts.

2. BIOMASS CONVERSION PROCESSES

2.1 Thermochemical Processes

Thermochemical processes involve the burning of biomass fuels (e.g., wood, sawdust, poultry-litter, biomass pellet) at various temperatures mostly greater than 400oC to produce the desired end products. These processes include pyrolysis, gasification, and combustion. Pyrolysis involves heating of organic materials at high temperatures (i.e., >430oC) in the absence of oxygen. The resulting products are solids and liquids in the form char and bio-oil respectively. Gasification is a process of heating organic materials with some amount of oxygen at elevated temperatures above 700oC. This process is referred to as Partial oxidation as biomass is burnt in air with activation energy to produce syngas (CO+H2) and gives off heat. On the other hand, combustion is a complete oxidation process that involves the burning of organic materials with excess oxygen at very high temperatures (i.e., >800oC) to produce excess heat, CO2 and water with other emitted pollutants.

2.2 Biochemical Processes

The biochemical processes involve the decomposition/breaking down of organic materials by the activity of micro-organisms in both aerobic and anaerobic conditions. These processes include extraction, fermentation and anaerobic digestion. Oil-based plants (such as soybean, groundnut) undergo extraction process to remove the oil content of the plants to be further used in the transesterification process for production of biodiesel. An alternative to biodiesel production is the use of marine biomass (algae) to convert carbon into a record amount of energy-rich fat, which can then be processed into biodiesel. Root crops (such as cassava, potatoes); grains (such as corn, wheat, sorghum); and sugar-based crops (sugarcane, molasses, sugar beets) are used in the production of Bioethanol. Upon breaking down the complex sugar of the biomass crops through milling (dry or wet process), the fine particles are then undergone hydrolysis prior to the fermentation process (i.e., conventional or Simultaneous Liquefaction Saccharification Fermentation- SLSF) to produce bioethanol. Anaerobic digestion is the microbial digestion of feedstock releasing heat, methane, hydrogen sulphide, carbon dioxide and under specific conditions hydrogen gas. This process takes place over several days in large tanks where the ideal conditions are maintained. After the process, the remaining solid digestate is suitable for use as fertilizer and the gases released are collectively referred to as biogas. The biomass to energy conversion processes are shown in Figure 2.

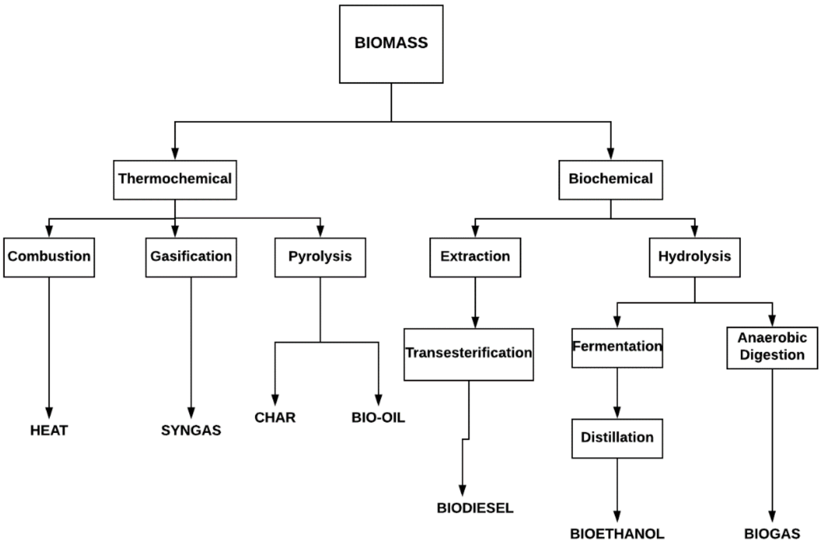


Figure 2. Biomass-to-Energy Conversion Pathways

3. POULTRY LITTER AS A SOURCE OF ENERGY

In general, waste from the poultry industry includes a mixture of excreta (manure), bedding material (e.g. wood shavings or straw), waste feed, dead birds, broken eggs and feathers removed from poultry houses. Other wastes include those from cages, conveyer belts and water flushing systems (Kelleher et al., 2002).

