The Effect of Microwave and Alkaline Treatment on Biogas Production from Organic Fraction of Municipal Solid Waste

تأثير المعالجة بالموجات القصيرة والمعالجة القلوية لنفايات البلدية العضوية الصلبة على إنتاج الغاز الحيوي

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May /2016
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Signature: 
Date: 2016/5/2
Abstract

Background: Renewable energy sources have received increased interest from the international community with biomass being one of the oldest and the most promising ones. In the concept of exploitation of solid organic waste residues, the present study investigates the pre-treatment and biogas fermentation potential of the solid organic waste. Solid organic waste is the solid waste generated houses of leftovers. Organic Fraction of Municipal Solid Waste (OFMSW) is the most solid organic waste material resource for obtaining energy. Therefore, it is necessary to apply a convenient pretreatment method to increase the biogas yield. Microwave pretreatment method assists to break down hard OFMSW for improved degradation of solid organic waste and releasing of biogas.

General Objective: Evaluating the production of biogas from OFMSW using microwave radiation and sodium hydroxide treatment.

Methodology: The Biogas test is one method that can be used to estimate the amount of biogas that could be produced from anaerobically digesting organic waste at mesophilic temperatures. A known quantity of organics based on the volatile solids fraction is added to OFMSW inoculum. The mixture is anaerobically digested until biogas production ceases, during which time the quantity and quality of biogas produced is measured.

- Alkaline treatment (NaOH).
- Microwave treatment power operated at 2450 MHz and 450 W.
- Combined treatment (Microwave _Alkaline).

Results: In both pretreatment methods, remarkable findings were obtained as biogas concentration. The maximum produced total biogas amount of 3L was achieved after ten minutes of pretreatment time in 300 mL of 2% NaOH solution (w/v) at microwave power of 450 W with 60 g OFMSW. The results suggest that microwave and microwave-alkali pretreatment can increase total biogas production.

Conclusion

1. A long-time (25 min) microwave treatment can improve the reducing biogas yield greatly for the hydrolysis of OFMSW, but leads to high sugar loss during the pretreatment.

2. Combined microwave-alkaline treatment at near room temperature, the time of biological process was shortened to 120 hour and the efficiency of NaOH pretreatment was enhanced.

3. The combined pretreatment process is favorable for further development and application of biological pretreatment.

Keywords: fermentation, alkaline pre–treatment biogas, microwave irradiation, Anaerobic digestion, Organic solid waste.
ملخص دراسة

الخلفية:
حصلت مصادر الطاقة المتجددة على اهتمام متزايد من المجتمع الدولي وتُعد الكتلة البيولوجية منن ققندم وقهن هذه المصادر. في ظل مبدق استثمار بقايا النفايات العضنوية الصنلبة، تبحن هنذذه الدراسنة فني نمكااينة المعالجنة الم نبقة للنفايات العضوية الصلبة وتخمير الغاز الحيوي الناتج. تنتج النفايات العضوية الصلبة من بقايا النفايات الصلبة للمنازل.

وفقاً لمصادر الطاقة المتجددة، تم استخدام المعالجنة المزدوجة (OFMSW) في تحفيز النفايات العضوية الصلبة للفائدة الفوائد وتقليل ضرر النفايات العضوية الصلبة. العملية المعالجة المزدوجة يُستخدم في تحفيز المعالجة. Therefore, من المهم استخدم أكثر المناهج العلاجية المستخدمة لمعالجة النفايات العضوية الصلبة، وتعمل على زيادة استثمار المعالجة المزدوجة (OFMSW).

الأهداف العامة:
تقييم نتاج الغاز المنبثق من الجزء العضوي للنفايات المحلية باستخدام إشعاع المايكرويف وتشميم الطاقة (الميكرويف القلوي).

منهج البحث:
يمكن استخدام اختبار الغاز الحيوي (Biogas test) في تخدم نسبة الغاز الناتج من المعالجة في محارب النفايات العضوية الصلبة (OFMSW) لتحسين عملية تفكك النفايات العضوية الصلبة والغاز الحيوي. هذه الدراسة تهدف إلى البحث في فعالية المايكرويف والمعالجة المزدوجة باستخدام المايكرويف القلوي في تحفيز الجزء العضوي للنفايات المحلية.

النتائج:
من خلال تطبيق المنهجين، تم التوصل إلى نتائج ملحوظة حيث كان هناك تركيزاً للغاز الحيوي. كانت الفاصل الزمني للغاز المنبثق 3,000 مل بعد 10 دقائق من المعالجة السوقية 300 مل من معدل 2% من محلول هيدروكسيده الصوديوم ومجمل الطاقة 450 وات و60 دقيق. إمكانية hangs على أنه بإمكان العلاج باستخدام المعالجة المزدوجة زيادة الإنتاج الكلي للغاز الحيوي.

الاستنتاج:
1. يمكن استخدام العلاج عن طريق المايكرويوف لمدة طويلة (25 دقيقة) أن يؤدي إلى تخزين كبير في تقليل الانبعاثات الغازية للحالة OFMSW، ولكن يؤدي هذا العلاج إلى حبوب شديد في السكر أثناء العلاج المسبق.
2. أدى استخدام العلاج عن طريق المايكرويوف القلوي عند درجة حرارة الغرفة إلى تقليل وقت عملية الغاز الحيوي إلى 120 ساعة، ويؤدي هذا العلاج المسبق لجودة الغاز الحيوي المحسن المزدوج للخلايا الميكرويف القلوي.
3. يفضل استخدام عملية العلاج المسبق المركب لتحسين في المستقبل والتفاعل العلاج البيولوجي.

الكلمات المفتاحية: التخمير، العلاج المسبق القلوي للغاز الحيوي، إشعاع المايكرويوف، الهضم اللاهوائي، النفايات العضوية الصلبة.
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<th>Definition</th>
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<tbody>
<tr>
<td>AD</td>
<td>Anaerobic Digestion.</td>
</tr>
<tr>
<td>BMP</td>
<td>Biochemical Methane Potential.</td>
</tr>
<tr>
<td>CSTR</td>
<td>Continuous Stirred Tank Reactor</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed natural gas</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide.</td>
</tr>
<tr>
<td>CCF</td>
<td>Central Composite Face Centered.</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical oxygen demand</td>
</tr>
<tr>
<td>C:N</td>
<td>Carbon to Nitrogen Ratio.</td>
</tr>
<tr>
<td>°C</td>
<td>Degrees Celsius.</td>
</tr>
<tr>
<td>EHF</td>
<td>Extremely high frequency.</td>
</tr>
<tr>
<td>HPR</td>
<td>Herbal-Extraction Process Residue.</td>
</tr>
<tr>
<td>HRT</td>
<td>Hydraulic Retention Time.</td>
</tr>
<tr>
<td>HS</td>
<td>High solids.</td>
</tr>
<tr>
<td>IMWE</td>
<td>Irradiated Microwave Energy.</td>
</tr>
<tr>
<td>MW</td>
<td>Microwave.</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal Solid Waste.</td>
</tr>
<tr>
<td>MS</td>
<td>Medium Solids.</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane.</td>
</tr>
<tr>
<td>MS</td>
<td>Medium solids.</td>
</tr>
<tr>
<td>MWPL</td>
<td>Microwave Power Level.</td>
</tr>
<tr>
<td>OFMSW</td>
<td>Organic Fraction of Municipal Solid Waste.</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>LS</td>
<td>low solids</td>
</tr>
<tr>
<td>SSO</td>
<td>Source-separated organics.</td>
</tr>
<tr>
<td>SRT</td>
<td>Solids retention time.</td>
</tr>
<tr>
<td>SCOD</td>
<td>Soluble Chemical Oxygen Demand.</td>
</tr>
<tr>
<td>SHF</td>
<td>Super-High Frequency.</td>
</tr>
<tr>
<td>TCOD</td>
<td>Total Chemical Oxygen Demand.</td>
</tr>
<tr>
<td>TOC</td>
<td>Total organic carbon.</td>
</tr>
<tr>
<td>TS</td>
<td>Total Solids.</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra high frequency.</td>
</tr>
<tr>
<td>VS</td>
<td>Volatile Solids.</td>
</tr>
<tr>
<td>VFA</td>
<td>Volatile fatty acids.</td>
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<tr>
<td>VSS</td>
<td>Volatile suspended solids.</td>
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1.1 Overview

Municipal solid waste (MSW) is the waste generated in a community with the exception of industrial and agricultural wastes (Henry, 2002). Hence MSW includes residential waste (e.g., households), commercial (e.g., from stores, markets, shops, hotels etc), and institutional waste (e.g., schools, hospitals etc). Paper, paperboard, garden, and food waste can be classified in a broad category known as organic or biodegradable waste. According to statistics and reports, the Gaza Strip generates 1400 to 1500 tons of solid wastes per day. Some local surveys and estimates indicate that household waste accounts for 45 to 50% of the total solid wastes and that 60 to 70% of them is an organic material. The wastes of construction and industrial sectors together constitute 20 to 25%, and the remaining types (e.g. commercial and institutional) contribute 25 to 30% (Al-Hmaidi, 2002). On the other hand, hazardous material is to some extent present in all these waste types. Although it is difficult to obtain adequate data for calculating overall levels of solid waste generation, it is estimated to an acceptable degree of accuracy that total annual solid waste generation in the Gaza Strip exceeds 400,000 tons. Moreover, Gaza Strip municipalities spend annual operational expenses of collection, transfer, and disposal of around $6.5 million. In addition, the area needed for landfills is around 32,000 m² annually (Riyadh, 2013).

Biogas can be produced from regionally available raw materials such as recycled waste. It is a renewable energy source and in many cases exerts a very small carbon footprint. Biogas is produced by anaerobic digestion with anaerobic bacteria or fermentation of biodegradable materials such as manure, sewage, municipal waste, green waste, plant material, and crops (Ahmed, 1994).

Solid wastes generation rates have become a major concern worldwide and different issues about their disposal are still arising. Solid wastes have an average composition, on a weight basis, of 45% of yard wastes, 26% of food wastes, 13% of plastics, 12% of paper, 3% of textiles and 1% of metals whereby the vegetable and food wastes account for more than 50% of the waste (Rita, 2007).
Food wastes is a fraction of solid wastes which can be defined as organic residues that have been generated by handling, storage, sale, preparation, cooking or serving of foods and which are intended or required to be discarded (Adedibu, 1985). Food wastes can be categorized as pre-consumer food waste is food waste that is thrown away by staff within the control of the food service operator, and as post-consumer food waste is food which was primarily sold or served to customers, guests, students, patients and visitors but in the end is discarded as food wastes. Both aerobic and anaerobic treatments have been relatively promising solutions for decreasing the amount of solid wastes by providing treatment of a wide spectrum of wastes streams and at the same time producing renewable energy. Anaerobic digestion (AD) is a promising solution for both waste management and energy production (Buffiere, 2008).

Because of its economic and environmental benefits, feedstock characteristics, lignocelluloses content, reactor design and operation conditions affect the design and performance of an anaerobic digestion (AD) process. The first step of AD is hydrolysis and consists in the breakdown of cellulose, hemicelluloses, and lignin into monomers by the enzymatic action of hydrolytic fermentative bacteria. The resulting products are then converted during the acid genesis process by acidogenic bacteria to acetic acid in the absence of oxygen. The final phase involves the action of methanogens on the acetic acid to produce biogas having a methane content of 40 to 60% by volume. Food waste can also be digested an aerobically for biogas production (Demirbas, 2000).

The recalcitrant lignocelluloses content of the food wastes needs to be pretreated and then hydrolyzed during the rate determining hydrolysis step before being digested by the enzymes/microorganisms. Pretreatment is needed because the sugars necessary for biochemical reactions are trapped inside the cross linking structure of the lignocelluloses, thus inhibiting the process and decreasing yield (Zheng, 2009).

To solve this problem and reduce the high cost of hydrolysis associated with anaerobic digestion processes, various physical, physicochemical, chemical and biological pretreatments have been actually employed. Pretreatment methods such as microwave (MW) irradiations, sonication and electron beam irradiations (EB) are gradually immersing in the application of (green) radiation technology for biomass pretreatment. MW irradiation at low frequency has been shown to aid significantly in breaking down the complex flock structures of secondary sludge in order to cause the complex organic molecules of intracellular and extracellular components to unfold,
denature, decrease in their size and eventually become more biodegradable (Eskicioglu, 2007).

1.2 General Objective

Evaluate the production of biogas from organic fraction of municipal solid waste (OFMSW) by using microwave radiation and sodium hydroxide treatment.

1.3 Specific Objective

1- Evaluate of biogas production from organic fraction of MSW.

2- Enhancement of biogas production

a) Estimate chemical pretreatment by Alkali on biogas production potential.

b) Estimate physical microwave treatment on biogas production potential.

c) Estimate combined Alkali & microwave treatment on biogas production potential.

1.4 Significance

Biogas production is the most challenging area with respect to environmental and renewable energy problems. Palestine suffers from shortage of energy supply and sustains development resources. The study will focus on evaluation of biogas production from MSW by aid of microwave and Alkaline treatment. This study is a pioneering one which will introduce a doubled-suggested solution for two major problems in the Gaza Strip which are accumulation of MSW and gas supply shortage.
Chapter 2

Literature Review

2.1 The Energy Challenge

Worldwide demand for energy is growing at an alarming rate. The European “World Energy Technology and Climate Policy Outlook” (WETO) predicts an average growth rate of 1.8% per annum for the period 2000-2030 for primary energy worldwide. The increased demand is being met largely by reserves of fossil fuel that emit both greenhouse gasses and other pollutants. Those reserves are diminishing and they will become increasingly expensive. Currently, the level of CO₂ emissions per capita for developing nations is 20% of that for the major industrial nations. As developing nations industrialize, this will increase substantially (Arvelo, 2000).

By 2030, CO₂ emissions from developing nations could account for more than half the world CO₂ emissions. Industrialized countries should lead the development of new energy systems to offset this energy security is a major issue. Fossil fuel, particularly crude oil, is confined to a few areas of the world and continuity of supply is governed by political, economic, and ecological factors. These factors conspire to force volatile, often high fuel prices while, at the same time, environmental policy is demanding a reduction in greenhouse gases and toxic emissions (IPCC, 2001).

2.2 Solid Waste Global Burden

Solid waste management is a challenge for the cities’ authorities in developing countries mainly due to the increasing generation of waste, the burden posed on the municipal budget as a result of the high costs associated to its management, the lack of understanding over a diversity of factors that affect the different stages of waste management and linkages necessary to enable the entire handling system functioning. An analysis of literature on the work done and reported mainly in publications from 2005 to 2011 (Faccio, 2011).

Industrial countries account for a disproportionately high share of the world's waste relative to their share of world population, while developing countries account for a disproportionately high share of the world's waste relative to their share of world income. Analyses across countries and over time reveal that the generation of municipal solid waste is positively related to variations in per capita income and that the generation of municipal solid waste per capita does not vary with population size among countries with comparable
per capita income. Practices for collecting, processing, and disposing of municipal solid waste vary widely across countries, generally in accord with the nature of the waste stream and key environmental and economic features. The least efficient practices tend to be found in developing countries, creating serious threats to local environmental quality and public health (Letsrecycle, 2012). Addressing the issues of energy shortages, social & health problems & increasing expenditure of MSW treatment especially in developing countries, it is important to create innovative ways to get rid from MSW problems. Biogas production technology represents an ideal way to solve environmental and energy problems raised from MSW Accumulation.

2.3 Benefits of Biogas Production

To a certain extent, the benefits associated with renewable natural gas are similar to those of natural gas: increasing energy security (since both are domestically produced), paving the way for fuel cell vehicles, and improving public health and the environment through reduced vehicle emissions. Beyond these, however, renewable natural gas (RNG) is a renewable resource that can displace non-renewable resources such as fossil fuel-derived natural gas, gasoline, or diesel. When (RNG) is used in place of these fuels to power motor vehicles, it produces not only important energy security benefits, but also major reductions in criteria pollutant and greenhouse gas emissions (Agnolucci, 2005).

