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Biogas Upgrade to Biomethane from Landfill Wastes: A Review

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Abstract

Wastes from landfills originate from many spheres of life. These wastes are produced as a result of human activities either domestically or industrially. Wastes are generally regarded as by-products nevertheless; they could be useful resources in wrong hands or location. Due to the fact that biogas could be produced from two main sources such as landfills and digesters chambers [1]. It is important to critically look into the biodegradable materials that ends up as wastes on our landfills because they could be converted into biogas as a result of the high concentration of carbon and hydrogen contained in such wastes and majority of which are from agricultural and domestic locations. Recently, producing biogas is not good enough for some applications therefore the need to upgrade it for usage as a vehicular fuel [2]. This paper reviews landfill waste categorization, biogas production processes, biogas to biomethane upgrade, and biomethane utilization.

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Keywords: Biofuel; Biogas; Biomethane; Biogas Upgrading; Landfill; Waste; Energy

1. Introduction

Due to the ever growing demand for energy globally and the rate of depletion in the quantity of world oil reserve annually which stands at 2.1%, there is an urgent need to look into other sources of energy than solely depending on fossil fuels which is currently the main supplier of about 88% of global energy [3]. Fossil fuels have contributed to the development of the world in an immense way nevertheless man has also not been spared from its dangers and

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harm as a result of the exploration activities. It is also one of the world most consumed natural resources and it is forecasted that OPEC will reach its production peak by 2026 at a rate of 53MMSTB/D [3]. The world at large has benefitted from the exploration of fossil fuels in all sectors such as transportation, energy (electricity), industrial, labour amongst many others nevertheless the world has also been affected by oil spillage, global warming, acid rain, Greenhouse gases emission (GHGs) and many more. Due to the unpleasant and non-environmental issues associated with the use of fossil fuels various countries in the world are beginning to explore alternative sources for energy and the most predominant option being renewable energy. According to the American Energy Information Administration (EIA) and the International Energy Agency (IEA), the world-wide energy consumption will on the average continue to increase by 2% per year [4]. Although, fossil fuel may not be totally replaced by biofuels for the short and medium term in fact the largest increase in world energy consumption is predicted to be from fossil fuels as shown in Fig I. Nevertheless, due to energy security reasons, environmental benefit, foreign exchange savings and socio-economic gains relating to renewable energy it will continue to receive tremendous attention in South Africa and the world at large.

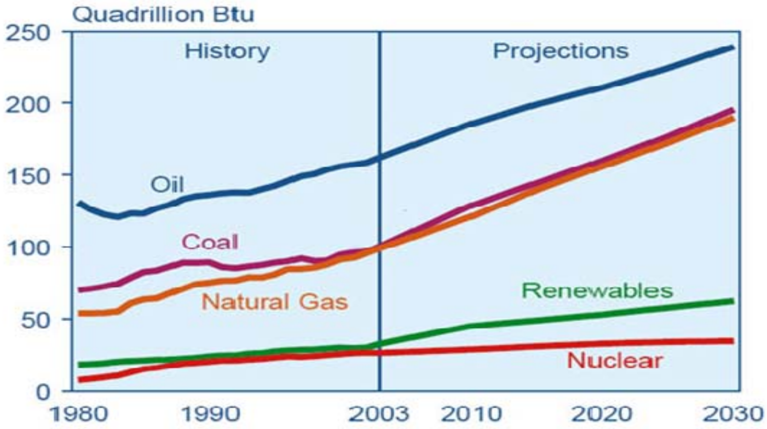

Fig.1: World Marketed Energy use by Fuel Type, 1980-2030 [4]