Poultry litter refers to a mixture of poultry manure (excreta), bedding materials (e.g., wood shavings, sawdust, straw, and pine or rice husk), spilled feed, and feathers (Lynch et al., 2013). In 2009, assuming 1.4 ton of litter per 1,000 birds, a total of about 25 million tons of poultry litter was generated by the US and the EU (Lynch et al., 2013). According to a U.S. Department of Agriculture estimate, the population of broilers, layers and turkeys in the U.S. (about 10.7 billion birds in total) produce about 550 million tons of manure annually (Coker, 2017). Due to its rich nutrient contents (e.g. N, P, K), most poultry litter have traditionally been utilized as a source for organic fertilizer on agricultural land (Kelleher et al., 2002). However, the environmental consequences of applying poultry litter include the release of ammonia and nitrous oxide (a GHG) together with contamination of ground and surface water with nitrate, phosphate and pathogens (Seidavi et al, 2019). As a result, excess application of poultry litter poses a risk to the health and wellbeing of humans, animals, and the aquatic ecosystem (Abelha et al., 2003; Li et al; 2008).

Poultry production is associated with greenhouse gas (GHG) emissions but at a much lower extent than other livestock. In a study by Seidavi et al (2019), it was stated that poultry waste is contributing 33.7 million metric tons of CO2 eq./year or 0.0337 gigatons (Gt) CO2 eq per annum. This represents only 0.64% of agricultural GHG emissions, if 2% of the nitrogen contained is lost as nitrous oxide with a global warming potential (GWP) of 298 CO2 equivalents (eq.) per unit as GHG.

3.1 Poultry Litter to Biogas

Anaerobic digestion is used worldwide as a unit treatment for industrial, agricultural and municipal wastes. This is a biochemical process of decomposing organic materials under the influence of microbial organisms in the absence of oxygen, leading to the formation of methane as main product alongside other inorganic products as shown in equation 1.

$$\text{Poultry Litter} + H_2O \longrightarrow CH_4 + CO_2 + NH_3 + H_2S + \text{heat} \quad (1)$$

The organic components of poultry litter can be classified into broad biological groups: proteins, carbohydrates and lipids or fats. The poultry litter contains a higher fraction of biodegradable organic matter than other livestock wastes, and this includes high levels of organic nitrogen due to the high content of protein and amino acids. (Kelleher et al., 2002). Anaerobic digestion of poultry litter involves two stages- Hydrolysis and Fermentation. The former involves dilution of the organic wastes with water at a ratio depending on reactor size and then homogenized. Under the activity of anaerobic bacteria, the products of hydrolyses undergo fermentation to yield methane gas and CO2 as major products. The produced methane gas can be converted to electricity using a generator, used as fuel for boilers in place of natural gas (to heat up poultry houses) or used as fuel for cooking stoves. The spent sludge can be further processed into fertilizers as shown in Figure 3. This in return can generate more income for farmers and reduce the overall production cost of poultry farming.