Biogas plant can reduce landfill area and protect groundwater quality. Due to anaerobic processes, organic matters can be reduced down to 4% which reduce landfill area and protect the groundwater. Furthermore, because the reduction of biomass is significant, reuse of the residue from biogas process, such as fertilizers, can cut down the expenditure of organic wastes. If co-substrates are used in biogas plants, mineral fertilizers can be replaced by residue. The advantages are cutting down spends. They can reach the cycle of nutrients and reduce nitrate leaching. Methane and nitrous oxide emissions (N₂O) are reduced when residue and manure are digested instead of being spread on the field or stored. The digested residue also produces less odorous. It can reduce the fees for the management of wastewater. Also, there is a significant reduction has been monitored of pathogenic germs in the digested residue after anaerobic process. It can minimize the spread of weed seeds. After the fermentation process, liquid manure becomes more highly liquid which is much easier for soil to absorb (Dela-Rubia, 2002).
2.4 Energy and Air Pollution in Palestine

The main sources of air pollution in Palestine are the various means of transportation, the smoke rising from the chimneys of factories, the heavy dust from quarries, the burning of solid wastes, and the effects of water treatment projects. The Israeli industries in the West Bank, Gaza Strip, and inside the part of Palestine occupied in 1948 are the biggest cause of atmospheric pollution in Palestine. Many Israeli sawmills pollute the air across the West Bank with large quantities of greenhouse gases. A (2009) study prepared by George Karzam of the Ma’an Development Centre predicts that the greenhouse gases emitted from the territories occupied in 1948 will increase by 40 percent by the year 2020 (Karaeen, 2012).

In the Gaza strip, the issue of air pollution is attributed to the density of motor vehicles, estimated at about 60,000, and especially to the number of old vehicles. Also, air pollution is caused by the gases and smog emitted from Israeli factories, especially from coal-operated power stations, and transferred to Gaza Strip by the wind. These factories are located in Isdude (Ashdod) and Al-Majdal (Ashqelon) inside the part of Palestine occupied in 1948. If we were to look at the effects the unjust siege of the Gaza Strip has had on the environment, we would find painful facts about air pollution. Toxic gases, including sulphur dioxide and carbon monoxide, which harm the respiratory system, are released into the air because of the use of the large numbers of people who run home generators to compensate for the shortage in electricity caused by Gaza’s inability to run its power plant full-time due to the acute shortage of fuel. It is estimated that there are about 100,000 of these generators in use and that they consume about 500,000 litres of fuel per day. Therefore, the environment in Gaza Strip requires a more thoughtful and comprehensive policy of planning, awareness, and conservation (Karaeen, 2012).

Palestine is a developing nation, its access to considerable amounts of energy is essential to achieve economic growth and development. While most of Palestine has access to electricity there are many challenges facing Palestine, arising mainly from its energy dependence. Its energy is not provided through domestic means but rather provided through Israel which controls the quantity and quality of energy imported. With complete dependency on Israel for its energy needs, Palestine is put in a vulnerable position given its complex political and security situation. Such a threat has given rise to the importance of using renewable energy such as solar, wind, geothermal and biomass. Renewable energy
can offer Palestine many benefits which will not only revolve around the reduction of conventional energy consumption and reducing harmful emissions, but most importantly will help achieve sustainable development for a Palestine that has little natural resources. Biomass, if utilized properly, could become one of Palestine’s major energy resources. Currently, biomass energy constitutes approximately 15% of Palestinian energy supply; it is used mainly for heating purposes. Palestine is known, historically, for its agriculture and trading. Agriculture is still a predominant economic activity. As a result, Palestine has a strong potential for biomass energy. People living in rural areas may benefit from producing biomass energy in various forms, including wood, crop residues and biogas. Presently, no crops are grown in Palestine specifically for use as fuel (Abu Hamed, 2011).

2.5 Composition of MSW Organics

2.5.1 Food Waste

The municipal solid waste (MSW) stream is diverse and contains a variety of organic and inorganic materials. Typically, the identifiable organic fractions include food waste and leaf and yard waste (L&YW). Source-separated organics (SSO) waste is a commonly used term that refers to the combination of the MSW organic fraction from residences and the industrial, commercial, and institutional (ICI) sector. (FCM, 2009).

Food waste represents a significant proportion of organic material found in residential waste. It is generated primarily by the residential and industrial, commercial, and institutional sectors, and can be either postconsumer, originating from residential and commercial kitchens (i.e., restaurants and hospitals), or preconsumer, coming from distribution and retail agents (i.e., transporters and supermarkets). Food waste has a high moisture content, which can lead to the generation of leachate and odours during handling and processing. In this technical document, soiled paper products are included as part of the food waste discussion. Soiled paper products that cannot be recycled (e.g., paper towels, napkins, soiled or waxed cardboard, soiled newspaper, and tissues) are often included in organic waste diversion programs. These materials are readily degradable, so including them in diversion programs can be beneficial, since they act as an absorbent for other liquids during collection (Arsova, 2010).
2.6 Biogas

Biogas typically refers to a mixture of different gases produced by the breakdown of organic matter in the absence of oxygen. Biogas can be produced from raw materials such as agricultural waste, manure, municipal waste, plant material, sewage, green waste, or food waste. It is a renewable energy source and in many cases exerts a very small carbon footprint. Biogas can be produced by anaerobic digestion with anaerobic bacteria, which digest material inside a closed system, or fermentation of biodegradable materials (NNFCC, 2011).

Biogas is primarily methane (CH\(_4\)) and carbon dioxide (CO\(_2\)) and may have small amounts of hydrogen sulphide (H\(_2\)S), moisture and siloxanes. The gases methane, hydrogen, and carbon monoxide (CO) can be combusted or oxidized with oxygen. This energy release allows biogas to be used as a fuel; it can be used for any heating purpose, such as cooking. It can also be used in a gas engine to convert the energy in the gas into electricity and heat. Biogas can be compressed, the same way natural gas is compressed to CNG (Compressed natural gas), and used to power motor vehicles. In the UK, for example, biogas is estimated to have the potential to replace around 17% of vehicle fuel (Milton, 2005). It qualifies for renewable energy subsidies in some parts of the world.
Biogas can be cleaned and upgraded to natural gas standards, when it becomes biomethane.

2.6.1 Biogas Characteristics

The biogas generated by the AD process is primarily composed of methane and carbon dioxide. The methane concentration of the biogas is highly dependent upon on the feedstock composition, biological consortia, and operating conditions of the digesters. Biogas generated from MSW organics typically contains 60% methane. Hydrogen sulphide, nitrogen, ammonia, and hydrogen are also present in biogas, but in smaller concentrations. Although hydrogen sulphide is not a major component of biogas, it can be present at levels that pose a health and safety risk to site personnel, and can cause problems for equipment that uses biogas as fuel if it is not reduced to lower levels. Concentrations of $\text{H}_2\text{S}$ in biogas from MSW feedstocks typically vary from 200 to 4000 parts per million (ppm) by volume (Verma, 2002).

Hydrogen sulphide is immediately dangerous to life and health at 100 ppm by volume. Other trace contaminants, which may be present in biogas and can affect its use for energy production, include siloxanes, chlorinated organics (which can be corrosive), and other VOCs. When burned as part of the biogas, siloxanes produce a hard silica residue that can damage engine parts. Slogans are commonly found in landfill gas and biogas produced by digestion of wastewater biosolids. However, there is little published data about siloxanes in biogas produced from digestion of MSW organics, especially from Source-separated organics (SSOs). Volatile organic compounds (VOCs) in biogas vary widely and are produced from contaminants materials, such as solvents and cleaners discarded with the organic wastes, rather than being created in the digestion process. Halogenated VOCs can be a problem for equipment combusting biogas because they can produce acid gases when burned, which cause corrosion. In general, concentrations of these compounds should not be expected to be problematic unless there is reason to believe that contaminant rates will be high. However, it may be prudent to sample gases generated during biochemical methane potential tests, which produce a gas similar to those produced in a full-scale digester for these compounds. Alternatively, biogas samples from the operational facility can be taken to confirm the VOC concentrations (Pierce, 2005).
2.6.2 Biogas Quantities

The quantity of biogas that each ton of feedstock can produce is referred to as the biogas yield, which depends primarily on the waste type of the solid waste. Table 4.5 shows some VS and corresponding methane gas yields reported for various individual components of solid waste feedstocks based on actual cases. The degradation rates of waste organic matter can vary significantly with the substrate composition. As shown in Table 4.6, food wastes typically have higher biogas production than high-cellulose materials such as grass, leaves, paper, and brush. Fats, oil, and grease are reported to provide the highest biogas yields, but at the same time, due to their poor bioavailability, require the highest retention times. (Steffen, 1998).

**Table (2.1): Biogas production benchmarks (Zhang, 2007).**

<table>
<thead>
<tr>
<th>Waste mix</th>
<th>Biogas production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic fraction of MSW</td>
<td>100 to 150 m³/t of Source-separated organics</td>
</tr>
<tr>
<td>Food waste with grass cuttings</td>
<td>165 m³/t of Source-separated organics</td>
</tr>
<tr>
<td>Residential food waste</td>
<td>144 m³/t of Source-separated organics</td>
</tr>
</tbody>
</table>

The actual quantity of biogas that can be harvested can be estimated through laboratory testing. Representative samples of the feedstock are assessed using a biochemical methane potential test. The tests, which are conducted in laboratory-scale digesters, estimate the ultimate methane production that can occur under optimal digester conditions (Owens, 1993). In practice, the actual quantity of biogas produced can vary considerably from the theoretical yield. The actual yield depends, in part, on whether the feedstock mixture exhibits properties that may inhibit the biochemical digestion process, such as high nitrogen content that can lead to ammonia toxicity. Actual yield is also affected by digester design and efficiency, and retention time. For example, poor nutrient and water circulation, or less than optimal temperatures within the digester vessel, can result in reduced conversion efficiency. Similarly, shortening the residence time in the digester vessel means that not all of the biogas potential can be captured. Table 2.1 summarizes recent reports of actual biogas production from organics in the MSW stream. These may be considered rough benchmarks for proposed projects in the absence of more specific data on feedstocks for a given project (Recycling, 2006).
Table 2.2: Summary of biogas and methane yields (BNQ, 2005).

<table>
<thead>
<tr>
<th>Waste type</th>
<th>Biogas yield (m³/t waste)</th>
<th>Methane (%)</th>
<th>Methane yield (m³/t waste)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaves</td>
<td>23</td>
<td>60</td>
<td>14</td>
</tr>
<tr>
<td>Grass</td>
<td>34</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>Mixed paper</td>
<td>112</td>
<td>60</td>
<td>67</td>
</tr>
<tr>
<td>Brush</td>
<td>67</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Food waste</td>
<td>144</td>
<td>60</td>
<td>86</td>
</tr>
<tr>
<td>FOG</td>
<td>390</td>
<td>60</td>
<td>234</td>
</tr>
</tbody>
</table>

2.6.3 Challenges of Biogas Digesters

Despite the many benefits of biogas digesters, there are also a number of drawbacks that can make the implementation of this technology difficult. Since the methanogens have many specific parameters, such as temperature and pH, this hinders widespread commercialization of anaerobic digesters (Chen, 2008).

Another challenge is hydraulic retention time (HRT), which is the average time that the input slurry spends in the digester before it is removed. In tropical countries, the HRT is 30 to 50 days, whereas in colder climates, it can be as long as 100 days, which requires a larger digester volume and raises costs (Yadvika, 2004).

While digesters can provide an energy savings or even income to small-scale owners at farms—by way of selling electricity produced back to the power company—finding the right economies of scale posses yet another challenge. To illustrate this, for dairy farms analyzed by one study in Wisconsin, it is estimated that 800 to 1,000 cattle are needed in order to make a digester project economically feasible (Kramer, 2009). This has a tendency to shut out smaller operations, making biogas digesters affordable for only large-scale sites. While biogas digesters do indeed offer a valuable way to reduce food waste and to capture energy that would otherwise be squandered, the actual potential of anaerobic digestion to produce a great deal of electricity is fairly limited. According to the same Wisconsin study, if all 23 million tons of manure generated annually in the state were treated through biogas digesters, this would supply a mere 4.4 percent of the state’s natural gas needs (Kramer, 2009).
Likewise, a scenario analyzed by another study, in which all of the manure in the US was digested to produce electricity, would yield only 1.8 to 3 percent of the national demand for electricity (Cuellar, 2008). Yet, even if the energy-producing capacity of biogas is small, given the waste-reducing benefits of anaerobic digestion, combined with its ability to slow climate change, pursuing policies to make digesters more common makes a great deal of sense. The main challenge will be to find the right scale in order to make biogas digesters more economically feasible.

2.7 The Biology of Biogas Production

The Biology of Biogas production can be illustrated in several points:

1. Methanogenic archaea do not degrade sugar or even complex substances, they use either acetate or hydrogen + carbon dioxide to survive. They are old and primitive organisms, that originate back to the beginning of life, even before glucose was formed by other organisms, therefore they can feast on very basic energy sources. There are not any other "methanogens" in other branches of the evolution tree (Willey, 2011).

2. The stochiometric ratio of methane/carbon dioxide formation from carbohydrates is $\text{CH}_4/\text{CO}_2 = 50/50$, from fats $= 62.5/37.5$ and from proteins $71/29$ (due to absorptive properties of the sediment), so the number mentioned is presumably based on anaerobic microbial protein degradation? (Khanal, 2009).

3. The chain of microorganisms is not only highly likely, but is confirmed by the means of certified analytical techniques, such as the techniques of molecular biology and can be even seen under the electron microscope. The sole biochemistry and the termoenergetics of the methane formation process from polymers reveal that it is impossible for the process to start and finish in only one type of unicellular procaryotic microorganisms (or any other). We have pictures of microorganisms of species that are literally "glued one another" for better substrate / intermediate exchange, and this is no exception but a necessity for their survival. Currently it is believed that around 800 species are involved in the biogas formation community (not all at the same time) but this number is increasing rapidly (e.g. 2008 this number was around 400). Personally I believe this number to be much greater, as methanogenic micro biota is found on very diverse parts of the planet and is a common way of surviving in areas with no / low oxygen concentrations (Dworkin, 2006).
4. The issue of CO₂ which has ben adressed needs some basic insight in the process. The dissolved CO₂ that is produced intermediately in the proceses of acetogenesis (some also in the hydrolysis and acetogenesis) is, as said, a substrate for the production of methane, and is taken up very rapidly by the archaea. Therefore, you should not look at the intermediate CO₂ as a product but as a reactant. As most of the biogas (at least up to 70%) is formed via acetate decarboxylation to methane and CO₂. The partial pressures of surplus CO₂ equilibrate in the headspace of the reactor and the liquid, so the CO₂ that you get in biogas is actually mostly the product of acetoclastic methanogenesis (Jaenicke, 2011).

2.8 Digestate Characteristics, Quantities, and Processing

Digestate is the solid or semi-solid material left over at the end of the digestion process once any liquid effluents or percolates have been drained off. This material can be useful as compost or fertilizer after processing.

2.8.1 Digestate Characteristics and Processing

In wet (low-solids) and high-solids-slurry digestion systems, the digestate is the solid material extracted from the bottom of the digestion tanks. In high-solids-stackable digestion systems, the digestate is the solid material removed from the digestion tunnels. Digestate from all types of systems has a moisture content similar to the material in the digester. The unit weight of undewatered digestate from highsolds- slurry and -stackable digestion systems is in the 900 to 1000 kilograms per cubic metre (kg/m³) range because of the presence of undigested leaf and yard waste (L&YW) that is typically mixed with the food and other highly digestible wastes in these systems. Digestates from wet (low-solids) digesters that are not dewatered have unit weights of 1200 kg/m³ and greater because the solids in wet digesters typically have a higher density (Metcalf, 2002). Digestates from high-solids digestion systems are often composted immediately after removal from the digester, without dewatering. Digestate from wet (low-solids) digestion systems are usually dewatered to approximately 50% moisture content (Recycling, 2006) and further treated and used in a variety of ways, including agricultural land spreading as fertilizer (where allowed), composting, or drying to 10 to 15% moisture (85 to 90% solids) and pelletizing for use as fertilizer (Al Seadi, 2013).
2.8.2 Digestate Quantities

The digestate quantities produced are the result of removing organic materials and water from the incoming waste. Thus, the digestate quantities from a given process can be estimated by subtraction if the organics destruction and water removal quantities are known. For this purpose, the organic solids quantities in the waste materials are approximated by the volatile solids (VS) content. Typical VS contents in urban food waste are 70%, and may be as much as 97% by weight of the total solids in the wastes (Zhang, 2007). Destruction of VSs (resulting in biogas production) in the digestion process varies from 67% (Rittman, 2001) to 77%. The total solids in the waste are reduced by approximately 50 to 75% by weight in the digestion process, but because the solids are only a part of the total (most of the waste is water), the total reduction in weight in a wet digester is only 5 to 20%, especially in high-solids digestion systems. Volume reduction in high-solids stackable digestion systems has been reported to be typically in the 30 to 35% range (Bogg, 2012). A typical quantity of digestate for all digester types is 0.85 t of dewatered digestate for each of wet SSO added to the digester.