2. Landfill Wastes Categorization

The act of dumping wastes on landfill sites is the oldest, cheapest and most common form of waste management [5]. A landfill which is also known as dumping ground or rubbish dump is a site where waste materials are disposed and buried. Landfills are allocated by the municipality of a state or province and it is the only designated place where disposal of wastes is environmentally acceptable. Some countries of the world such as: South Africa, United States of America, Germany amongst others have waste classification and management regulations which are enforced into law by the country's Waste Act. In USA, the Environmental Protection Agency (EPA) uses the Resource Conversation and Recovery Act (RCRA) Section 4001, Subtitle D to regulate Garbage, Refuse, Sludges, Non-hazardous industrial wastes and other discarded materials [6]. Waste Act is often revised due to the complexity of waste generated by various sectors especially from the industrial sector and as soon as various tests are carried out on certain class of waste to determining risk posed by the waste on the environment and human life Waste Acts are amended to accommodate the risk and classify such waste accordingly. Generally, landfills can be broadly categorized into two namely: (i) Sanitary Landfills and (ii) Secure Landfills.

2.1. Sanitary Landfills

Sanitary landfills are sites designated for the disposal of non-hazardous wastes where it could be spread in layers, compacted and covered with earth (soil) at the end of each day the landfill is in operation. Non-hazardous wastes are often regarded as general waste because if properly managed they tend not to pose any significant threat to the health of the public and the environment [7]. This category of waste is mostly generated from four major areas namely: Residences, Institutions, Industries and Construction/Demolition as shown in Table 1.

Table 1. Non- hazardous wastes and their sources. [8]

Waste Sources	Waste Materials
Domestic/Residential	Food wastes, yard trimmings, plastics, metals, rubber, leather, textiles, wood, glass, cans, paper, and special wastes (viz: consumer electronics, furniture, batteries, etc.)
Commercial	Packaging materials, office supplies, food wastes.
Institutions	Similar to domestic and residential wastes.
Industrial	Special wastes, food wastes, paper, plastics, glass, metals, textiles, wood, rubber
Construction & Demolition	Concrete, soil, brick, wood, metal, steel, packaging materials, ceramics, plastics, and the like.

2.2. Secure Landfill

Secure landfills are sites designed to accommodate wastes that are regarded as hazardous. Hazardous wastes are wastes with properties that can cause damage to the environment and be harmful to human health [9]. Secure landfill is designed to enable hazardous wastes to be properly disposed of by burial in holes or trenches into grounds that are lined with impervious plastic sheeting to prevent leakages or leaching of dangerous substances into soil or water bodies. Hazardous wastes are only permitted to be disposed on hazardous waste landfills or secure landfills otherwise they could cause a severe damage to lives and environment if wrongfully disposed. Hazardous wastes are classified by Department of Environmental Affairs under the Waste Management Acts of different countries according to the risks associated with various substances or materials and as a result the classification is based on how hazardous the substance could be either extreme or moderate. Different countries apply different ranking methods some of which are the use of numerical, alphabets, etc. Nevertheless, the criterion for categorization of hazardous wastes is based on four factors as shown in Table 2. Also, household hazardous wastes are to be disposed on a secure landfill as they fall into the four categories.

Table 2. Characteristics of Hazardous Waste. [10]

Properties	Characteristics	Household Hazardous Waste
Toxic	Carcinogen Bioaccumulative properties Wastes containing heavy metals/ organics Waste oil	Pesticides, Rat poison, Pharmaceuticals, Cleaning fluids
Corrosive	When pH < 2 or > 12.5	Batteries, Drain cleaners, oven cleaners
Ignitable or Flammable	Liquid with flash point of < 140ºF (60ºC) Solids that burns spontaneously Oxiders	Pool chemicals, Ammonia, Bleach, Aerosols
Reactive	Unstable materials Explosives Water reactive Cyanide or Sulphide – bearing wastes	Gasoline, Paints, BBQ starters, Oils, Solvents, Propane Cylinders

3. Biogas Production

The use of Anaerobic Digestion (AD) for treating organic is attractive for many reasons that involve economic as well as environmental aspects [11,12]. Anaerobic Digestion is the collection of processes by which microorganisms break down biodegradable material in the absence of oxygen [13]. There are basically four stages involve in the production of biogas from organic wastes by Anaerobic Digestion. AD is mainly a mesophilic and thermophilic biological decomposition and stabilization of biodegradable wastes at controlled anaerobic conditions such as temperature, pH, retention time etc. The four stages for biogas production are: Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. At each phase specific bacteria namely: Hydrolytic, Acidogenic, Acetogenic and Methanogenic respectively is used to carry out the decomposition process. The process of Anaerobic Digestion is summarized in Fig. 2.

