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RESEARCH ARTICLE

BIOGAS PRODUCTION FROM ANAEROBIC DIGESTION-A SYSTEMATIC REVIEW.

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Abstract

Biogas, a renewable source of energy has been the focus of research for the past decades. It is simple to produce and environmentally friendly. Due to the current increase in population, emission of greenhouse gases and the UN concern to achieve 100% renewable energy globally by 2050, the use of biogas for electricity and for combined heat and power is the surest way forward. Anaerobic digestion thus far has been the surest way to achieve in the production of this renewable energy. The process, however, involves the consortium of microorganisms to breakdown feedstocks such as food waste and agricultural biomass through a complex pathway to generate mainly the methane and carbon dioxide. Feedstocks utilized by researchers from the past decades include water hyacinth, wood chips, corn silage, food wastes, and sugarcane bagasse. Process parameters that influence the anaerobic digestion process include pH, temperature, organic loading rate, feedstock type, mixing, hydraulic retention time, and the carbon to nitrogen ratio. This paper reviews the scope of biogas production from the anaerobic digestion process and details the various parameters affecting the process.

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Introduction:-

The increase in fuel prices, emission of greenhouse gases, and the over reliance on non-renewable sources of energy has braved researchers in the past decades to find alternatives methods to obtain a sustainable form of energy. Urbanisation has also led to the rapid production of wastes leading to poor waste management practices in developing nations (Tawoma, 2015). The synthesis of a renewable energy source as an alternative to non-renewable energy source has been evaluated where energy is produced from biogas through anaerobic digestion process (El-Mashad & Zhang, 2010). Biogas is a renewable fuel that consists of 60-70% methane, 20-30% carbon dioxide and other trace compounds such as hydrogen sulfide. The gas produced, can be used to generate electricity and also in the production of combined heat and power generation using appropriate technologies (Maile, Muzenda, & Mbohwa, 2016).

The effluent from biogas, which is the digestate from anaerobic digestion of organic materials (T. Abbasi, S. Tauseef, & S. Abbasi, 2012a; Biarnes, 2017) can be largely used as fertilizers. In anaerobic digestion, the organic matter of the biomass is decomposed by the intensive reaction of a large range of microorganisms in the absence of

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oxygen (Liew, Shi, & Li, 2012). Since it is carried out by these microorganisms and dependent on factors such as temperature, hydraulic retention time (HRT), carbon to nitrogen ratio, etc., it is quite a slow process. According to research findings, a biogas plant can be measured by studying and monitoring the variation in parameters which includes, the organic loading rate, temperature, agitation, carbon-nitrogen ratio, hydraulic retention time, and the pH. A sharp change in these parameters could adversely affect the biogas production process (Simo, Jong, & Kapseu, 2016).

Currently, efforts are been made to a larger extent to disrupt and/or remove the lignin and hemicellulose from lignocellulosic materials, thereby creating a high cellulose accessibility to facilitate enzymatic saccharification using pretreatment methods (Fan et al., 2016). Hydrothermolysis, a pretreatment method has been found to also increase biogas yield from 85.63 NI/gVS to 100 NI/gVS (Simo et al., 2016).

Drawbacks such as *process instability, process failure, poor methane yield, the larger retention time of 30-50 days and reactor failures have limited the full exploitation of the anaerobic digestion process* (Nges, 2012). Processes such as co-digestion, low organic loading, pretreatment methods (for example, liquid hot water, acid hydrolysis, steam explosion, and alkaline hydrolysis), and the use of energy crops as feedstocks, have been found to increase the efficacy of biogas production through anaerobic digestion (Alvira, Tomás-Pejó, Ballesteros, & Negro, 2010; Eliyan, 2007; Ribeiro, Passos, Gurgel, Baêta, & de Aquino, 2017). This paper presents a comprehensive view of the various anaerobic digestion processes to produce and enhance the biogas production rate from biomass and the factors affecting the process.