2.9 Overview of the AD for biogas production

The moisture content at which a digester is designed to operate is the most important decision regarding which process technology is best for a given feedstock mix. This decision determines the basic design parameters for the digester vessel, conveyance systems, feedstock preparation systems, and digestate handling systems. It also affects operating costs, with higher moisture contents generally incurring greater costs.

Wet digesters are designed to handle materials dissolved or suspended in water. A wet digester vessel is a stirred tank. In high-solids digesters, the materials are either pumped into a digester tank as slurry or stacked in place. When stacked in place, water is percolated through the materials to distribute nutrients and microorganisms; they are not submerged in a tank (Henry, 2002).

Wet or high-solids digesters may be designed to operate as:
- High-temperature (thermophilic), at a temperature greater than 45 degrees Celsius (°C)
- Mid-temperature (mesophilic), at temperatures between 20 and 45°C
- Low-temperature (psychrophilic), at temperatures less than 20°C

Digesters can also be configured as single-stage or two-stage systems. Most digesters are single stage, with the entire biological digestion process-taking place in a single vessel.
In two-stage systems, the first and second stages of the process occur in two different vessels, which are optimized for the microorganisms active in each digestion stage. Multi-stage digestion systems (i.e., more than two stages) are used for other waste types, but MSW organics digesters have been restricted to two stages (Arsova, 2010).

2.10 Operating Parameters

Solid-state anaerobic digesters that operated under mesophilic conditions (37–42°C) exhibited a poor start-up performance. So, thermophilic (55–65°C) digesters were developed and have been established as a reliable and acceptable option for solid-state anaerobic digestion. Operating solid-state anaerobic digestion systems at thermophilic conditions can accelerate the anaerobic digestion process and provide the added benefit of increased pathogen kill-off during the anaerobic phase. The increased amount of heat required for thermophilic operation can be offset by the higher gas production yields and rates. Most of the solid-state digesters are operated with a solids content between 20% and 40% and an operating C/N ratio of 20 to 30, with an optimal ratio of 25 (Li, 2011).

2.10.1 Hydrolysis/Liquefaction

In the first step (hydrolysis), the organic matter is enzymolyzed externally by extracellular enzymes (cellulase, amylase, protease, and lipase) of microorganisms. Bacteria decompose the long chains of the complex carbohydrates, proteins, and lipids into shorter parts. For example, polysaccharides are converted into monosaccharides. Proteins are split into peptides and amino acids (Gavrilescu, 2002).

2.10.2 Acidogenesis

Acidogenesis, also called fermentation is a process by which soluble molecules are used as carbon and energy sources by fermentative bacteria and converted into volatile fatty acids (VFAs), alcohols, and biogas. Acidogenesis is very important in anaerobic digestion as it is a step where $H_2$ is produced. $H_2$ comes from the mechanism of dehydrogenation of pyruvate by ferredoxin and NADH reductase enzymes and also from the conversion of formic acid by formate dehydrogenase. $H_2$ is one of the substrates from which methane ($CH_4$) is formed. For acidogenesis to take place, some conditions such as nature of the culture, temperature, pH and $H_2$ partial pressure must be controlled to direct the process to the formation of expected end products (Gavrilescu, 2002).

There are mainly four fermentation types in the anaerobic acidogenesis of organic matters (e.g. glucose), namely acetic acid fermentation, propionic acid type fermentation,
butyric acid type fermentation and ethanol type fermentation. Most of the microbial communities exhibit acetic acid fermentation with acetate acid as a major product (Chan et al, 2003).

2.10.3 Acetogenesis

Acetogenesis is part of the fermentation process where more reduced compounds such as aromatic compounds, long VFAs and alcohols are converted to acetic acid and H₂. VFAs such as acetate, propionate, butyrate, are major intermediate products in acidogenesis and acetogenesis stages of anaerobic biochemical degradation. The stability of over-all biochemical reactions relied on the degradation of VFA by anaerobes to the final gaseous products. Butyrate degradation differs from that of acetate as it includes acetogenesis step in the biochemical reactions, shown in the following reaction,

\[
\text{Butyrate} + 2 \text{H}_2\text{O} \rightarrow 2 \text{acetate} + 2 \text{H}_2 + \text{H}^+ 
\]

Conversion of butyrate to acetate is not thermodynamically favorable unless the acetate and hydrogen produced by the acetogens can be readily removed by acetotrophic and hydrogenotrophic bacteria, respectively. The conversion of acetate to hydrogen according to this reaction:

\[
\text{CH}_3\text{COOH} + 2 \text{H}_2\text{O} \rightarrow 4 \text{H}_2 + \text{CO}_2 \quad \Delta G^\circ = + 104.6 \text{kJ/mol}
\]

Is thermodynamically unfavorable at moderate temperatures (\( \Delta G =+ 104.6 \text{kJ mol}^{-1} \)) and is strongly determined by the hydrogen partial pressure. For acetate oxidation to hydrogen the H₂ partial pressure must be kept very low by H₂ removal (Claassen, 1999)

2.10.4 Methanogenesis

This process involves methanogenic bacteria which convert 2H and acetate and CO₂ produced by the fermentation step to methane (CH₄). Methanogenesis is the final stage of the anaerobic digestion. Two groups of methanogenic microorganisms are involved: aceticlastic methanogenesis, and hydrogenotrophic methanogenesis which involve hydrogen oxidation to methane: Aceticlastic methanogenesis

\[
\text{Acetate} + \text{H}_2\text{O} \rightarrow \text{CH}_4 + \text{HCO}_3^- 
\]

\( \Delta G^\circ = -31 \text{kJ/mol methane} \)

Hydrogenotrophic methanogenesis

\[4 \text{H}_2 + \text{HCO}_3^- + \text{H}^+ \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}\]

\( \Delta G^\circ = -135.6 \text{kJ/mol methane} \)
By using the mass balance the complete oxidation of glucose substrate to $\text{H}_2$, $\text{CO}_2$ and byproducts form, can be used to estimate the net hydrogen yield by each type of Bacteria (MasilelaPh, 2011).

**Figure (2.3)**: The three-stage anaerobic fermentation of biomass from: Production and Utilization of Biogas in Rural Areas of Industrialized and Developing Countries, Schriftenreihe der gtz, No. 97, p. 54; after: Mrkl, H.: Mikrobielle Methangewinnung; in: Fortschritte der Verfahrenstechnik, Vol. 18, p. 509, Dsseldorf, FRG (Dela-Rubia, M.A2002 ).
2.11 Factors Affecting Anaerobic Digestion

The anaerobic digestion of organic material is a complex process, involving a number of different degradation steps. The microorganisms that participate in the process may be specific for each degradation step and thus could have different environmental requirements (Hartmann, 2005).

2.11.1 Oxygen Concentration

Composting is an aerobic process, which means that degradation occurs in the presence of oxygen. Adequate oxygen is vital so that the desired types of bacteria, fungi, and actinomycetes are present to break down the organic feedstocks. The oxygen exists and permeates through the air voids between individual particles within the composting pile. Anaerobic processes are those that occur in the absence of oxygen. Aerobic processes are typically able to decompose organic waste more quickly than anaerobic processes. Anaerobic processes also tend to generate more odours. The rate at which oxygen is consumed (i.e., the oxygen demand) varies during the composting process. Oxygen consumption is highest during the first two to three weeks of active composting, when bacteria populations are at their largest, and is then reduced as the size of the microorganism populations decline later in the active composting step and during curing (Arsova, 2010).

2.11.2 Free Air Space, Particle Size, and Structure

In composting, three controlled parameters are directly correlated to oxygen concentrations and decomposition rate time:

1. Free Air Space (FAS) is a measure of the space between individual particles in the compost pile that are filled with air and is fundamental to active composting and curing, as there must be enough void space in the compost pile for oxygen. It is also critical that the spaces between the particles are interconnected so that air can move through the compost pile passively, or be forced through with aeration fans. Generally, FAS of 40 to 60% is required during the active composting step FAS in the composting pile is affected by the size range of the individual particles, and the relative amounts of differing particle sizes (i.e., the particle size distribution or gradation). Generally, a material that consists mainly of large particles has more FAS than a material comprising mainly smaller particles. It is possible to measure FAS in a compost sample, but the procedure requires the use of specialized instruments that are generally too cumbersome to be used in the field on a
regular basis. Instead, bulk density is often used as an indicator of FAS. For example, the bulk density of feedstocks and amendments processed in an actively aerated composting system should be in the range of 475 to 590 kilograms per cubic metre (kg/m³). Materials composted using a passively aerated method (e.g., static piles and windrows) should have a lower density (e.g., less than 475 kg/m³), which is indicative of a higher FAS (Speece, R.E. 2008).

2. **The Size** of individual particles affects the rate of decomposition. Smaller particles have a greater surface area relative to their volume, and more surface area means more of the material is exposed to microorganisms. Particles should typically be between 3 and 50 mm in size. While smaller particles increase the rate of decomposition, they also affect the FAS within the material: compost piles comprising many small particles may not have enough FAS, so the concentration of oxygen within the compost pile can be too low. Smaller particle sizes may also lead to larger bacterial populations and faster degradation rates. The higher populations can result in the oxygen being rapidly consumed by the microorganisms, and developing anaerobic conditions (Seereeram, 2004).

3. **The Term Structure** refers to the strength or “rigidity” of individual particles, as well as their resistance to degradation and compaction over time. It is important that enough of the particles in the composting pile maintain their structural properties throughout the composting process so that the appropriate amount of FAS is also maintained. If all of the particles have poor structural characteristics (like cardboard, which becomes wet and loses its initial rigidity), the FAS within the composting pile is reduced, and anaerobic conditions can develop (Kelleher, 2007).
2.11.3 Temperature

Many researchers have reported significant effects of temperature on the microbial community, process kinetics, stability, and methane yield.

There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – mesophilic and thermophilic ranges. The mesophilic range is between 20 °C and 40 °C and the optimum temperature is considered 30 °C to 35 °C. The thermophilic temperature range is between 50 °C and 65 °C. It has been observed that higher temperatures in the thermophilic range reduce the required retention time (Murthy, 1976).

**Table (2.3):** Digester operating temperature ranges (Rittman, 2001).

<table>
<thead>
<tr>
<th>System</th>
<th>Operating range</th>
<th>Optimal conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesophilic</td>
<td>30 to 38°C</td>
<td>35°C</td>
</tr>
<tr>
<td>Thermophilic</td>
<td>50 to 60°C</td>
<td>55°C</td>
</tr>
</tbody>
</table>
2.11.4 PH

Optimum biogas production is achieved when the pH value of the input mixture is between 6 and 7. During the initial period of digestion, large amounts of organic acids are produced and the pH of the mixture decreases. As digestion continues and the concentration of ammonia increases, due to the digestion of nitrogen, the pH value increases. When the methane gas production stabilizes, the pH remains between 7.2 and 8.2. When plant material is fermented in a batch system, the acetogenesis/fermentation stage is rapid, producing organic acids which reduce the pH and inhibit further digestion. In such situations, reduction in pH can usually be controlled with the addition of lime (He, R., et al, 2012).

2.11.5 Moisture

High moisture contents usually facilitate the anaerobic digestion; however, it is difficult to maintain the same availability of water throughout the digestion cycle initially water added at a high rate is dropped to a certain lower level as the process of anaerobic digestion proceeds. High water contents are likely to affect the process performance by dissolving readily degradable organic matter. It has been reported that the highest methane production rates occur at 60–80% of humidity studied methanogenesis processes during anaerobic digestion at different moisture levels i.e., 70% and 80%. They found that the onset of the methanogenic phase took place around day 70 in both cases, at 70% and 80% moisture. However, bioreactors under the 70% moisture regime produced a stronger leachate and consequently a higher methane production rate. At the end of the experiment, 83 ml methane per gram dry matter were produced at the 70% moisture level, while 71 ml methane per gram dry matter were produced with the 80% moisture. Nonetheless, bioreactors from both moisture regimes showed similar ratios (0.68) of bio-chemical oxygen demand (BOD) to chemical oxygen demand (COD) (Herandez, 2008).

2.11.6 Substrate/Carbon Source

The rate of anaerobic digestion is strongly affected by the type, availability and complexity of the substrate (Ghaniyari, 2009). Different types of carbon source support different groups of microbes. Before starting a digestion process, the substrate must be characterized for carbohydrate, lipid, protein, and fiber contents. In addition, the substrate should also be characterized for the quantity of methane that can potentially be produced
under anaerobic conditions. Carbohydrates are considered the most important organic component of municipal solid waste for biogas production (Dong, 2009).

However, starch could act as an effective low cost substrate for biogas production compared to sucrose and glucose. It was reported that the initial concentration and total solid content of the substrate in the bioreactor can significantly affect the performance of the process and the amount of methane produced during the process (Fernandez, 2008).

2.11.7 Nitrogen

Nitrogen is essential for protein synthesis and primarily required as a nutrient by the microorganisms in anaerobic digestion (Fricke, 2007). Nitrogenous compounds in the organic waste are usually proteins that are converted to ammonium by anaerobic digestion (Sawayama, 2004). In the form of ammonium, nitrogen contributes to the stabilization of the pH value in the bioreactor where the process is taking place. Microorganisms assimilate ammonium for the production of new cell mass. A nutrient ratio of the elements C:N:P:S at 600:15:5:3 is considered sufficient for methanization. Ammonia in high concentration may lead to the inhibition of the biological process and it inhibits methanogenesis at concentrations exceeding approximately 100 mm found that the amount of ammonia in the digester may also affect the production of hydrogen and removal of volatile solids. Total biogas production was unaffected by small increases in ammonia nitrogen while higher increases reduced the biogas production by 50% of the original rate. In the fluidized-bed anaerobic digester, the methane formation decreased at ammonium concentrations of greater than 6000 mg NH₄ –N/l. It was reported that methanogenic activity is decreased by 10% at ammonium concentrations of 1670–3720 mg NH₄ –N/l, while by 50% at 4090–5550 mg NH₄–N/l, and completely zero at 5880–6000 mg NH₄ – N/l (Hartmann, 2005).

2.11.8 C/N Ratio

The relative proportions of carbon and nitrogen present in an organic material is expressed in terms of the carbon/nitrogen (C/N) ratio. C/N ratio in the range of 20–30 is considered optimum for anaerobic digestion. If the C/N ratio is too high, the nitrogen is consumed rapidly by the methanogens to meet their protein requirement and is no longer available to react on the leftover carbon content in the material. As a result, the biogas production gets depressed if the C/N ratio is too low, nitrogen is liberated and accumulates
in the form of ammonia. This increases the pH of the material. When pH value rises higher than 8.5 it begins to exert a toxic effect on the methanogenic bacteria. Animal waste, such as cow dung, which has been the most preferred feed in lowrate biogas systems, has an average C/N ratio of 24. Plant materials contain a high percentage of carbon and so the C/N ratio is high; for example, rice straw and sawdust have C/N ratios of 70 and 7,200 respectively (Table 2.5). Human excreta have a C/N ratio of about 8. To maintain the C/N level of the digester material at optimum levels, materials of high C/N ratio can be mixed with materials of low C/N ratio (HilkiahIgoni, 2008).