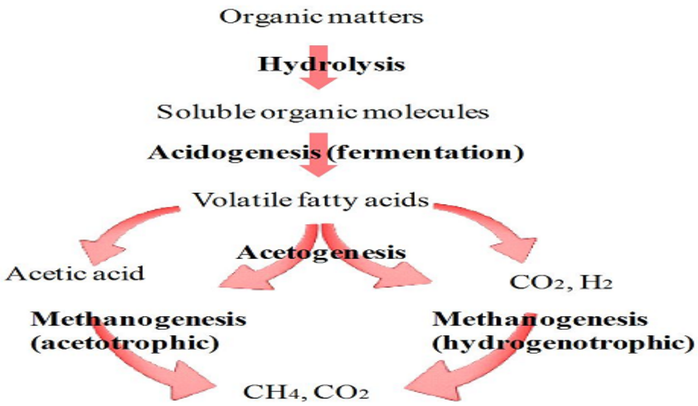

Fig. 2: Anaerobic Digestion Biochemical Conversion Pathway [12]

Hydrolysis stage: This stage involves the breaking down of large protein macromolecules, fats and carbohydrate polymers (such as starch and cellulose) to amino acids, long chain fatty acids and sugars [12].
Acidogenesis stage: At this stage, the small organic molecules produced in the hydrolysis stage are fermented to form three, four, and five volatile fatty acids such as lactic acid, butyric acid, propionic acid, valeric acid and low alcohols [13].
Acetogenesis stage: At this stage, acetogenic bacteria consume the fermented products from the acidogenic stage to produce acetic acid, carbon dioxide and hydrogen [14].
Methanogenesis stage: This is the final stage where methane is produced as a result of the consumption of acetate, hydrogen and carbon dioxide. Three biochemical pathways are used by methanogens to produce methane gas [12]. The pathways along with the stoichiometries of overall chemical reactions are shown in (1), (2) and (3).

- Acetotrophic methanogenesis: $4CH_3COOH \rightarrow 4CO_2 + 4CH_4$ (1)
- Hydrogenotrophic methanogenesis: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (2)
- Methylotrophic methanogenesis: $4CH_3OH + 6H_2 \rightarrow 3CH_4 + 2H_2O$ (3)

4. Biogas to Biomethane Upgrade

Biogas which is a renewable source of energy is typically a mixture of different gases produced by the breaking down of organic matters in the absence of Oxygen with calorific value that varies from 20-25MJ/M^3[15]. It is essential to upgrade raw biogas produced from digestion because it is not always of high quality due to its low percentage of methane (about 60%) and corrosive contaminants such as H_2S that is always present [16]. Nevertheless, raw biogas could be used for some applications even without upgrading. To produce biomethane, hydrogen sulphide is usually removed first due to its corrosive nature and unpleasant odor nevertheless some technologies provide the room for removal of carbon dioxide (CO_2) and hydrogen sulphide (H_2S) concurrently. Upgraded biogas could be compressed and used as vehicle fuel for transportation. Also, it could be injected into the natural gas grid for electricity. The process of upgrading biogas to biomethane for fuel grade involves two stages namely: cleaning and methane (CH_4) enrichment. The cleaning phase is the removal of acidic gases and impurities while enrichment phase simply separates carbon dioxide (CO_2) from the biogas giving rise to a corresponding increase in the methane concentration. There are some known technologies for the cleaning of biogas that is, the removal of hydrogen sulphide (H_2S) namely: (i) Air Injection (ii) Iron Chloride Injection (iii) Iron Oxide or Hydroxide Bed (iv) Activated Carbon sieve (v) Water Scrubbing (vi) Selexol Scrubbing (vii) Sodium Hydroxide Scrubbing (viii) Biological Filter. Also, there are some various technologies that can be applied for the enrichment of methane which is the removal of carbon dioxide (CO_2) [17] among which are: (i) Water Scrubbing (ii) Pressure Swing Adsorption (iii) Chemical Scrubbing (iv) Methane Separation (v) Cryogenic Separation. Furthermore, in order to complete the upgrading process of biogas, there is a need to remove water vapour from the biogas. Removal of water mainly requires biogas received during the wet fermentation and after treatment processes using water [18]. It is important to remove moisture from biogas because it can lead to formation of corrosive acids such as in the case of water reacting with H_2S present in biogas to form Sulphuric acid (H_2SO_4) also, when moisture react with CO_2 it forms carbonic acid (H_2CO_3).