The Anaerobic Digestion process and biogas production:-

Biogas is an extremely useful source of renewable energy, whilst the digestate is a highly valuable biofertilizer (Lukehurst, 2009). The anaerobic digestion process also offers a range of benefits such as lowering fossil fuel usage, mineral fertilizer replacement (from the digestate), and renewable energy production and also in wastewater treatment. The hydrolysis process which is the rate-determining step of the overall process converts a wide range of solid organic materials (polymeric) into sugars, fatty acids and amino acids (Saady & Massé, 2015). Fermentation of these materials produces volatile fatty acids. Acidogenesis forms hydrogen, carbon dioxide and acetate from VFAs. The methanogenesis produces biogas, a mixture of methane, carbon dioxide, and numerous trace compounds such as hydrogen sulfide, ammonia, carbon monoxide, etc. (Rivard & Boone, 1996).

Cheung and Anderson (1997) reported in a study that the simultaneous saccharification and fermentation process was simple to use and could be feasible for further researches. The hydrolysis process of anaerobic digestion is often the rate-limiting step when the fibrous material is used as the feedstock because of the recalcitrant presence of lignin (Vorgelegt, 2017). In this case, substrate pretreatment could be an alternative to improve the AD process by increasing the accessible surface area, modifying the crystalline structure or partially depolymerizing cellulose, solubilizing hemicellulose and lignin or modifying lignin structure. In this study, Vorgelegt (2017) recommended the addition of urea to the anaerobic digestion process of sugarcane vinasse to improve the digestates quality thereby increasing the alkalinity in the reactor. This could be due to the degradation of OH^- and NH_4^+ ions. In the same studies, it was observed that cattle manure was a suitable alternative inoculum for remote rural areas without access to digestate from stable anaerobic reactors. This is due to the high initial organic acids concentration and proper acclimation period of around 20 days required to avoid the risk of process failure during the reactor start-up (Vorgelegt, 2017).

Renewable energy such as biogas could replace the conventional sources of energy such as fossil fuel and oil which pose serious environmental problems and depletes at faster rates. Though biogas has several benefits, its potential could not be completely tapped due to limitations such as longer hydraulic retention times (about 30 to 50 days) and low production of gas during winter (Sreekrishnan, Kohli, & Rana, 2004). According to Sreekrishnan et al. (2004), efforts that could harness the limitations in the biogas production are the inclusion of additives chemically and biologically by stimulating the microbial activities under operating conditions, recycling of slurry and slurry filtrate, variations in operational parameters like temperature, hydraulic retention times and the size of the substrate. They, however, concluded that an extensive study of these techniques is warranted. The anaerobic digestion pathway involved in biogas production is presented in (Fig.1).

Factors affecting the Anaerobic Digestion Process:-

Biogas plant can be measured by studying and monitoring the variation in parameters like temperature, loading rate, hydraulic retention time and pH, etc. as a sharp change in these could adversely affect the biogas production process. The following however details the various parameters.

Anaerobic co-digestion:-

Several types of research have been devised to find ways to improve the performance of digesters and one of these is the concept of anaerobic co-digestion (Esposito et al., 2012). Anaerobic co-digestion is defined as the simultaneous digestion of two or more substrates which is a feasible option to overcome the drawbacks of mono-digestion and to improve plant's economic feasibility (Eliyan, 2007; Mata-Alvarez et al., 2014). Co-digestion of waste biomass and crop biomass has been found to achieve a significant improvement in methane yield compared to digestion of only the waste biomass (Nges, 2012). Combining different organic wastes results in a substrate better balanced and assorted in terms of nutrient supplementation. The effect of co-digestion is mainly nutrient balance as waste materials found to be rich in proteins have relatively higher nitrogen amounts, for example, manure and animal slurry. These wastes rich in proteins, however, have higher organic contents in terms of the biological oxygen demand (BOD) as C/N ratio has been found to be almost always low (Callaghan, Wase, Thayanithy, & Forster, 2002). Ammonia inhibition in anaerobic digesters is as a result of high nitrogen concentrations leading to digester failures.