Table (2.4): C/N ratio of some biodegradable materials (HilkiahIgoni, 2008).

<table>
<thead>
<tr>
<th>Raw material</th>
<th>C/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duck dung</td>
<td>8</td>
</tr>
<tr>
<td>Human excreta</td>
<td>8</td>
</tr>
<tr>
<td>Chicken dung</td>
<td>10</td>
</tr>
<tr>
<td>Goat dung</td>
<td>12</td>
</tr>
<tr>
<td>Pig dung</td>
<td>18</td>
</tr>
<tr>
<td>Sheep dung</td>
<td>19</td>
</tr>
<tr>
<td>Cow dung</td>
<td>24</td>
</tr>
<tr>
<td>Water hyacinth</td>
<td>25</td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td>40</td>
</tr>
<tr>
<td>Elephant dung</td>
<td>43</td>
</tr>
<tr>
<td>Maize straw</td>
<td>60</td>
</tr>
<tr>
<td>Rice straw</td>
<td>70</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>90</td>
</tr>
<tr>
<td>Saw dust</td>
<td>&gt; 200</td>
</tr>
</tbody>
</table>

2.11.9 Dilution

Water should be added, if necessary, to the raw material to generate slurry which is neither too thick nor too thin. If a material is diluted too much, the solid particles may settle down in the digester and may not be degraded properly. If the slurry is too thick, it may be difficult to stir and may impede the flow of gas to the upper part of the digester. Different systems can handle different levels of slurry density, generally in the range of 10–25% of solids (Aumônier, 1997).
2.11.10 Retention Time

“Retention time” is the duration for which organic material (substrate) and microorganisms (“solids”) must remain together in a digester to achieve the desired extent of degradation. Shorter the “substrate retention time” required achieving this objective in an anaerobic reactor, more efficient the reactor. But to achieve low “substrate retention times” it is necessary to simultaneously achieve high micro-organism (“solids”) retention times as explained in the following sub-sections (Pavan, 1999).

2.11.11 Sulphide Concentration

The presence of high sulphide (as H$_2$S) levels inhibits the digestion process. It was shown that sulphide concentrations in excess of 50 milligrams of sulphide per litre (mg S-L) inhibit methane generation (McCartney, 1993), most likely due to high loading of sulphur compounds, including proteins. Proteins are the usual source of sulphides in MSW organics. Sulphides are measured by taking and analyzing samples from the digester or percolate.

Table (2.5): Typical process parameters for anaerobic digestion of MSW organics (Seereeram, 2004).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High-solids</td>
</tr>
<tr>
<td></td>
<td>Stackable</td>
</tr>
<tr>
<td>Moisture content</td>
<td>Less than 60%</td>
</tr>
<tr>
<td>pH</td>
<td>6.0 to 7.0a</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>More than 100 mg/L</td>
</tr>
<tr>
<td>VFAs</td>
<td>Less than 4000 mg/L</td>
</tr>
<tr>
<td>Temperature</td>
<td>Mesophilic digesters: 30 to 38°C</td>
</tr>
<tr>
<td></td>
<td>Thermophilic digesters: 50 to 60°C</td>
</tr>
<tr>
<td>Retention time</td>
<td>14 to 40 days</td>
</tr>
<tr>
<td>C:N ratio</td>
<td>30:1</td>
</tr>
<tr>
<td>Ammonia</td>
<td>200 mg/L</td>
</tr>
<tr>
<td>Sulphide</td>
<td>Less than 50 mg/L</td>
</tr>
</tbody>
</table>
2.12 Pretreatment Methods Used to Improve Biogas Production from Organic Matters.

2.12.1 Physical Pretreatment

Physical pretreatments include mechanical (grinding, chipping, milling, knife mill, scissors), microwaves, ultrasound, steam explosion, and hot water. Mechanical pretreatments generally lead to a reduction of particles size (between 5 cm to few mm), decreasing the degree of crystallinity of cellulose, and increasing the accessible surface area and pore size of the substrate (Palmowski, 1999). Therefore, the organic matter availability to enzymes or microorganisms is favored (Hemery, 2009). For instance, ball milling pretreatment was found to be effective in increasing the specific surface area and in decreasing the crystallinity index. Some authors considered this process not cost-effective because it requires too much energy and it has been shown that greater amounts of energy are needed to reduce the size when biomass has higher moisture content (Yu, 2006). Nevertheless, the energy consumption of mechanical pretreatments is strictly related to the final particle size and to the kind of substrate used (structure and moisture content).

The effect of mechanical pretreatment on methane production was investigated by many authors, suggesting that the impact on methane production and hydrolysis kinetics may depend on pretreatment methods (cutting milling, ball milling, chipping, grinding), particle size reductions, and physical structure of substrates (Mukhopadhyay, 2009). It also studied the degradation and biogas potential of sisal fiber with sizes ranging from 10 cm to 2 mm. It was shown that the methane yield was inversely proportional to particle size with an increase of 22% when the fibers were cut at 2 mm size (220 L CH₄ kg⁻¹ VS for 2 mm, compared to 180 L CH₄ kg⁻¹ VS for untreated fibers). Found an increase of methane potentials after mechanical pretreatment of barley straw (by 54% for particle size of 0.5 cm) and wheat straw (by 83.5% for particle size of 0.2 cm). On the contrary, no significant methane potentials improvement was noticed for maize stalks. (Dumas, 2010) found no significant differences on the maximum methane production of wheat straw after a cutting mill and centrifugal grinding pretreatment between 804 and 45 μm particle sizes. Nevertheless, they found a significant increase in the first order kinetic constant between 113 and 45 μm (Ficara, 2011), found that particle size variations between 2 and 5 mm did not have relevant effects on the hydrolysis rate on ensiled maize and sweet corn mixture.
2.12.1.1 Ultrasounds or Microwaves

These types of pretreatment lead to cleavage of β-1,4-glucan bonds increasing the accessible surface area and reducing the crystallinity of cellulose (Chandra et al., 2012). Microwaves pretreatment was found efficient in increasing the solubilization of cellulose from switchgrass as glucose content in the hydrolyzate of 400 mgL were noticed after 90°C and 150°C respectively. Nevertheless, ultrasounds and microwaves technologies have several disadvantages, including high-energy consumption (Chandra, 2012), production of possible inhibiting byproducts like phenolic acids (Jackowiak, 2011), complex operation procedures and strict monitoring of equipment (Pan et al, 2003), that actually limit their commercial applications.

Irradiation can cause significant breakdown of the structure of lignocellulosic wastes (LSW). Microwave irradiation at a power of up to 700 W at various exposure times resulted to weight loss due to degradation of cellulose, hemicellulose and lignin, and the degradation rates are significantly enhanced by the presence of alkali (Zhu 2005a, 2005b, 2006). In addition, gamma radiation has been shown by to cause significant breakdown of the structure of powder of 140-mesh wheat straw, leading to weight loss and glucose yield of 13.40% at 500 k. The earliest known study involving microwave pretreatment examined the effect of microwave radiation on rice straw and bagasse immersed in water reported an improvement in total reducing sugar production by a factor of 1.6 for rice straw and 3.2 for bagasse in comparison to untreated biomass (Ooshima et al., 1984).

Microwave pretreatment of sugarcane bagasse and rice hulls soaked in water followed by lignin extraction was reported to yield 77-84% of total available reducing sugars (Azuma, 1984). A similar study involving microwave pretreatment of rice straw and sugarcane bagasse followed by lignin extraction reported a yield of 43-55% of total available reducing sugars (Kitchaiya, 2003). Microwave-based pretreatment of rice straw soaked in dilute alkali resulted in glucose yield and total carbohydrate conversion of 65 % and 78 % respectively (Zhu, 2005). Recently studies on microwave-based alkali pretreatment of 86 switchgrass have also been reported (Hu, 2008).

Switchgrass samples immersed in water, dilute sulfuric acid, and dilute sodium hydroxide solutions were exposed to microwave radiation at varying levels of radiation power and residence time. Pretreated solids were enzymatically hydrolyzed and reducing sugars in the hydrolysate were analyzed. Microwave radiation of switchgrass at lower power levels resulted in more efficient enzymatic hydrolysis. The application of
microwave radiation for 10 minutes at 250 watts to switchgrass immersed in 3% sodium hydroxide solution (w/v) produced the highest yields of reducing sugar. Results were comparable to conventional 60-minute sodium hydroxide pretreatment of switchgrass. The findings suggest that combined microwave-alkali is a promising pretreatment method to enhance enzymatic hydrolysis of switchgrass (Ravoof, 2012).

Chandler (1980) used microwave-assisted dilute nitric acid pretreatment and could enhance the enzymatic digestibility of rice straw by 14% when compared to the convection-heating mode. It also reduces the pretreatment time from 60 min to 7 min and highest yield of reducing sugars were obtained at 2% of acid concentration.

Li (2012) used the microwave assisted alkali pretreatment and enzymatic hydrolysis of banana pseudostem (BPS) for the production of bioethanol. Pretreatment of BPS was performed at different alkali concentration, liquid-solid ratio, temperature and microwave exposure time. Enzymatic hydrolysis of pretreated BPS was done at constant cellulase enzyme loading and yield of reducing sugars (YRS) with respect to time was observed. It was found that when BPS was pretreated by 10 % NaOH with 4:1 liquid to solid ratio at 90°C for 8 min, the yield of reducing sugars reached 84 % by enzymatic hydrolysis of with cellulase enzyme. Compared with convection mode of heating of alkali pretreatment, microwave assisted alkali pretreatment and enzymatic hydrolysis was more effective for BPS.

Y. Lin (2009) used the feasibility of microwave assistant KOH pretreatments to enhance enzymatic hydrolysis of bamboo. Pretreatment was carried out by immersing the bamboo in KOH (12% and 8% w/w bamboo) solutions and exposing the slurry to microwave radiation power of 400 W for 30min. Chemical composition of the pretreated substrates and spent liquor was analyzed. Pretreated substrates were enzymatic hydrolyzed, and glucose and xylose in the hydrolysate were analyzed. The results showed that the pretreated substrate with microwave assisted KOH had significantly higher sugar yield than the untreated samples. The fermentation inhibitors formic acid, furfural, 5-(hydroxymethyl) furfural (HMF) and levulinic acid were much lower than acid pretreatment reported.
Figure (2.5): Difference between conventional Heating and Microwave Heating (Tyagi, 2013).
Table (2.6): Effect of Microwave (MW) Pretreatment on Anaerobic Digestion (Tyagi, 2013).

<table>
<thead>
<tr>
<th>Treatment Conditions</th>
<th>Anaerobic Digestion</th>
<th>Findings</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>91.2 °C, 7 min</td>
<td>SRT 15 days</td>
<td>25.9% VS reduction, 23.6% TCOD removal. 64% and 79% improvement in TCOD removal and in methane production. Anaerobic digestion of MW pretreated sludge reduced the reactor SRT from 15 days to 8 days. (Park, 2004)</td>
<td></td>
</tr>
<tr>
<td>96°C, 3% TS</td>
<td>Batch, 5 day SRT</td>
<td>30% Higher biogas production over control reactor and 26% higher VS removal (Eskicioglu, 2007)</td>
<td></td>
</tr>
<tr>
<td>85°C</td>
<td>Batch, 25 days SRT</td>
<td>12% and 16% improvement in VS destruction and in methane production, respectively (Kennedy, 2007)</td>
<td></td>
</tr>
<tr>
<td>175°C, 3% TS</td>
<td>Mesophilic batch,</td>
<td>31% Higher biogas production than the control (Eskicioglu, 2009)</td>
<td></td>
</tr>
<tr>
<td>170°C, 30 min</td>
<td>Batch, 30 d SRT</td>
<td>25.9% Higher biogas production, 12% higher VS removal over control (Qiao, 2010)</td>
<td></td>
</tr>
</tbody>
</table>

2.12.1.2 Steam Explosion:

During steam explosion process, lignocellulosic biomass is heated rapidly to a high temperature (160-260 °C) with sufficient pressure (1-7 MPa) to enable water molecules to penetrate the substrate structure for a few minutes. The pressure is then suddenly released to allow the water molecules to escape in an explosive manner. Steam pretreatment can be improved by using an acid catalyst, such as H$_2$SO$_4$ or SO$_4$ (0.3-3 g acid 100g-1), which increases the recovery of cellulose and hemicelluloses sugars (Montané et al, 2009). This pretreatment opens up the plant cells, increases surface area, and enhances the digestibility of biomass (Lam PS, 2011). On his part, Kumar has shown that SO$_4$ steam explosion at 190°C during 2 min increase the accessible surface area of wheat straw from 1.1 m2 g-1 (untreated wheat straw) to 1.9 m2 g-1. Limitations of steam explosion are the incomplete disruption of the lignin-carbohydrate matrix and the formation of hemicelluloses and cellulose degradation byproducts as water acts as an acid at high temperature (e.g. furfural and hydroxymethylfurfural) (Kumar, 2009).
Steam explosion has been also widely investigated to enhance methane potential from lignocellulosic residues. When steam explosion at 180°C for 25 min was applied to wheat straw, methane production increased by 31% (Bauer, 2009). Combination of steam explosion with 2 g NaOH 100g^{-1} substrate and 2 g H_{2}O_{2} 100g^{-1} substrate enhanced the methane yield of paper tube residues from 238 L CH_{4} kg^{-1} VS to 493 L CH_{4} kg^{-1} VS (Bochmann, 2010).

2.12.1.3 Liquid Hot Water (LHW)

LHW is a hydrothermal treatment that does not require rapid decompression and does not employ any catalyst or chemicals. Pressure is generated to maintain water in the liquid state at elevated temperatures (200–240 °C) for few minutes (Kumar, 2009). However, actually liquid hot water pretreatments performed at relative low temperature (90°-170°C) for 0.5-1 h, were also applied. Water under pressure penetrates into the biomass, increasing surface area and hence removing hemicelluloses and lignin (Mosier, 2005). Three types of reactor can be used for liquid hot water pretreatment: co-current (biomass and water are heated together for a certain residence time), counter-current (water and lignocelluloses move in opposite directions), and flow-through (hot water passes over a stationary bed of lignocelluloses) (Liu, 2010). In general, liquid hot water pretreatments are attractive for their cost-savings potential: no catalyst requirement and low-cost reactor construction due to low-corrosion potential. However, water and energetic requirement remain higher (Alvira, 2010). Liquid Hot Water pretreatments have been investigated to enhance methane production from lignocellulosic residues. After thermal pretreatment at 120°C during 1 h, Menardo et al. (2012) showed 32% and 64% methane increase respectively for rice straw and wheat straw. Monlau et al. (2012c), showed an increase in methane production of 14%, by treating sunflower stalks at 170°C for 1h.
2.12.2 Chemical Pretreatment

Chemical and Physico-chemical Pretreatment is performed by introducing one or more chemicals to treat the ligno-cellulosic biomass. Some of the main techniques used in this treatment are as follows.

1. Acidic Pretreatment.
2. Oxidizing Agents.
3. Alkaline Pretreatment

Ca(OH)\(_2\), has been extensively used in improving biodegradability because of its low cost, high recoverability, safe handling, and minor environmental effects. (Torget, 1990) reported that the lignin, cellulose, and hemicellulose of rice straw were significantly degraded, and the highest methane yield of 225.3 ml/g VS, was obtained with 9.81% Ca(OH)\(_2\) (w/w TS) for 5.89 day pretreatment time, and 45.12% inoculums content. Pretreatment time considerably affected the degradation of the main components of rice straw and that long treatments increased the reduction in cellulose and hemicellulose contents under certain conditions. At the same pretreatment time, a high lime concentration resulted in a high decrease in cellulose and hemicelluloses. These results indicate that a high pretreatment concentration more effectively breaks down the lignocellulose matrix and changes its chemical components. The high Ca(OH)\(_2\) considerably changed the microstructure of the cell wall and increased the accessibility of contents to anaerobic microorganisms, facilitating the use of soluble compounds with low molecular weights by microorganisms and increasing biodegradability (Sun Y, 2002). Lime pretreatment led to limited lignin reduction that ranged from 4.4% to 24.3%, a value considerably lower than those generated by other alkaline chemicals, such as NaOH and NH\(_3\)\cdotH\(_2\)O (McLaughlin, 2002).