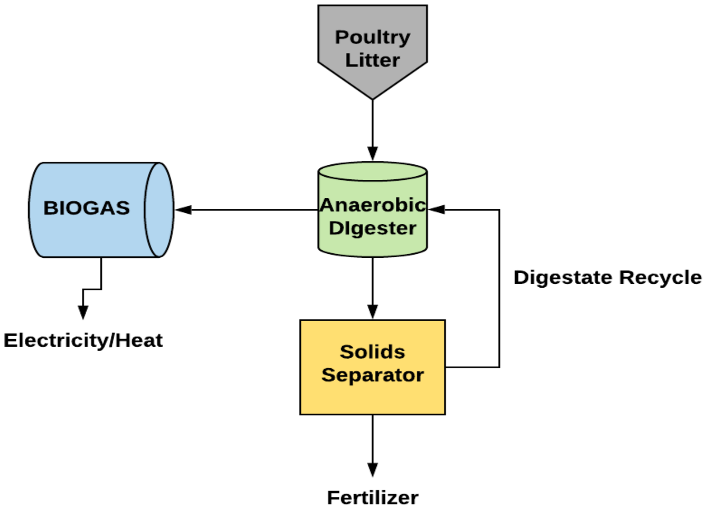


Figure 3. Biochemical Process Flowchart of Poultry Litter Digestion

Anaerobic digestion of poultry litter produces a collectable biogas mixture with an average methane content of 60%. The amount of methane gas produced, and its quality potential can be increased through the process of co-digestion with other substrates. Babaee et al. (2013) evaluated co-digestion of poultry litter and straw, and found highest gas yield (0.12 m3 CH4/kgVS) and highest methane content (70.2%) at loading rates of 3.0 kgVS/m3-d, hydraulic retention time of 15 days and operating temperatures of 35°C (95°F), but that yield and quality dropped off significantly at higher loading rates and at lower temperatures. Another study on co-digestion of poultry litter with hog shows that higher yield of methane was produced, up to 200 +/- 30 mL/g volatile solids destroyed, and methane, up to 130 +/- 20 mL/g volatile solids destroyed when using either waste alone (Magbanua et al., 2001). Biogas contains 50-60% of methane gas and has a heating value of 5-6KW with 30 to 45% carbon dioxide (CO2), traces of hydrogen sulphide (H2S) and hydrogen (H2), and fractions of water vapor. Every kg of organic matter yields 0.5m3 of biogas. It takes 30 days for complete digestion of poultry litter. A 1000kg of poultry litter with 55% dry matter containing 42% organic matter has a capacity to yield 200m3 of biogas, which can generate 420KW of electricity (Bijman, 2014).

A major concern in anaerobic digestion of poultry litter is the presence of ammonia, which inhibits the process. To eliminate ammonia inhibition, the 25-30% total solids waste must be diluted with water to achieve a <10% total solids waste. However, this reduction in total solids percentage takes 5-8 times the volume of water, and therefore creates a subsequent water disposal problem after the digester (DVO, 2019). Thereby, making the process economically non-viable. The environmental hazard posed by burning biogas in engines is the presence of H2S which on reaction with water vapor form Sulphuric acid (H2SO4). In large concentrations, hydrogen sulphide is toxic and poses health hazard. Prior to burning of raw biogas in engines, hydrogen sulphide and Carbon-dioxide must be removed using activated carbon.

3.2 Thermochemical Processes

Direct combustion has been another major alternative for production of useful energy (e.g., heat, electricity) from poultry litter. It has the potential to provide space heating for poultry houses and on large scale production of steam heat for running a turbine to generate electricity. As shown in Figure 4, thermochemical process of converting poultry litter to useful energy involves burning of the litters in excess air at a temperature >800oC in a Fluidized Bed Combustor (FBC). There are three main types of fluidized beds, bubbling, turbulent or circulating bed types. All designs consist of a bed of sand in a refractory-lined chamber through which primary combustion air is blown from below. Adjusting the airflow fluidizes the sand particles. Cyclones are placed after the furnace to separate the bed particles from flue gas, and then recirculate the particles to the furnace. FBC facilitates the dispersion of incoming fuel, where it is quickly heated to ignition temperature, and provides enough residence time in the reactor for complete combustion (Kelleher et al., 2002). The equation 2 below shows the poultry litter combustion process resulting into generation of heat, ash and gaseous products (such as carbon-dioxide, nitrogen oxides (NOx), sulphur-dioxide, and particulate matters).

$$\text{Poultry Litter} + O_2 \longrightarrow CO_2 + H_2O + \text{heat} \qquad (2)$$