Effect of Temperature on Biogas Production:-

Different temperature ranges occur during anaerobic digestion; psychrophilic (<30°C), mesophilic (30-40°C) and thermophilic (50-60°C) (Bouallagui, Cheikh, Marouani, & Hamdi, 2003; Ward, Hobbs, Holliman, & Jones, 2008). Thermophilic temperature often yields higher biogas than mesophilic temperatures because higher temperatures favor higher methane production compared to low temperatures (Muvhiiwa et al., 2016). However, anaerobes have been found to be most active at mesophilic and thermophilic temperatures (Mital, 1997). Studies have also shown that thermophilic bacteria tend to be more efficient in terms of the loading rate, gas yield and the hydraulic retention time but tend to require a higher heat input.

Moreover, thermophilic bacteria are sensitive to temperature fluctuations and environmental variables than mesophilic bacteria (T. Abbasi, S. M. Tauseef, & S. A. Abbasi, 2012b). The thermophilic temperature was advantageous as it resulted in a more rapid, higher methane production and a less pronounced decrease in methane content after feeding. Temperature plot for the anaerobic digestion is illustrated in (Fig. 2).

Pretreatment of Feedstocks for Biogas Production:-

The pretreatment of feedstock for biogas production has been found to increase the methane yield in the anaerobic digestion process. It aims at improving the digestibility of the lignocellulosic biomass as each pretreatment has its own effect(s) on the cellulose, hemicellulose, and lignin (Hendriks & Zeeman, 2009). Fan et al. (2016) have also found that the role of pretreatment is to disrupt and/or remove the lignin and hemicellulose from lignocellulosic materials, to create high cellulose accessibility and facilitate enzymatic saccharification as shown in (Fig. 3). Cellulose, lignin, and hemicellulose components in a lignocellulosic plant cell are shown in (Fig. 4).

Creation of favorable conditions for biodegradation and biogas production has been achieved using ultrasonic pretreatment as this method seeks to disintegrate the particles within the biomass. Application of ultrasonic pretreatment increases the daily biogas production thereby reducing the volatile solids during anaerobic digestion (Braguglia, Gianico, & Mininni, 2011).

Mechanical pretreatments such as milling and ultrasonic pretreatments are used in anaerobic digestion process (Liyakathali, 2013; Yoshida et al., 2008). Milling reduces the particle size of the feedstock before it is taken into the digester. The investigation into the comparison of wet and dry ball milling of various lignocellulosic substrates indicates that terminal crystallinity index following enzymatic hydrolysis usually decreases after milling and increases after dry milling in accordance with increased friability (Rivers & Emert, 1987). The size of the particles is one of the important parameters that play significant roles in biogas production. Smaller particle size tends to increase the substrate utilization because smaller particle size provides increased microbial activity (Palmowski & Müller, 2000).

There is, however, an increasing recognition of ionic liquids as pretreatment for various biomasses to produce biogas over the few decades. Ionic liquids do solubilize complex biomass and thus provides industrial scale-up potential (Badgujar & Bhanage, 2015). The unique abilities of some ionic liquids to selectively dissolve biomass components or whole native biomass have been demonstrated (Reddy, 2015). Hence, the application of ionic liquids to lignocellulosic materials in areas such as fractionation, cellulose composites preparation and its derivatives, analysis, and removal of pollutants is a new avenue for the efficient utilization of this solvent (Zhu, 2008). Ionic liquids have been found the most expensive research-grade solvents under investigation for the dissolution of biomass (Brandt, Gräsvik, Hallett, & Welton, 2013). To prevent interferences from inhibitors in the anaerobic digestion process, ionic liquids and their co-solvents require successful recoveries. One of such recovery is by forming aqueous biphasic systems. Some pretreatment methods applied to some feedstocks in literature is shown in Table 2.

Mixing:-

Mixing is required in a digester to maintain homogeneity as stability prevents solid deposition at the bottom of the digester and produces higher methane yield (Kaparaju, Buendia, Ellegaard, & Angelidakia, 2008). This ensures intimacy contact between microorganisms and substrate and ultimately results in an improved digestion process (Sreekrishnan et al., 2004). The absence of agitation has been found to result in a reduction in specific gas production between the substrate and the microorganisms

Gomez, Cuetos, Cara, Morán, and Garcia (2006) studied the anaerobic co-digestion of primary sludge and fruit and observed that for low mixing conditions, the systems absorbed the disturbance of a shock load. Mixing aids the combination of the fresh incoming material with microorganisms prevents scum formation in the digester and maintains uniformity in substrate concentration and other environmental factors (Deepanraj, Sivasubramanian, & Jayaraj, 2014).