Reduced lignin reduction may have resulted from the formation of calcium-lignin complex. Calcium ions, which carry two positive charges, tend to crosslink negatively charged lignin molecules under alkaline conditions. Cross linking is caused by the ionization of functional groups, such as carboxyl, methoxyl, and hydroxyl, through the formation of stoichiometric bonds, thereby weakening lignin solubility by Ca(OH)\(_2\) during pretreatment processes (Sun Y, 2002).
2.12.2.1 Process Description and Mode of Action

Chemical pretreatment is used to achieve the destruction of the organic compounds by means of strong acids, alkalis, or oxidants. AD generally requires an adjustment of the pH by increasing alkalinity, thus alkali pretreatment is the preferred chemical (Li H, 2012). Acidic pretreatments and oxidative methods such as ozonation are also used to enhance the biogas production and improve the hydrolysis rate. The effect of chemical pretreatment depends on the type of method applied and the characteristics of the substrates. Chemical pretreatment is not suitable for easily biodegradable substrates containing high amounts of carbohydrates, due to their accelerated degradation and subsequent accumulation of VFA, which leads to failure of the methanogenesis step (Wang, 2011).

2.12.2.2 Alkali Pretreatment

During alkali pretreatment, the first reactions that occur are salvation and saponification, which induce the swelling of solids (Val del Rio, 2011). As a result, the specific surface area is increased and the substrates are easily accessible to anaerobic microbes. Then, COD solubilization is increased through various simultaneous reactions such as saponification of uronic acids and acetyl esters, as well as neutralization of various acids formed by the degradation of the particulates. When substrates are pretreated with alkali methods, an important aspect is that the biomass itself consumes some of the alkali, thus higher alkali reagents might be required for obtaining the desired AD enhancement (Hendriks, 2009).

2.12.2.3 Acid Pretreatment

Acid pretreatment is more desirable for lignocellulosic substrates, not only because it breaks down the lignin, but also because the hydrolytic microbes are capable of acclimating to acidic conditions (Mussolini, 2012). The main reaction that occurs during acid pretreatment is the hydrolysis of hemicellulose into perspective monosaccharides, while the lignin condensates and precipitates. Strong acidic pretreatment may result in the production of inhibitory by-products, such as furfural and hydroxymethylfurfural (HMF). Hence, strong acidic pretreatment is avoided and pretreatment with dilute acids is coupled with thermal methods. Other disadvantages associated with the acid pretreatment include the loss of fermentable sugar due to the increased degradation of complex substrates, a high cost of acids, and the additional cost for neutralizing the acidic conditions prior to the AD process (Kumar, 2011).
2.12.2.4 Effects of Accompanying Cations Present in the Acid/Alkaline Reagents

In addition to the effects of the alkali and acid themselves, the AD might be affected by the accompanying cations present in these reagents including sodium, potassium, magnesium, calcium, since the chemicals are added mostly as salts or hydroxides of these cations. Therefore, the inhibitory concentrations of these cations should be considered (Appels, 2008).

Zhang (2007) studied the inhibition effect of cations concentration AD of FW, and reported that more than 5 g/L of sodium resulted in lower biogas production. Sodium is more toxic to propionic acid utilizing bacteria as compared to other VFA degrading bacteria. The inhibitory level of the potassium ion starts at 400 mg/L, though anaerobic microbes are able to tolerate up to 8 g/L potassium. The potassium ion is more toxic to thermophilic anaerobes as compared to mesophilic or psychrophilic anaerobes. The optimum concentrations of calcium and magnesium ions have been reported to be 200 mg/L and 720 mg/L, respectively. Excessive amounts of calcium ions can cause precipitation of carbonates and phosphates, which results in scaling of the reactors, pipes, and biomass; thus, it reduces the specific methanogenic activity and results in a loss of buffer capacity.

Also high concentrations (>100 mM) of the magnesium ion can cause disaggregation of methanogens, thus the conversion of acetate is inhibited. Furthermore, AD could also be enhanced indirectly due to the supplementation of trace metals such as cobalt (Co), molybdenum (Mo), selenium (Se), iron (Fe), tungsten (W), copper (Cu) and nickel (Ni), which play a role in many biochemical reactions of the anaerobic food web. For instance Zhang and Jahng used supplements of trace metals such as Fe, Co, Mo and Ni to stabilize a single-stage reactor treating FW, and concluded that Fe was the most effective metal for stabilization of the AD process (Zhang, 2007).

(Facchin, 2013) achieved a 45–65% higher methane production yield from FW with supplementation of a trace metals (Co, Mo, Ni, Se, and W) cocktail. Nevertheless, supplementing trace metals to solid waste AD plants should not be considered as a pretreatment method, though it could be an effective method for achieving higher biogas production rates with higher methane content.
2.12.2.5 Ozonation

Another chemical pretreatment method is coronation, which does not cause an increase of the salt concentration and no chemical residues remain as compared to other chemical pretreatment methods. Moreover, it also disinfects the pathogens. Hence, ozonation has gained great interest for sludge pretreatment, and to a lesser extend OFMSW. Ozone is a strong oxidant, which decomposes itself into radicals and reacts with organic substrates in two ways: directly and indirectly (Sri Bala, 2011). The direct reaction depends on the structure of the reactant, whereas the indirect reaction is based on the hydroxyl radicals. As a result, the recalcitrant compounds become more biodegradable and accessible to the anaerobic bacteria (Carballa, 2008).

2.13 Thermochemical Pretreatment

Different kinds of bases and acids can be used in thermochemical pretreatment (ammonia or solvents can also be used, in theory). Thermochemical pretreatment at temperatures from 60 to 220 °C have been investigated. As with other pretreatments involving heat, temperatures of more than around 160 °C, particularly in combination with acids, show a drop in methane production, depending on input material (Bolzonella, 2012). Acid pretreatment of cassava with heating was investigated by (Zhang, 2011). A 57% higher gas yield was found during batch AD for pretreated cassava, when compared to untreated cassava, using 160 °C, 3% H₂SO₄ and 20 minutes retention time. The influence of thermal, chemical and thermochemical pretreatment on dewatered pig manure was analysed by (Rafique, 2010). High concentrations of lime (5%) showed maximum enhancement of gas yield at 70 °C, much better than lime alone or heat alone. An increase of 78 % biogas was observed during batch AD tests. Monlau (2012) compared the effect of different chemicals and temperatures on methane yields from sunflower stalks. They used batch tests and found that pretreatment with heat alone was not very effective, but that pretreatment with H₂SO₄ or NaOH (4 g / 100 g total solids) did increase methane yield by about one third at 55 °C (rather than 30 or 80 °C). They found that this pretreatment solubilised lignin. Pretreatment with HCl at 170 °C increased methane yield by around 20% and solubilised hemicellulose but not lignin. Thermochemical pretreatment with acids below 160 °C could be very useful for recalcitrant, lignocellulose- rich substrates, provided the energy needed can be offset by the energy gained. Thermochemical pretreatment with alkali at around 50 °C could be useful for lignin or phenol-rich substrates.
2.14 Mechanical Pretreatment of OFMSW

Mechanical pretreatments such as rotary drum were used as an effective technology for OFMSW separation and pretreatment prior to AD, which could enhance the biogas production by 18–36% (Zhu, 2009). Davidson et al. found small variations in both methane yields per g VS (gram volatile solids) and content of methane in biogas while studying the biomethane potential of source-sorted OFMSW pretreated with different mechanical methods including screw press, disc screen shredder, FW disposer and piston press (Davidson, 2007).

Hansen et al. (2007) studied the effects of the same pre-treatment technologies on the quantity and quality of source-sorted OFMSW. They found that screw press pretreatment resulted in a smaller substrate particle size, while a shredder with magnetic separation yielded a higher (5.6–13.8%), as compared to the other methods, methane production (Hansen et al, 2007). In contrast, Bernstad et al. reported that the screw press pretreatment method also result in a loss of biodegradable materials and nutrients, even though it enhances the biogas production in general. Izumi et al (2010) studied the effect of the particle size on FW biomethanation. Size reduction through a beads mill resulted in a 40% higher COD solubilization, which led to a 28% higher biogas production yield. However, excess size reduction to particles smaller than 0.7 mm caused an accumulation of VFA (Izumi et al, 2010). As the methanogens are sensitive to acidic intermediates, excessive size reduction may result in a decreased AD process performance. Few researches on electroporation, liquefaction, and high frequency sonication pretreatment methods to enhance OFMSW have been conducted. Electroporation pretreatment of OFMSW resulted in 20–40% higher biogas production (Carlsson, 2008) and liquefaction resulted in 15–26% higher biogas production, whereas sonication resulted in 16% higher cumulative biogas production as compared to untreated substrates. The higher biogas production was mostly due to the more extensive solubilization of the particulates (Cesaro, 2013).
2.15 Combined Microwave-Chemical Pretreatments:

Microwave irradiation has been widely used in chemistry because it has high heating efficiency and can, in some cases, increase reaction rate and reduce reaction time which could lead to considerable energy savings. However microwave processing might have the side effect of producing heat-induced inhibitors such as phenolic compounds and furfural (Huang, 2009).

As a result, it is important to control pretreatment conditions to avoid the formation of these inhibitors. Therefore, microwave has not been used individually for lignocellulosic biomass pretreatment, but usually it has been used to provide heat for assisting acid or alkaline pretreatment at relatively low temperatures without compromising pretreatment effects. Zhu et al. (2005) used microwave and alkali (NaOH) at 700 W for 30 min and 1% NaOH. The result showed that rice straw had a weight loss of 44.6% and composition cellulose 69.2%, lignin 4.9%, and hemicellulose 10.2%. The enzymic hydrolysis of pretreated rice straw was also investigated and the results indicate that rice straw pretreated by microwave/alkali had a higher hydrolysis rate and glucose content in the hydrolysis in comparison with the one by alkali alone (Deepak, 2007).

Combination of microwave and chemical pretreatment also reported by with organic acid (acetic acid and propionic acid). Under optimal conditions (25% acid concentration, 1:15 solid-liquid ratio, 230 W microwave intensity, and 5 min irradiating time), the removal ratios of lignin are 46.1 and 51.54%, and the sugar yields are 71.41 and 80.08%. This suggests that microwave-assisted organic acid pretreatment is effective in improving the enzymatic hydrolysis sugar yield of rice straw. They also reported that the sequence of influence strengths of the factors was microwave intensity > solid-liquid ratio > acetic acid concentration > microwave irradiating time (Sun et al, 2010).

Another chemical combined with microwave is hydrogen peroxide (H$_2$O$_2$). Under optimum condition (H$_2$O$_2$ 2%, microwave intensity 100 W, for 3 min) maximum reducing sugar obtained through microwave assisted H$_2$O$_2$ is 1,453.64 μg/mL and has a significantly high crystalline index (63.64%) than untreated rice straw sample (52.2%). Microwave assisted H$_2$O$_2$ pre-treatment disrupted the silicon waxy structure and broken down all ether linkages between lignin and carbohydrates and thus, efficiently remove lignin (Soroushian, 2006).
Table (2.7): Summarizes results of Various works on Microwave (MW) assisted Pretreatments and Operating Conditions as indicated by (Tyagi, 2013).

<table>
<thead>
<tr>
<th>Pretreatment Type</th>
<th>Operating Conditions</th>
<th>Findings</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW assisted Acidic</td>
<td>0 to 0.02 M, 180°C for 30 Min</td>
<td>0.02 best concentration, 80 to 98% hemicellulose hydrolyzed</td>
<td>(Chen, 2012)</td>
</tr>
<tr>
<td>MW assisted Acidic</td>
<td>1:15 solid to liquid, MW various time</td>
<td>Optimum fermentative hydrogen production</td>
<td>(Khamtib, 2011)</td>
</tr>
<tr>
<td>MW assisted Acidic</td>
<td>0-0.4 N acid, MW 700 W, 5-90 min</td>
<td>Enhanced hydrogen production</td>
<td>(Liu, 2010)</td>
</tr>
<tr>
<td>MW assisted Alkali</td>
<td>0 to 5% concentration, 140°C MW</td>
<td>MW enhanced enzymatic hydrolysis and hydrogen yield</td>
<td>(Cheng, 2011)</td>
</tr>
<tr>
<td>MW assisted Alkali</td>
<td>0.05-0.3 g/g biomass, 70-190°C MW</td>
<td>MW assisted in enzymatic digestibility, and sugar yield</td>
<td>(Hu, 2008)</td>
</tr>
<tr>
<td>MW assisted Alkali</td>
<td>2-5% Alkali, 60-140°C MW</td>
<td>Very effective in extracting 80% or more hemicellulose</td>
<td>(Janker, 2012)</td>
</tr>
<tr>
<td>MW assisted Alkali</td>
<td>1% alkali, MW 300 to 700 W, 15 min to 2 Hrs</td>
<td>Enhanced enzymatic hydrolysis rate</td>
<td>(Zhu, 2005)</td>
</tr>
<tr>
<td>MW assisted Alkali</td>
<td>1% Alkali, MW 700 W for 25 min</td>
<td>Optimum ethanol production (64.8%) obtained</td>
<td>(Zhu, 2006)</td>
</tr>
<tr>
<td>MW assisted Alkaline</td>
<td>1% Alkali, MW 120-200°C, 5 min</td>
<td>Enhanced glucose yield by enzymatic hydrolysis</td>
<td>(Tsubaki, 2013)</td>
</tr>
<tr>
<td>MW assisted Ball Milling</td>
<td>Ball Milling for 1-6 Hrs, MW 800W, 20 min</td>
<td>Optimum conditions for glucose yield</td>
<td>(Peng, 2013)</td>
</tr>
<tr>
<td>MW assisted Chemical</td>
<td>33-117g biomass in 62.5% chemical</td>
<td>Optimum glucose yield by enzymatic hydrolysis</td>
<td>(Li, 2013)</td>
</tr>
<tr>
<td>MW assisted Chemical</td>
<td>50 ml chemical, MW 800 W, 5 min</td>
<td>Optimum conditions for reducing sugar production</td>
<td>(Lü, 2011)</td>
</tr>
<tr>
<td>MW assisted Chemical</td>
<td>30 % Chemical, variable MW setting</td>
<td>Optimum conditions for biogas and free liquid fraction</td>
<td>(Shahriari, 2012)</td>
</tr>
<tr>
<td>MW assisted Chemical</td>
<td>Various Chemicals, MW 80 to 140°C, 30 min</td>
<td>High sugar yield (59.5C%) obtained at 140°C at 30 min</td>
<td>(Verma, 2011)</td>
</tr>
<tr>
<td>MW assisted Chemical</td>
<td>Various Chemicals and settings compared</td>
<td>Most optimum conditions for enzymatic hydrolysis</td>
<td>(Zhu, 2006)</td>
</tr>
</tbody>
</table>
2.16 Previous Studies on biogas production from pretreated liquid and solid municipal waste.

Treatment of liquid and solid municipal waste in anaerobic digestion optimized for biogas production was investigated. Food left overs, such as kitchen waste have high energy potential but are low in structural compounds, and the biogas-forming process is often impaired by accumulation of volatile organic acids. The effect of additional biofilm carriers were tested in two of four parallel operating experimental digesters of 10L volume. Already a very low amendment of plant structures for biofilm formation significantly stabilized methane production compared to control digesters (Kompogas, 2011).

Optimization of Process Parameters Affecting Biogas Production from Organic Fraction of Municipal Solid Waste via Anaerobic Digestion were. The parameters studied were initial pH, substrate concentration, and total organic carbon (TOC). The experimental results showed that initial pH and substrate concentration and TOC had significant individual effect (p < 0.05) on biogas yield. However, there was no interactive effect between these variables (p > 0.05). The highest level of biogas produced was 53.4 L/Kg VS at optimum pH, substrate concentration and total organic carbon of 6.5, 99g TS/L and 20.32 g/L respectively (Visvanathan, 2004).