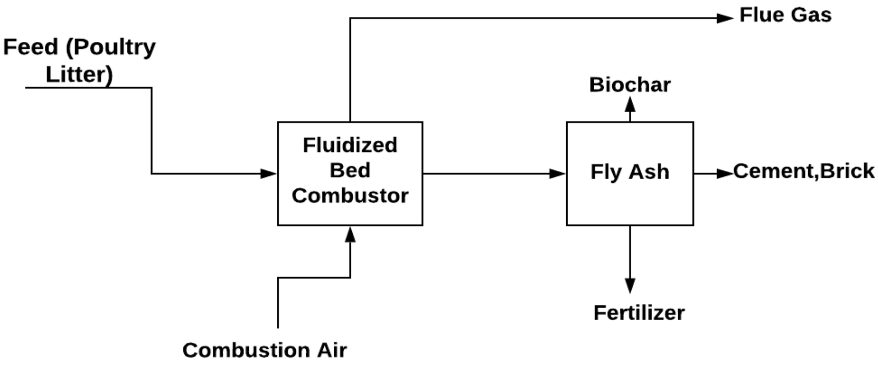


Figure 4. Flowchart of Poultry Litter Combustion

High moisture content present in raw poultry litter is a major setback in converting the waste to energy. The calorific value of the litters reduced with increasing moisture content. Poultry litter has a heating value between 6.78 and 27.90 MJ/kg with an average of 14.08 MJ/kg (Qian et al., 2018) Lower Heating Values (LHVs) on a wet basis range are much lower (mean values of 2664 kJ/kg) due to the high moisture content of poultry manure (Quiroga et al., 2010). Overcoming the 35-40% moisture content requires additional technology to dry the litters to lower moisture content (<10%) prior to the combustion process. High volume of ash generated during the combustion process of poultry litter poses environmental hazards alongside other gaseous pollutants. Therefore, researchers across the globe work continuously on converting the high-volume ash to useful products in different fields. The ash is generally a valuable fertilizer, high in phosphorous, potassium and other micronutrients (Echols et al., 2006). Fly ash can be used as prime material in many cement-based products, such as poured concrete, concrete block, and brick (Rodriguez, 2019). A similar use of fly ash is as biochar and substrates for bioremediation of soil (Sitarz-Palczak and Kalembkiewicz, 2012). Fine particulate matters produced in the combustion process of poultry litter are handled by installing cyclone and electrostatic precipitator (ESP). On a large scale, energy conversion of poultry litter via combustion process is economically not feasible as technologies needed for an efficient and environmentally friendly production are expensive and impact the overall cost of operations. A way of improving poultry litter conversion to heat energy is via co-combustion process. Co-combustion is defined as the combustion of renewable fuel (i.e., biomass) along with the primary fuel (coal, natural gas, furnace oil, etc.) (Sami et al., 2001). Co-combustion of poultry litter with natural gas has the following advantages: (i) reduction in fuel costs since biomass is cheaper than fossil fuel; (ii) minimization of waste and reduction of soil, water, and air pollution; and (iii) reduction of the anaerobic release of CH4, NH3, H2S, volatile organic acids and other chemicals since the storage time is reduced (Sweeten et al., 2003).

A case study of improved thermochemical conversion of poultry litter to heat energy via the co-combustion process is the facility provided in Centre for Advanced Energy Systems and Control Technologies (CAESECT) lab in Industrial and Systems Engineering Department, Morgan State University, Maryland, USA (Qian et al., 2019). Figure 5 shows the lab-scale FBC used in the CAESECT lab having a diameter of 304.8mm and a height of 1500mm. The chamber was fabricated with a carbon steel pipe covered inside with a 12.7mm thickness refractory ceramic. The primary air for combustion is supplied at the bottom of the chamber at varying speeds. Above this line, the feed (poultry litter) is introduced from a screw feeder at a varying rate and the secondary air lines are introduced tangentially to the bed at heights 650mm, 850mm and 1100mm respectively (Zhu et al., 2005; Qian et al., 2019). The heat recovery system installed involves the use of shell and tube heat exchanger to condense the total heat generated, which passes through a set of connected pipes to four radiators placed in an empty mobile trailer for space heating. Poultry litter is being collected from poultry farms in Chesapeake Bay's Delmarva area of Maryland. The collected waste with 20-25%moisture content, is combusted with natural gas in the lab-scale bubbling FBC at 80:20 percent ratio. At 4.5-5.5% feeding rate, 20-25cfm of primary air with low amount of secondary air, the maximum chamber temperature was observed to be 850-950oC, resulting in a temperature of greater than 90oF in the mobile trailer. According to the study by Qian et al. (2019), 905 W of electricity was reached under a water flow rate of 13.1 L/min and an engine head temperature of 584 °C. It was found that excess air (EA) ratios between 0.79 and 1.08 can relatively produce more electricity with lower emissions (under acceptable standards).