5. Biomethane Utilization

Upgraded biogas that reached about 95% of methane (CH4) possesses identical gas quality properties as natural gas as a result it could be used as a perfect replacement for natural gas. Developed countries such as Germany, Sweden and Switzerland have defined quality standards for biogas injection into the natural gas grid. In order for biogas to be injected into a natural gas grid, all its contaminants must be removed and it must meet the quality requirement of more than 95% methane for different gas appliances [19]. It must also be void of bacteria and molds that could cause a risk to human health and equipment so it must be screened by the use of filters [20]. One important advantage of using gas grid for biomethane distribution is that the grid connects the production site of biomethane, which is usually in rural areas, with more densely populated areas. Also, it could be used as transport fuel either in light- duty vehicles or heavy- duty vehicles. They are mostly used in bi-fuel vehicles where the vehicle system permits the use of petrol or biomethane. Nevertheless, some vehicles are solely designed and their system is optimized to operate on natural gas or biomethane. As in the case of light-duty vehicle, there has been some development in the substitution of diesel by gaseous fuels. These systems are referred to as dual fuel engines where Methane-Diesel technology is used for compression –ignition engines in heavy-duty vehicles. In dual fuel engines diesel is being used as pilot ignition where it acts as a liquid spark plug, igniting the regasified methane mixed together with air. These systems allow the introduction of biomethane as gaseous fuel into the cylinder with varying degrees of precision, ranging from fumigation of the inlet manifold to much more accurate injection into individual ports of the engines onto the back of the inlet valves [21]. The major pathway for the utilization of biomethane includes:

- Production of heat and steam
- Electricity generation / combined heat and power production (CHP)
- Natural gas replacement (gas grid injection)
- Compressed natural gas (CNG) and diesel replacement (transport fuel usage)
- Liquefied natural gas (LNG) replacement (transport fuel usage)

6. Biomethane Transportation

Due to the relatively low demand for biomethane on-farm or plant compared to its production it is important to transport excess biomethane produced to appropriate refueling stations or ultimate point of consumption through the right channels. There are two major ways of transporting or distributing biomethane produced from upgraded biogas, they are through the use of pipelines and road transport. Biomethane can be transported to a refueling station either by a dedicated biomethane pipeline or natural gas pipeline. Depending on the ultimate consumption point, if biomethane is to be used for CNG vehicles, it could be channeled through a dedicated biomethane pipeline that is laid aboveground to a CNG refueling station. For biomethane to be distributed using a natural gas pipeline it must meet local gas utility pipeline gas quality standards [20] in order for it to be used as a direct substitute for natural gas by any piece of equipment connected to the natural gas grid, including domestic gas appliances, commercial or industrial gas equipment and CNG refueling stations. Transporting biomethane through road is a means of overcoming infrastructural challenges associated with biomethane distribution via pipeline. For transporting of compressed biomethane, bulk transport vehicles otherwise known as tube trailers are used and for it to be economical, biomethane has to be compressed to relatively high pressure (between 3,000 to 3600 psi) [22]. For transporting liquefied biomethane, LNG tankers used for transporting cryogenic liquid at relatively low pressures could be used.

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