Investigation of biogas production from MSW with garage type bioreactor was performed. The goal of the investigation was to identify how suitable the garage-type bioreactor and production technology for biogas production from MSW (municipal solid wastes) and to identify the biogas obtaining potential. Biogas output was investigated at 37-38 °C. The garage-type bioreactor and production technology is suitable for biogas production using MSW. The fermentation process was measured on pH 7.21-7.99 levels. The obtained biogas value of 1 ton of waste in 4 weeks:

Investigation A – average 23.21 Nm³ biogas,
Investigation B – average 34.23 Nm³ biogas,
Investigation C – average 40.89 Nm³ biogas (Dubrovskis, 2009).

Enhancement of Biogas production and organic reduction of sludge by different pretreatment processes was investigated. Anaerobic digestion (AD) is the most common process for dealing with primary and secondary wastewater sludge; four pre-treatment methods (ultrasonic, chemical, thermal, and thermo-chemical) are investigated Wastewater Treatment plant in order to find their effect on biogas production and volatile solid
removal efficiency during anaerobic digestion. Two frequencies of ultrasonic wave were used 30 KHz and 50 KHz during the pre-treatment. Sodium hydroxide was added in different amounts to give three pH values of 9, 10 and 11 in chemical pre-treating processes. The sludge was heated at 60C° and 80C° through thermal pre-treatment experiment. Also, the sludge was treated thermo-chemically at 80 C° and pH 11 prior to anaerobic digestion. Maximum biogas production (6009 ml) was obtained at ultrasonic pre-treatment method with 30 kHz. The volumetric ratio of produced biogas to the initial volume of sludge is about 4:1 (Clisso, 2010).

Investigation of microwave (MW) irradiation pretreatments effect on the anaerobic digestion of food residues using biochemical methane potential (BMP) assays was performed. Low solids systems with a total solids (TS) content ranging from 5.0-10.0% were analyzed. The inoculums to bulk mass of substrates to water ratio was 1:2:2 (mass basis). The experimental conditions for pretreatments were as follows: a control (no MW irradiation), two runs with MW irradiation for 15 and 30 minutes at 320 W, and another two runs with MW irradiation at 528 W for 30 and 60 minutes. The cumulative biogas production were 6.3 L and 8.7 L for 15min/320 W and 30min/320 W MW irradiation conditions, respectively, and 10.5 L and 11.4 L biogas for 30min/528 W and 60min/528 W, respectively, as compared to the control giving 5.8 L biogas. Both an increase in exposure time of irradiation and power of MW had increased the rate and yield of biogas. Single factor ANOVA tests (p<0.05) indicated that the variations in VS, TS, COD and cumulative biogas generation were significantly different for the pretreatment conditions. Results from this study indicated that MW irradiation had enhanced the biogas production and degradation of total solids with a significant improvement in VS and COD solubilization (sadugh, 2009).

Miksch (2010) studied the influence of microwave irradiation on biodegradability of waste, and this influence activated sludge biodegradability. The aim of that work was to establish the most appropriate time of microwave exposure, which ensures effective sludge lyses. The assessment of the sludge disintegration was based on a release of organic (COD) and inorganic (PO₄³⁻, NH₄⁺, Ca²⁺, Mg²⁺) substances into liquid phase as well as the quantity and quality of the biogas produced. It was established that an increase in sludge biodegradability caused by a rise in COD, had a positive impact on the amount of biogas generated. Based on the results obtained, the optimum microwave exposure time amounted to 4 min, and was correlated with the sludge temperature of 60C° for the power of 700W.
and 80°C for power of 900W. As compared to the amount of biogas generated with raw sludge, the optimum exposing time allowed to generate 49% and 60% more biogas at 700W and 900W respectively. Microwave treatment at both powers, did not have an influence on the CH₄ content in biogas produced.

Borjesson (2008) investigated effects of alkaline pretreatment on the biogas generation potential of vegetable wastes. It has been found that chemical treatment of vegetable wastes with alkali (NaOH(aq)) enhanced biogas yield over a 35–day retention period of anaerobic digestion. The limitation, which has been observed to the anaerobic digestion of the fruit and vegetable wastes studied here, was a high volatile fatty acids production, which may have stressed and inhibited an optimum activity of the methanogenic bacteria. From this study, it may be deduced that alkaline pretreatment with NaOH has had a positive effect in improving the rate and yield of biogas production.
Chapter 3
Materials and Methods

3.1 Materials

3.1.1 Microorganisms

In this work, a consortium of anaerobic microorganisms was obtained from anaerobic digester of Sheikh Ijleen wastewater treatment plant.

3.1.2 Collection and preparation of OFMSW

Household solid waste material was collected and sorted to separate the biodegradable fraction including papers. The biodegradable fraction was weighed to estimate the wet weight, then it was dried to evaluate the weight, and the dried material has been ground by a coffee machine for use in the treatment processes.

Part of the dried sample was used to estimate COD (chemical oxygen demand), TOC (total organic carbon) and TKN (total Kjeldahl nitrogen). Those tests were used to estimate and adjust carbon/nitrogen C/N ratio in the range 20/35.

The dried samples of biodegradable wastes were subjected for subsequent pretreatment processes (alkaline, microwave and combined alkaline microwave treatments) for biogas production and as control experiments that was not subjected for any treatment.

3.1.2 Reactor Design

There were six 1000 ml-glass bottles caped with rubber stoppers, which acted as digester. The bottles were settled in a thermostat water bath where the temperature could be observed nearly 38 °C. There was a hole in each rubber cap attached with a tube. The tube then went from the bottle to another cap that was connected to a graduated cylinder containing water at a specified level. All graduated cylinders were calibrated before the tests were started. As the gas was produced in the bottle, this decreased the water column in the graduated cylinder which finally reached. Then a "bubbling" recorded the volume of water that decreased. Following each bubbling, water returned to the starting level. A records date, time, temperature, air pressure and the volume of gas were achieved (Fig.3.1, 3.2)
Figure (3.1): The batch anaerobic digestion of experimental laboratory set up.

Figure (3.2): Reactor design
3.2 Methods

3.2.1 Alkaline Treatment

For alkaline pretreatment, 300 ml of NaOH with different concentrations for each process (1, 2 %) was mixed with (40, 60, & 75g) of dried organic matter in 500 ml Erlenmeyer flask for 5 minutes, and shaken well. The pH of the mixture was adjusted by HCl to pH 6.8 and then was inoculated with the bacterial consortium (10%) and then passed to the anaerobic digester for biogas production. A control anaerobic digestion for biogas production was operated parallel to the alkaline treated ones for comparison. The optimized best result in term of total biogas production and rate of biogas production was investigated during the subsequent combined microwave-alkaline treatment experiments. All experiments were carried out in duplicate.

3.2.2 Microwave Treatment

Microwave treatment was carried out using a domestic microwave instrument (JAC, China). The microwave instrument was operated at 2450 MHz and 450 W (Binod et al, 2012). For the purpose of microwave treatment, (40, 60, & 75g) of dried organic matter was mixed with 300 ml of water in 500 ml Erlenmeyer flask and incubated in the microwave for 5 minutes with shaking. Mixtures were collected and were passed to shaking water path and cooled to the room temperature. The pH of the reaction mixture was adjusted to 6.8 with 4M NaOH and 1M HCl. After pH adjustment, the mixture was inoculated with the bacterial consortium (10%) from anaerobic digester for biogas production. A control anaerobic digestion for biogas production was operated parallel to the microwave-treated ones for comparison. The optimized best result in term of total biogas production and rate of biogas production was investigated during the subsequent combined microwave-alkaline treatment experiments. All experiments were carried out in duplicate.

3.2.3 Combined Microwave-alkaline Treatment

Microwave-alkaline treatment was carried out using a domestic microwave instrument (JAC, China). The microwave instrument was operated at 2450 MHz and 450 W (Binod et al, 2012). For at combined pretreatment, 300 ml of NaOH with different concentrations of each experiment at (1, 2 %) was mixed with (40,60 & 75 g) of dried organic matter in 500 ml Erlenmeyer flask for 5 minutes and shaken well. The mixture then exposed to
microwave for five minutes. The resulted mixture was cooled to room temperature and the reaction mixture was neutralized with 1M HCl solution. All experiments was carried out in duplicate.

3.2.4 Monitoring Parameters

During the experimental period, the amount of biogas in each reactor is monitored to evaluate the biogas yield.

3.2.5 Biomethane Assay

Biomethane estimation analysis was performed by volumetric method. Sixty ml of the collected gas was taken with a syringe from the top of the gas collecting cylinder that has rubber cover and the gas is injected through a series of scotch bottles tightly closed: The first contains 10% NaOH to precipitate CO$_2$ gas and the other contains 5% NH$_4$OH precipitate H$_2$S. The third bottle contains H$_2$O which is collected in measuring cylinder upon displacement and accounted for CH$_4$ gas.

**Fig (3.3):** Schematic diagram of the experimental set up of the biochemical methane potential assay used for the anaerobic digestion of substrates used in this study.
4.1 Evaluation of Biogas Production

In this study, the researcher assessed the gas by taking several samples of solid organic waste to produce biogas. These samples of total carbon (51.272%) have low total nitrogen (0.645%) and high Carbon/Nitrogen (C/N) ratio (20-35). The results obtained by analyzing solid material without any treatment were of pH (6.8-7.00) before and after the fermentation process; it was to measure the rate of C/N 20-35. All experiments were carried out under a water bath in range of 38°C-40°C. Glucose was measured before biogas production and post-production of biogas in order to determine the glucose consumption in the process of anaerobic digestion in biogas production and to investigate the value of the remaining organic matter consumed during the anaerobic digestion process.
4.2 The Effect of NaOH Treatment on Biogas Production by OFMSW

In this part of work, three different amounts (40, 60, & 75 g) of OFMSW were subjected separately for NaOH treatment. Two concentrations of NaOH (1 % & 2 %) were applied independently for each time. Each treatment was duplicated. All treatments were operated for biogas production in parallel with a control bottle without any treatment. Treatment of alkaline is important as increasing the soluble organic matter content of samples will theoretically increase the easily biodegradable content of the waste and thus will lead to an improved performance of the anaerobic digestion (AD) process (Haug, 1978), Results of such treatment are shown in Tables 4.1, 4.2 & 4.3.

The results in Table 4.1 illustrate cumulative amounts of biogas production by 40 g of OFMSW treated with 1 % & 2% NaOH in pearled with control bottle. From Table 4.1, results indicated little increase of total biogas production when OFMSW was treated with 1 % NaOH comparing to control, 900 ml, & 850 ml respectively.

Comparing the rate of produced biogas between treated and controlled experiments, the researcher observed that 1% NaOH treated samples showed (300-1300 ml) biogas per hour in the reactor, and 2 % NaOH showed (500-1930 ml) of biogas per hour while the control showed (500-1900 ml) of biogas per hour. Thus, when there is an increase in NaOH the production of biogas was also increased.

The results of 40g OFMSW showed that increasing concentration of NaOH to 2% has a negative effect on total biogas production when compared to control and 1% NaOH treatment. Treatment of OFMSW with 2 % NaOH decreased the total biogas production to 576 ml per reactor of biogas production also decreased to 7.68 ml of biogas produced per hour per reactor, comparing to control reactor & 1 % NaOH treatment. Following the effect of NaOH treatment, 60 g of OFMSW and application of the same parameters were used with 40 g OFMSW experiments. The result showed that increasing OFMSW amount lead to an increase in total biogas production for control and NaOH treatment experiment was compared to biogas production by using 40 g. Accordingly, when NaOH treatment was applied, a decrease in total biogas production was noticed when OFMSW was treated with 1 % NaOH from 1900 ml total biogas (TBP) reactor for control to 1300 ml (TBP) reactor for 1 % NaOH treatment. Increasing NaOH amount up to 2 % treatment caused increasing in biogas
production up to 1930 ml (TBP) reactor, slightly exceeding the control reactor. This results suggested relationship between NaOH ratio & amount of OFMSW (see Table 4.2 & 4.3 & Figures 4.1, 4.2 & 4.3).

**Table (4.1):** Effect of Alkaline Pretreatment when Total OFMSW was 40g

<table>
<thead>
<tr>
<th>Time</th>
<th>NaOH</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>675</td>
<td>850</td>
<td>850</td>
<td>850</td>
<td>850</td>
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<td>18g</td>
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<tr>
<td>1%</td>
<td></td>
<td>725</td>
<td>850</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>120</td>
<td>60</td>
<td>35g</td>
<td>17.5g</td>
</tr>
<tr>
<td>2%</td>
<td></td>
<td>350</td>
<td>450</td>
<td>575</td>
<td>575</td>
<td>575</td>
<td>110</td>
<td>42</td>
<td>28g</td>
<td>15g</td>
</tr>
</tbody>
</table>

**Table (4.2):** Effect of Alkaline pretreatment when total OFMSW was 60g

<table>
<thead>
<tr>
<th>Time</th>
<th>NaOH</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
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<tbody>
<tr>
<td>control</td>
<td></td>
<td>1600</td>
<td>1750</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>587</td>
<td>180</td>
<td>60g</td>
<td>20g</td>
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<td>1%</td>
<td></td>
<td>900</td>
<td>1100</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
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<td>1800</td>
<td>1930</td>
<td>1930</td>
<td>350</td>
<td>160</td>
<td>48g</td>
<td>24.5g</td>
</tr>
</tbody>
</table>

**Table (4.3):** Effect of Alkaline Pretreatment when Total OFMSW was 75g

<table>
<thead>
<tr>
<th>Time</th>
<th>NaOH</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
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<td>680</td>
<td>534</td>
<td>175</td>
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</table>
**Figure (4.1):** A Cumulative Biogas Production for Samples Pretreated with NaOH 1% & 2% at 38°C Total Solid Material of 40g.

**Figure (4.2):** A Cumulative Biogas Production for Samples Pretreated with NaOH 1% & 2% at 38°C Total Solid Material of 60g.

**Figure (4.3):** A Cumulative Biogas Production for Samples Pretreated with NaOH 1% & 2% at 38°C Total Solid Material of 75g.
4.2.1 The Effect of NaOH on TS

Total solid was checked after pretreatment with NaOH. On treating a total 40g OFMSW with 1 % NaOH concentration, there was a reduction of 56.5 % TS after fermentation. When 2% NaOH was added to the OFMSW, the reduction was about 53%. And, in total 60g OFMSW with 1% NaOH, there was 57.5% reduction in TS after fermentation. On mixing 2 % NaOH with OFMSW, there was 40% reduction in TS after fermentation. For total 75g OFMSW with 1% NaOH concentration, there was a reduction of 54% TS after fermentation. When 2 % NaOH was added to the OFMSW, the reduction was about 54 %. Such results indicate that as the concentration of NaOH exceeded a particular limit, the TS reduction was decreased, indicates that alkali pretreatment increases the OFMSW solubility and its property is improved for bio gas generation process and composting process (Lo´pez Torres & Ma. del C. Espinosa, 2008 ; Fernandes, et al. 2009). as shown in figures 4.4, 4.5 and 4.6.

Figure (4.4): Total solid Residue before and after fermentation at a weight of 40 g of organic matter.
4.2.2 The Effect of NaOH on Glucose Concentration

From the previous results, the researcher can conclude that increasing OFMSW from 40, 60 and 75g leads to increase in TGP in all cases for control of 1% 2% NaOH. The researcher observed that increasing NaOH ratio improved the TGP except when used with 40 g of OFMSW that suggested a relation between NaOH ratio and the used amount of OFMSW. Results from Tables (4.1, 4.2, & 4.3) and Figure (4.7, 4.8, & 4.9) revered that alkaline treatment caused reduction in free glucose amount compared to control samples. This may indicate a conversion of free glucose into derivatives like furfurals that may negatively affect the TGP even though the treated sample kept better results than controls. This may be attributed to a degradation effect of NaOH on polymers found in OFMSW, making them more accessible to the bacteria. Alkali pretreatment refers to the application of alkaline solutions such as
NaOH, remove lignin and a part of the hemicellulose, and efficiently increase the accessibility of enzyme to the cellulose. The alkali pretreatment can result in a sharp increase in saccharification, with manifold yields (Kassim EA, 1985). Pretreatment can be performed at low temperatures but with a relatively long time and high concentration of the base. For instance, when OFMSW was soaked in NaOH liquor (1% & 2% ) for 120 h at temperature 38 °C the glucose decreased by 51.45% and 40.16% respectively (Xu Z, 2010). However, alkaline pretreatment was more effective on OFMSW compared with control samples. Glucose was checked by pretreatment with NaOH. When OFMSW was treated with 1 % NaOH, there was a reduction of 50 % in glucose concentration before fermentation compared with the control samples. When 2 % NaOH was added to the OFMSW, the reduction was about 40 % and in 1 % NaOH mixed OFMSW and there was 75% reduction in glucose after fermentation. In addition, when 2% NaOH was mixed with OFMSW, there was 80 % reduction in glucose after fermentation. This indicates that as the concentration of NaOH exceeded a particular limit, the glucose concentration was decreased, as shown in figures 4.7, 4.8 and 4.9.