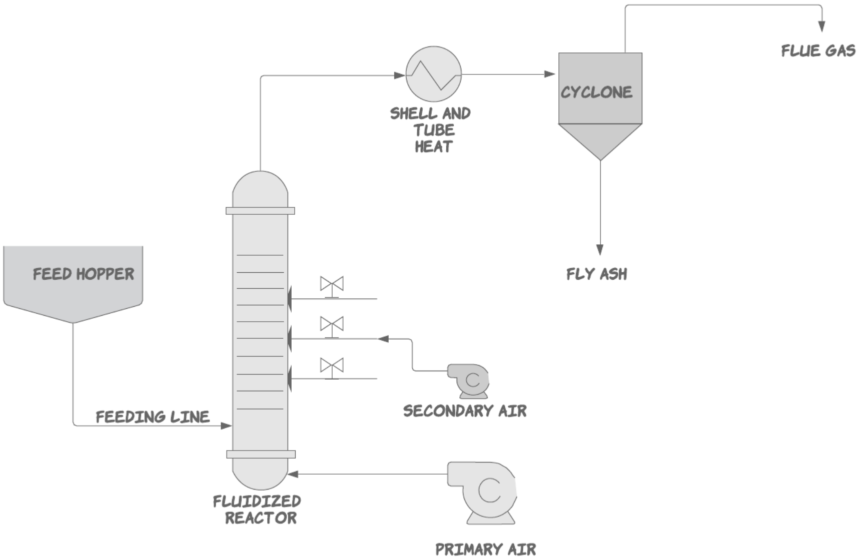


Figure 5. CAESECT Lab-Scale Fluidized Bed Combustor

4. BIOMASS-TO-ENERGY SUSTAINABILITY

Sustainable energy over the years has been defined as development of energy system which meets the need of the present without compromising the future's ability to meet its needs. Sustainability has been repeatedly explained by several researchers as an act of designing and developing a system that is environmentally friendly, economically viable and socially impactful as shown in Figure 6. The previous section compares the two processes under this study using poultry litter. Biochemical conversion process of biomass is said to be a clean, pure and efficient process among other processes (Chen and Wang, 2016), but cannot be said to be sustainable, balancing the three elements-environment, economy and society. The process generates primarily methane gas and a secondary waste in form of sludge with both requiring further processing to become environmentally safe. Furthermore, biochemical process requires pre-treatment (physical or chemical) of the biomass material; fully depends on particular strains of microbes and enzymes for large scale production; and requires longer reaction time for products formation (biomass fermentation takes 3-4 days before alcohol distillation, biomass digestion takes 15-30 days before biogas production). These reasons explain its economic non-feasibility.

On the other hand, thermochemical conversion process can be effectively applied to any biomass feedstock with or without pre-treatment process. Some feedstocks require pre-treatment (such as drying of poultry litter, sorting of MSW) to improve their products quality. Wood can be burnt directly without any pre-treatment, thereby making thermochemical processing more flexible. In addition, the thermochemical process requires less reaction time as the product in form of heat energy is formed immediately. Biomass resources can play a major role in reducing the reliance on fossil fuels by making use of thermochemical conversion technologies. However, raw biomass possesses low density (30–50 kg/m3) and its high moisture content limits its usage for thermochemical processes. The inclusion of a pelletizing process in thermochemical processes, allows easier economic storage, transportation, and energy conversion characteristics, and thus makes the process an efficient and sustainable approach to biomass-to-energy conversion. Burning of biomass waste has been largely considered as a better approach in that the CO2 generated during the process is balanced by an equivalent amount plants capture through photosynthesis while they are growing. As a result, the biomass is considered a carbon-neutral energy source, thus making the process environmentally sustainable. Furthermore, the increased utilization of biomass-based fuels will be instrumental in safeguarding the environment, generation of new job opportunities, sustainable development and health improvements in rural areas. Biomass Energy and Alcohol Fuels Act (1980), Energy Policy Act (EPA 1992) and Energy Independence and Security Act (EISA 2007) among others are governmental policies to address sustainability in the use of biomass for energy production.

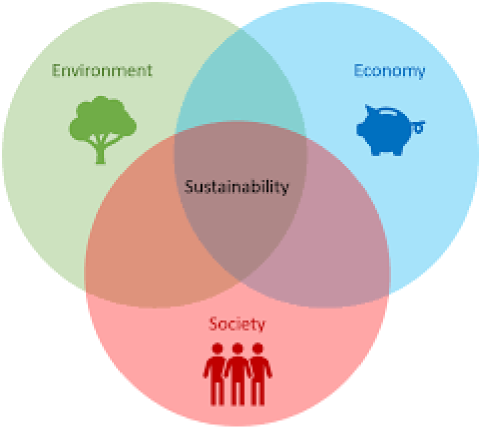


Figure 6. Elements of Sustainability (Deirdre, 2018)

5. CONCLUSIONS

The continuous overdependency on fossil fuel and its impact on climatic change has led researchers across the globe to design and develop energy system that is renewable, environmentally friendly, socially acceptable and economically feasible. In this study, the use of biomass feedstocks for energy production has been reviewed and the two mostly adopted biomass conversion processes have been compared using poultry litter as a case. Biochemical processes require pre-treatment of feedstock as well as post-treatment of products which increases the production cost, thereby making the process economically unstainable. Thermochemical processes require less reaction time (products formed immediately) while biochemical conversion requires 15-30 days for complete digestion prior to the formation of products. Furthermore, the thermochemical process has the capacity to generate more electricity with less emissions as the amount of CO2 produced is balanced out by the equivalent amount the biomass feedstock captured through photosynthesis. In addition, the biochemical process investigated in this study, generates high amount of ammonia which inhibits the process and, in a bit, to reduce the ammonia formation, a high volume of waste is generated. This renders the process economically non-viable. Therefore, thermochemical processing can be considered as an advantageous and viable means for energy production, offering an efficient and sustainable conversion process for biomass.

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