![Graph showing glucose before and after fermentation](image-url)  

**Figure (4.7):** Glucose before and after fermentation at a weight of 40 g of organic matter
Figure (4.8): Glucose before and after fermentation at a weight of 60 g of organic matter

Figure (4.9): Glucose before and after fermentation at a weight of 75 g of organic matter

4.3 The Effect of Microwave Treatment of Biogas Production by OFMSW

In this part of the study, the researcher observed the effect of MW irradiation time and the installed power, which are two fundamental parameters that affect the degradation of OFMSW structure, by measuring total biogas concentration. Parameters such as irradiation power (450 W) and the duration of treatment between (5, 10, 15, & 20) minutes were investigated. One MW power level (450W) was applied, and total biogas concentrations were determined for 5, 10, 15, and 20
minutes. There were significant increases of total biogas concentration for each power until 10 minutes.

In this respect, Nikolić et al (2008) observed similar results for MW. In this study and after 5 minutes, there was no remarkable increase in biogas concentration at 450 W power level, as well. It is shown that there were no differences between 10 and 15 minutes at a power level of 450 W with 40 g solid state total biogas concentrations of (500- 850 ml), 60g solid state ( 800-2500 ml) 60 and 75g solid state (600-1300 ml) of biogas respectively. As shown in table (4.4, 4.5 & 4.6). When the pretreatment time increased up to 10 minutes at 450 W power and 60 g solid state, the highest biogas concentration was determined with 2500 ml. In order to decide the optimum reaction time for further experiments under the same experimental conditions, it was carried out again just for 5 and 10 minutes in a wide range of MW power as shown in Figures 4.10, 4.11 & 4.12). When irradiation time was increased, total biogas concentration increased directly as illustrated. A gradual increase of total biogas concentration was observed from 10 min to 20 min. When the size of the solid material was increased from 40g to 75g directly, the biogas concentrations were not large enough. However, higher total biogas concentrations were obtained within 10 to 15 minutes using 60g of solid material. Accordingly, there was a decrease in total biogas concentrations by increasing the solid material. There were significant increases of total biogas concentrations for each power until 10 minutes.

**Table (4.4):** The Effect of MW Pretreatment with Total OFMSW at 40g and MW at 450 W for Various Durations

<table>
<thead>
<tr>
<th>Time (MW/min)</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>control</td>
<td>675</td>
<td>850</td>
<td>820</td>
<td>850</td>
<td>850</td>
<td>323</td>
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</tr>
<tr>
<td>5 min</td>
<td>350</td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>450</td>
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<td>80</td>
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<td>15g</td>
</tr>
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<td>575</td>
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<td>575</td>
<td>70</td>
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<td>25g</td>
<td>12g</td>
</tr>
<tr>
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<td>850</td>
<td>850</td>
<td>850</td>
<td>850</td>
<td>60</td>
<td>15</td>
<td>18g</td>
<td>10g</td>
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<tr>
<td>20 min</td>
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<td>820</td>
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<td>26</td>
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</table>
Table (4.5): The Effect of MW Pretreatment with Total OFMSW at 60g and MW at 450 W for Various Durations

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<th>Time (MW/min)</th>
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<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>control</td>
<td>1600</td>
<td>1750</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>587</td>
<td>180</td>
<td>60g</td>
<td>20g</td>
</tr>
<tr>
<td>5 min</td>
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<td>45g</td>
<td>23g</td>
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<tr>
<td>10 min</td>
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<td>2450</td>
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<td>280</td>
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<td>38g</td>
<td>21g</td>
</tr>
<tr>
<td>15 min</td>
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<td>1450</td>
<td>1550</td>
<td>1800</td>
<td>1800</td>
<td>320</td>
<td>170</td>
<td>30g</td>
<td>18g</td>
</tr>
<tr>
<td>20 min</td>
<td>450</td>
<td>680</td>
<td>760</td>
<td>780</td>
<td>780</td>
<td>380</td>
<td>230</td>
<td>25g</td>
<td>17g</td>
</tr>
</tbody>
</table>

Table (4.6): The Effect of MW Pretreatment with Total OFMSW at 75g and MW at 450 W for Various Durations

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<th>Time (MW/min)</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>control</td>
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<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>660</td>
<td>220</td>
<td>75g</td>
<td>33g</td>
</tr>
<tr>
<td>5 min</td>
<td>430</td>
<td>700</td>
<td>800</td>
<td>1250</td>
<td>1250</td>
<td>380</td>
<td>119</td>
<td>60g</td>
<td>18g</td>
</tr>
<tr>
<td>10 min</td>
<td>350</td>
<td>380</td>
<td>550</td>
<td>580</td>
<td>580</td>
<td>350</td>
<td>140</td>
<td>51g</td>
<td>36g</td>
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<td>530</td>
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<td>400</td>
<td>180</td>
<td>46g</td>
<td>33g</td>
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<tr>
<td>20 min</td>
<td>480</td>
<td>660</td>
<td>830</td>
<td>830</td>
<td>830</td>
<td>520</td>
<td>210</td>
<td>38g</td>
<td>35g</td>
</tr>
</tbody>
</table>
Figure (4.10): A Cumulative Biogas Production for Samples Pretreated with MW at 38°C and Total Solid Material of 40g

Figure (4.11): A Cumulative Biogas Production for Samples Pretreated with MW at 38°C and Total Solid Material 60g.
4.3.1 Effect of MW irradiation on TS

From Figures 4.13, 4.14 & 4.15, the researcher observed that there was a decrease in TS for both MW pretreated and non-pretreated substrates. Similar decreases in solid contents during anaerobic digestion, degradation caused by anaerobes would decrease the net available amount of TS and VS of organic wastes. It may be inferred that a decrease in TS concentration from 40g (hour 24) to 18g (hour 120), approximately 45% of the weight of the TS, occurred over the first 120 hours of the anaerobic digestion. The TS residues decreased almost 50% at each duration and at all weights used in the experimentation before and after fermentation (see Tables 4.4, 4.5, and 4.6).

Analytically, the gradual decrease in TS over the first 120 hours indicated that anaerobic bacteria were able to easily degrade the hydrolysable components in the TS residues. However, the these rates of decrease in TS were attributed to the microbial consumption of TS which had progressed the MW irradiation for the experimental conditions. There was a net decrease in TS for the MW pretreated substrates as compared to the control sample, as MW irradiation increased; the loss in total mass of substrates also increases. The results obtained in different concentrations of TS were as follows:
- OFMSW for 5 min at 450 W showed a net decrease in TS at 62.5%.
- OFMSW for 10 min at 450 W had a net decrease in TS at 70%.
- OFMSW at 450 W for 15 min showed an overall decrease of TS at 85%.
- OFMSW at 450 W for 20 min had an overall decrease of TS of 80%.

It is observed that there was a decrease in TS for both MW pretreated and non-pretreated substrates. Similar decreases in solids contents have also been reported by Meynell (1982), and Uzodinma and Ofoefule (2004), who explained that during anaerobic digestion, degradation caused by anaerobes would decrease the net available amount of TS of organic wastes.

MW irradiation has made organic molecules more bioavailable. In this sense, the higher the intensity of the MW irradiation was, the higher fraction of biodegradable molecules has been released and become more susceptible as food for biodegradation to microorganisms.

**Figure (4.13):** Total solid residue before and after fermentation at a weight of 40g of organic matter pretreatment by microwave operated at 450 W.
4.3.2 The Effect of MW Irradiation on Glucose Concentration

In this experiment, MW results were compared at 5, 10, 15, and 20 min. at 450 W in terms of glucose concentrations. Figures 4.16, 4.17, and 4.18 showed the glucose output before and after biogas production in 120 hours. However, these results showed that microwave power had a significant effect on glucose output. The results also showed that the glucose concentration remarkably went down in each 5-min period after treatment in the microwave at 450 W. Then, the glucose concentration began to increase gradually through increasing the duration of incubation of TS in the microwave. Even if yields are significantly different, it can be seen that the yield are
close. However these results show that microwave power has a significant effect on glucose yield. Same results are observed by Zhu et al., (2005) and Gong et al., (2010). In this one date shows that the power effect is not linear.

In a first part when microwave intensity increase reducing sugar yield increase also, until reaches a maximum (in their study 450 W). After this pick, reducing sugar yield decrease. It is explained that for too high power the increase of the temperature is too quick and oxygen bonds between monomers breaks to create free radicals. In this time, heating activate condensation reaction to form more stable structure.

**Figure (4.16):** Glucose before and after fermentation at a weight of 40g of organic matter by MW treatment.

**Figure (4.17):** Glucose before and after fermentation at a weight of 60g of organic matter by MW treatment
4.4 Effect of Combined Alkali and Microwave Treatment on Biogas Production by OFMSW.

In this part, MW and alkali pretreatment was applied to biomass under previously determined conditions. OFMSW was immersed in dilute sodium hydroxide solution at a concentration of 1% and 2% (w/v). The results of such treatment are shown in Tables 4.7, 4.8, 4.9, 4.10, 4.11 and 4.12. Although the results of MW pretreatment with NaOH solution were successful, the maximum total biogas concentration was observed at 2% with 60g solid state during 10 min. Such MW pretreatment gave 3L of biogas. The studies of Keshwani et al. (2009) and Hu et al (2008) and Zhu et al (2006) obtained almost similar biogas production (1300-2500 ml) after enzymatic hydrolysis of MW-alkali pretreated OFMSW. The pretreatment was conducted with 1% of NaOH concentration of 75g during 25 minutes of incubation time. As a result, alkaline treatment with microwave application resulted in an increase in the concentration of solid organic material that may work to increase the volume of biogas. For each step, 40, 60 and 75g of the sample was conducted for MW pretreatment by adding 300 ml distilled water and 10 ml of 1% NaOH respectively. In MW alkali pretreatment, almost three of the total biogas concentrations were obtained as the best result at 10 minutes of MW time for 450 W with 2% NaOH. However,
after 10 minutes, there were no significant increases for both MWs pretreatment with distilled water and MW-alkaline pretreatment method.

**Table (4.7)**: Estimate combined alkali a concentration of 1% NaOH & microwave treatment as operated at 450 W for time on biogas production potential solid content 40g

<table>
<thead>
<tr>
<th>Time</th>
<th>MW/min</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>control</td>
<td></td>
<td>675</td>
<td>850</td>
<td>850</td>
<td>850</td>
<td>323</td>
<td>150</td>
<td>40g</td>
<td>18g</td>
<td></td>
</tr>
<tr>
<td>5 min NaOH 1%</td>
<td></td>
<td>400</td>
<td>650</td>
<td>830</td>
<td>830</td>
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<td></td>
</tr>
<tr>
<td>10 min NaOH 1%</td>
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<td>1400</td>
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<td>130</td>
<td>86</td>
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<td>1650</td>
<td>1650</td>
<td>1650</td>
<td>200</td>
<td>156</td>
<td>20g</td>
<td>8g</td>
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</tr>
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<td>20 min NaOH 1%</td>
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<td>1300</td>
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<td>116</td>
<td>13g</td>
<td>10.5g</td>
<td></td>
</tr>
</tbody>
</table>

**Table (4.8)**: Estimate combined alkali a concentration of 1% NaoH & Microwave treatment as operated at 450 W for time on biogas production potential solid content 60g.

<table>
<thead>
<tr>
<th>Time</th>
<th>MW/min</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>587</td>
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<td>20g</td>
</tr>
<tr>
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<td>15g</td>
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Table (4.9) : Estimate combined alkali a concentration of 1% NaoH & microwave treatment as operated at 450 W for time on biogas production potential solid content 75g.

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<tr>
<th>Time (MW/min)</th>
<th>NaOH 1%</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
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</thead>
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<td>500</td>
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<td>500</td>
<td>660</td>
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<td>75g</td>
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</tr>
<tr>
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<td>500</td>
<td>500</td>
<td>500</td>
<td>660</td>
<td>220</td>
<td>75g</td>
<td>33g</td>
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<td>930</td>
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<td>2200</td>
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</table>

Table (4.10) : Estimate combined alkali a concentration of 2% NaOH & microwave treatment as operated at 450 W for time on biogas production potential solid content 40g.

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<th>Time (MW/min)</th>
<th>NaOH 2%</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
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<td>675</td>
<td>850</td>
<td>850</td>
<td>850</td>
<td>850</td>
<td>323</td>
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<td>18g</td>
</tr>
<tr>
<td>5 min NaOH 2%</td>
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<td>1250</td>
<td>1250</td>
<td>1250</td>
<td>1250</td>
<td>270</td>
<td>130</td>
<td>25g</td>
<td>10.5g</td>
</tr>
<tr>
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<td>1350</td>
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<td>1350</td>
<td>259</td>
<td>110</td>
<td>22g</td>
<td>16.5g</td>
</tr>
<tr>
<td>15 min NaOH 2%</td>
<td></td>
<td>1300</td>
<td>1450</td>
<td>1450</td>
<td>1450</td>
<td>1450</td>
<td>362</td>
<td>210</td>
<td>15g</td>
<td>8g</td>
</tr>
<tr>
<td>20 min NaOH 2%</td>
<td></td>
<td>900</td>
<td>950</td>
<td>1100</td>
<td>1100</td>
<td>1100</td>
<td>180</td>
<td>116</td>
<td>12g</td>
<td>10g</td>
</tr>
</tbody>
</table>
Table (4.11): Estimate combined alkali a concentration of 2% NaOH & microwave treatment as operated at 450 W for time on biogas production potential solid content 60g.

<table>
<thead>
<tr>
<th>Time</th>
<th>MW/min NaOH 2%</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>1600</td>
<td>1750</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>587</td>
<td>180</td>
<td>60g</td>
<td>20g</td>
</tr>
<tr>
<td>5 min NaOH 2%</td>
<td></td>
<td>1200</td>
<td>1600</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>250</td>
<td>100</td>
<td>44g</td>
<td>22g</td>
</tr>
<tr>
<td>10 min NaOH 2%</td>
<td></td>
<td>1160</td>
<td>2300</td>
<td>2760</td>
<td>3000</td>
<td>3000</td>
<td>290</td>
<td>150</td>
<td>35g</td>
<td>18g</td>
</tr>
<tr>
<td>15 min NaOH 2%</td>
<td></td>
<td>175</td>
<td>500</td>
<td>1430</td>
<td>1900</td>
<td>1900</td>
<td>355</td>
<td>180</td>
<td>35g</td>
<td>21g</td>
</tr>
<tr>
<td>20 min NaOH 2%</td>
<td></td>
<td>660</td>
<td>1200</td>
<td>1350</td>
<td>1350</td>
<td>1350</td>
<td>440</td>
<td>210</td>
<td>30g</td>
<td>29g</td>
</tr>
</tbody>
</table>

Table (4.12): Estimate combined alkali a concentration of 2% NaOH & microwave treatment as operated at 450 W for time on biogas production potential solid content 75g.

<table>
<thead>
<tr>
<th>Time</th>
<th>MW/min NaOH 2%</th>
<th>24Hour biogas produce (ml)</th>
<th>48Hour biogas produce (ml)</th>
<th>72Hour biogas produce (ml)</th>
<th>96Hour biogas produce (ml)</th>
<th>120Hour biogas produce (ml)</th>
<th>Glucose Before biogas produce mg/dl</th>
<th>Glucose After biogas produce mg/dl</th>
<th>Total solid Residue before fermentation</th>
<th>Total solid Residue after fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>660</td>
<td>220</td>
<td>75g</td>
<td>33g</td>
</tr>
<tr>
<td>5 min NaOH 2%</td>
<td></td>
<td>100</td>
<td>100</td>
<td>450</td>
<td>550</td>
<td>550</td>
<td>260</td>
<td>100</td>
<td>60g</td>
<td>33.5g</td>
</tr>
<tr>
<td>10 min NaOH 2%</td>
<td></td>
<td>425</td>
<td>1250</td>
<td>1350</td>
<td>1350</td>
<td>1350</td>
<td>290</td>
<td>150</td>
<td>49g</td>
<td>28g</td>
</tr>
<tr>
<td>15 min NaOH 2%</td>
<td></td>
<td>825</td>
<td>1600</td>
<td>1750</td>
<td>1750</td>
<td>1750</td>
<td>390</td>
<td>165</td>
<td>42g</td>
<td>21g</td>
</tr>
<tr>
<td>20 min NaOH 2%</td>
<td></td>
<td>200</td>
<td>750</td>
<td>750</td>
<td>750</td>
<td>750</td>
<td>450</td>
<td>180</td>
<td>35g</td>
<td>18g</td>
</tr>
</tbody>
</table>
Figure (4.19): Cumulative biogas production for samples pretreated with combined alkali a concentration of 1% NaOH & microwave treatment at 38°C and total solid 40g.

Figure (4.20): Cumulative biogas production for samples pretreated with combined alkali a concentration of 1% NaOH & microwave treatment at 38°C and total solid 60g.
**Figure (4.21)**: Cumulative biogas production for samples pretreated with combined alkali a concentration of 1% NaOH & microwave treatment at 38°C and total solid 75 g.

**Figure (4.22)**: Cumulative biogas production for samples pretreated with combined alkali a concentration of 2% NaOH & microwave treatment at 38°C and total solid 40 g.
Figure (4.23) : Cumulative biogas production for samples pretreated with combined alkali a concentration of 2 % NaOH & microwave treatment at 38°C and total solid 60 g.

Figure (4.24) : Cumulative biogas production for samples pretreated with combined alkali a concentration of 2 % NaOH & microwave treatment at 38°C and total solid 75 g.
4.4.1 The Effect of Combined Alkali and Microwave Treatment on TS

From Figures 4.25, 4.26, 4.27, 4.28, 4.29 & 4.30, the researcher observed that there was a decrease in TS for both combined alkali and microwave pretreated and non-pretreated substrates. Similar decreases in solids contents during anaerobic digestion and degradation caused by anaerobes would decrease the net available amount of TS of organic wastes. It may be inferred that a decrease in TS concentration from 40g (hour 24) to 18g (hour 120) of approximately 60 % of the volume of TS occurred over the first 120 hours of the anaerobic digestion. The variations in TS for both combined alkali and microwave pretreated and non-pretreated substrates were low since the TS was less than 50%. In addition, the gradual decrease in TS over the first 120 hours indicated that anaerobic bacteria were able to degrade the most easily hydrolysable components in the food residues. However, similar rates of decrease in TS also indicated that microbial consumption of TS had progressed microwave irradiation for the experimental conditions tested in this experiment. There was a net decrease in TS for the combined alkali and microwave pretreated substrates as compared to the control samples. As combined alkali and microwave irradiation was increased, the loss in total mass of substrates increased. The results obtained in different concentrations of TS were as follows:

OFMSW for 5 min at 450 W for 1% NaOH showed a net decrease in TS of 60 %,

OFMSW which was for 15 min at 450 W 1% NaOH had a net decrease of 80 %,

OFMSW at 450 W for 5 min 2 % NaOH showed an overall decrease of 73 % of TS

OFMSW at 450 W for 20 min 2 % NaOH had an overall decrease in TS of 80 %.

Combined alkali & microwave has been reported to make organic molecules more bioavailable. In this line of thought, the higher the intensity of combined alkali and microwave, a higher fraction of biodegradable molecules has been released and become more susceptible to as food for biodegradation to the microorganisms. Microwave and alkaline treatments are based on different mechanisms of OFMSW dissolution, the combination of these two methods means the advantages of both methods can be attained and better treatment efficiency can be achieved. Qiao et al. (2008) studied the effects of microwave treatment on OFMSW with alkali
addition using single factor experiments, with both solubilization of organic matters and settle ability of OFMSW investigated. It was found that most organic fractions dissolved into a solution within 5 min. Adding NaOH increased the VSS dissolution ratio above 50% and the suspended solids (SS) dissolution ratio above 10%. After 1 min of microwave treatment at 450 w with alkali (1% to 2% NaOH/g total solids (TS), the treated OFMSW showed settle ability improvement. Chan et al. (2010) investigated the effects of microwave irradiation time on nutrients release, solids destruction, particle size distribution and dewater ability of WAS using microwave and alkaline treatment. Higher irradiation levels tended to be more effective in the solubilization of nutrients and had more pronounced effects on the dewater ability of OFMSW, in contrast to the study of Qiao et al. (2008).

![Figure 4.25](image_url): Total solid residue before and after fermentation at a weight of 40 g of organic matter pretreatment with combined alkali 1% NaOH at microwave 450 W
Figure (4.26): Total solid residue before and after fermentation at a weight of 60 g of organic matter pretreatment with combined alkali 1% NaOH and microwave at 450 W.

Figure (4.27): Total solid residue before and after fermentation at a weight of 75 g of organic matter pretreatment with combined alkali 1% NaOH and microwave at 450 W.
Figure (4.28): Total solid residue before and after fermentation at a weight of 40 g of organic matter pretreatment with combined alkali 2% NaOH and microwave at 450 W.

Figure (4.29): Total solid residue before and after fermentation at a weight of 60 g of organic matter pretreatment with combined alkali 2% NaOH and microwave at 450 W.
Figure (4.30): Total solid residue before and after fermentation at a weight of 75 g of organic matter pretreatment with combined alkali 2% NaOH and microwave at 450 W.

4.4.2 The Effect of Combined Alkali and Microwave Treatment on Glucose Concentration

In this study, the microwave-assisted NaOH pretreatment positively affected the glucose concentration. The maximum yields of monomeric glucose were 40, 60, and 75g at 2% NaOH with 450 W. From Figures 4.31, 4.32, 4.33, 4.34, 4.35 and 4.36, the pretreatment OFMSW empty was done using the combination of MW and NaOH, and it was found that the enzymatic saccharification was significantly improved by increasing the duration of incubation in the microwave of glucose accessibility during the pretreatment.

The microwave/chemical pretreatment resulted in a more effective pretreatment than the conventional heating chemical pretreatment by accelerating reactions during the pretreatment process. Zhu et al. (2005) examined three microwave/chemical processes for pretreatment of OFMSW – microwave/alkali, microwave/450 w /alkali/NaOH 1%-2% – for its enzymatic hydrolysis and for glucose recovery from the pretreatment liquid. They found that xylose could not be recovered during the microwave/alkali pretreatment process, but could be recovered as crystalline glucose during the microwave/450W and alkali/NaOH of 1%-2% pretreatment. The enzymatic
hydrolysis of pretreated rice straw showed that the pretreatment by microwave/450W with alkali/NaOH 1%-2% had the highest hydrolysis rate and glucose content in the hydrolyzate.

Figure (4.31): Glucose before and after fermentation at a weight of 40g of organic matter by pretreatment with combined alkali of 1% NaOH and microwave at 450 W.

Figure (4.32) : Glucose before and after fermentation at a weight of 60g of organic matter by pretreatment with combined alkali of 1% NaOH and microwave at 450 W.
Figure (4.33): Glucose before and after fermentation at a weight of 75g of organic matter by pretreatment with combined alkali 1% NaOH and microwave at 450 W.

Figure (4.34): Glucose before and after fermentation at a weight of 40 g of organic matter by pretreatment with combined alkali of 2% NaOH and microwave at 450 W.
**Figure (4.35):** Glucose before and after fermentation at a weight of 60 g of organic matter by pretreatment with combined alkali of 2% NaOH and microwave at 450 W.

**Figure (4.36):** Glucose before and after fermentation at a weight of 75 g of organic matter by pretreatment with combined alkali of 2% NaOH and microwave at 450 W.
4.5 Biomethane Analysis

This part was conducted to assess the biochemical methane generation potential from municipal solid wastes when treated separately. Anaerobic digestion (AD) is a biological process in which organic matter is decomposed by an assortment of microbes under oxygen-free conditions to produce biogas (about 40-70% CH\textsubscript{4} and 30-60% CO\textsubscript{2}), with three different treatments:

- Alkaline treatment (NaOH).
- Microwave treatment power operated at 2450 MHz and 450 W.
- Combined treatment (Microwave with Alkaline).

The overall results indicated that methane production of the substrates was ascending. The methane production was as follows:

- In alkaline treatment (NaOH), the methane percentage 62-50%.
- In microwave treatment power operated at 2450 MHz and 450 W, the methane percentage was 65-67%.
- Combined treatment (Microwave-Alkaline) respectively, the methane percentage was 63-73%.

In the control sample, methane production percentage was much slower than that with inoculums. Hence, the overall performance is that cumulative methane generation was highest with combined treatment (Microwave-Alkaline) with the inoculums from the OFMSW after 120 hour of incubation.
Chapter 5
Conclusions and Recommendations

6.1 Conclusion

The current study focused on investigating the process of pretreatment and biogas fermentation potential of the solid organic waste. Organic Fraction of Municipal Solid Waste (OFMSW) was the most valid material to experiment on in order to get energy (biogas). Microwave and microwave-alkali pretreatment method assisted to break down hard OFMSW for improved degradation of solid organic waste and releasing of biogas. The microwave was operated at 2450 MHz and 450W with a change in incubation time durations and concentrations for each process using 1-2% of NaOH to achieve the maximal biogas production. Optimization of those variables was carried out by anaerobic digestion methodology using the batch anaerobic digestion. Optimization of the treatment processes resulted in the enhancement of biogas quantity and quality. Some adjustments proved to be vital while others proved to be ineffective. Batch testing on the digestion process showed that combined microwave-alkaline pretreatments were an effective factor during biogas production. Biogas production was highest on using combined microwave-chemical pretreatments 2% NaOH, 10 min, and 60g solid wastes.

The researcher would also mention the following essential remarks:

1- A long-time (25 min) microwave treatment can greatly treat and improve the reduced biogas yield from the hydrolysis of OFMSW, but it leads to high sugar loss during the pretreatment.

2- Combined microwave-alkaline treatment was used at near room temperature, the time of biological process was shortened to (120 hour), and the efficiency of NaOH pretreatment was enhanced.

3- The combined pretreatment process is favorable for further developments and applications of biological pretreatment.

4- MW irradiation had a positive effect on the overall anaerobic digestibility of the OFMSW. MW irradiation pretreatment also enhanced the solubilization of OFMSW and concomitantly increased the rates and cumulative production of biogas.
6.2 Recommendations

The present study is part of extensive researching devoted to meet challenges and requirements that human society currently encounters in sustainable developments. Producing fuel from renewable resources is becoming an important issue for the whole world. Therefore, relevant researches should be done for further developments of biogas production from biomass. The following suggestions could be of interest for future studies:

1. First recommendation for future studies would be the use of OFMSW solid waste as the substrate for biogas production. In addition to other common cellulosic biomass resources are market residue, wood, municipal solid wastes, wastes paper, agricultural residues and industrial residues.

2. We also recommended applying the microwave-base pretreatment techniques to other feedstocks, such as municipal solid wastes and other agricultural residues. Alternate processing methods to get higher release of reducing sugars could be tried to make the technology more efficient and profitable. Future work is advised to focus on the scale up of microwave-based pretreatment of lignocellulosic biomass. Radio frequency heating as the energy source for pretreatment is recommending for studying as well.

3. Development of new and more environmental-friendly pretreatments that include the use of fiber degrading enzymes and hot water and new strains of yeast and bacteria are critical points for the economics of biomass transformation. Although economical biogas production from fiber-based sources still requires a lot of research, with significant risks and uncertainties, we need to continue to be optimistic about its future.
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Glossary

Aerobic: Conditions An environment that is conducive to the microbial degradation of organic solid waste in the presence of oxygen. Anaerobic Conditions An environment in which microbial degradation of organic solid waste occurs in the absence of oxygen.

Anaerobic Digestion (AD): A controlled and managed biological process that uses microorganisms to break down organic material in the absence of oxygen.

Biodegradation: A process where organic materials are degraded by microorganisms.

Biogas: A gaseous byproduct of the anaerobic digestion process. The major components of biogas are carbon dioxide (CO2) and methane (CH4).

Biofuel: Fuel produce directly or indirectly from biomass. The term biofuel applies to any solid, liquid, or gaseous fuel produced organic (once living) matter. The word biofuel covers a wide range of products, some of which are commercially available today, and some of which are still in the research and development phase.

Biomass: Organic matter available on a renewable basis. Biomass includes forest and mill residues, agricultural crops and wastes, wood and wood wastes, animal wastes, livestock operation residues, aquatic plants, fast-growing trees and plants, and municipal and industrial wastes.

Bioreactor: A bioreactor is a vessel in which a biochemical process occurs. This usually involves organisms or biochemically active substances derived from such organisms.
**Carbon-to-Nitrogen (C:N) Ratio:** The ratio of the quantity of carbon (C) in a material (on a dry weight basis) to the amount of nitrogen (N) in the material (on a dry weight basis).

**Fermentation:** Conversion of carbon containing compounds by microorganisms for production of fuels and chemicals such as alcohols, acids or energy-rich gases. It is a biochemical reaction that breaks down complex organic molecules (such as carbohydrates) into simpler materials (such as ethanol, carbon dioxide, and water). Bacteria or yeast can ferment sugars to bioethanol.

**Fossil fuel:** solid, liquid, or gaseous fuels formed in the ground after millions of years by chemical and physical changes in plant and animal residues under high temperature and pressure. Oil, natural gas, and coal are fossil fuels.

**High-Solids-Slurry Digester:** A type of digester used to process feedstock’s in a slurry form (i.e., with a moisture content between 60 and 80%). Water or effluents may be added to the feedstocks to create the slurry.

**High-Solids-Stackable Digester:** A type of anaerobic digestion system that uses sealed tunnels. “Stackable” materials (i.e., with a moisture content less than 60%) are loaded into the tunnels with front-end loaders, and water that drains from the material during the process is recalculated to spray nozzles above the material to carry microorganisms and nutrients through the waste mass.

**Inoculum:** Feedstock that has already gone through the composting or digestion processes, or effluent from these processes, that is mixed with fresh feedstocks during pre-processing steps to initiate microbial activity

**Microorganism:** A living organism so small that it requires magnification before it can be seen.
Municipal Solid Waste (MSW): The solid waste discarded from residential, industrial, commercial, institutional, construction, and demolition sources but does not include hazardous waste.

**Organic matter:** Matter that comes from once living-living organism.

**pH:** A measure of the concentration of hydrogen ions in a solution. pH is expressed as a negative exponent. Thus, something that has a pH of 8 has 10 times fewer hydrogen ions than something with a pH of 7. The lower the pH, the more hydrogen ions present, and the more acidic the material is. The higher the pH, the fewer hydrogen ions present, and the more basic it is. A pH of 7 is neutral.

**Residence/Retention Time:** The amount of time materials remain in a composting or anaerobic digestion system (e.g., vessel, windrow, or pile).

**Sludge:** Sludge is formed in the reaction basin during biological waste water treatment process and separated by sedimentation. Sludges can be converted into biogas via anaerobic digestion.

**Thermophilic:** The temperature range most conducive to the maintenance of thermophilic microorganisms. Generally accepted as being greater than 45°C.

**Volatile Solids:** Organic compounds (plant or animal origin) that are removed or reduced through biological processes and have a calorific value and can create odours and other nuisances.