Organic Loading Rate:-

Biogas production is much dependent on the loading rate as methane yield has been found to increase with a reduction in loading rate (Vartak, Engler, Ricke, & McFarland, 1997). This can be expressed as the amount of chemical oxygen demand (COD) or volatile solids (VS) in Kg per m³ of the digester volume in a day (Vartak et al., 1997). Overloading can easily lead to system failure (Abbasi et al., 2012a). This can happen if there is inadequate mixing of the waste with slurry. To determine the impact of organic loading rate on psychrophilic anaerobic digestion of solid dairy manure, two duplicated laboratory-scale sequence batch bioreactors were also investigated (Saady & Massé, 2015). This was operated at organic loading rates (OLR) of 6.0 to 8.0 g total chemical oxygen demand (TCOD) kg⁻¹ inoculum day⁻¹ (d⁻¹) for 210 days. The results demonstrated that the process was feasible at treatment cycle length (TCL) of 21 days. The specific methane yield ranged between 124.5 ± 1.4 and 227.9 ± 4.8 normalized liters (NL) CH₄ kg⁻¹ volatile solids (VS) fed d⁻¹.

Effect of pH on Biogas Production:-

pH affects the growth of microbes during anaerobic digestion of biomass to produce biogas. According to Sreekrishnan et al. (2004), the pH of the digester should be kept within a desired range of 6.8-7.2 by feeding it at an optimum loading rate to obtain a higher yield of biogas. The volatile fatty acids production rate is much higher than the methane production rate, resulting in pH levels below the optimum range and can inhibit methanogens, because of their high level of sensitivity to acidic conditions (Khanal, 2008; Nijaguna, 2012). Ammonia has also been found to inhibit methanogenic bacteria (Dobre, Nicolae, & Matei, 2014). The pH level does not remain constant throughout the process because of the various anaerobic digestion process especially at the acidogenesis stage due to various acids that are produced.

Biogas production from bioethanol waste has also been found to produce higher yield at an optimum pH of 7.0 (Budiyono, Syaichurrozi, & Sumardiono, 2013). A pH of 8.0 has also been observed to produce a higher yield of biogas from biomass in a study by Ogbonda, Aminigo, and Abu (2007) which is in contrast with the optimum pH for higher yield of biogas as predicted by Budiyono et al. (2013). The operating temperature and pH level in a digester during anaerobic digestion and the retention time are key factors that affect the rate of biogas production.

Hydraulic Retention Time (HRT):-

This has been estimated as the average time a soluble compound remains in a reactor and is estimated by dividing the total capacity of the digestion tank by the rate at which matter is fed (Ibrahim, Quaik, & Ismail, 2016). The

retention time for waste treated in a mesophilic digester ranges from 15 to 30 days and 12 to 14 days for thermophilic digesters (Monnet, 2003).

The effects of temperature and hydraulic retention time (HRT) on the methanogenesis process during biogas production have been studied by Kim, Oh, Chun, and Kim (2006). In their study, the operational temperature was adjusted from 30°C to 55°C, and the HRTs ranged from 8 to 12 days. The rates of biogas and methane production by thermophilic digesters were higher than those by mesophilic digesters regardless of the HRT. Although maximum biogas production occurred for an HRT of 10 days, the methane yield was the highest in the reactor for an HRT of 12 days. Digestion stability then decreased for an HRT of 8 days. Bouallagui et al. (2003) also investigated biogas production at mesophilic temperatures from fruit and vegetable waste (FVW) in a tubular digester. It was observed that varying the HRT between 12 and 20 days showed no effect on the fermentation stability, pH remained between 6.8 and 7.6, and an inhibition of methanogenic bacteria was observed at an HRT below 12 days. On day 20, there was a 75% conversion efficiency of FVW into biogas with a methane content of 64% achieved. Zhang et al. (2006) also investigated the effects of HRT on biohydrogen production and its mixed anaerobic microbial community grown with glucose in a continuous stirred tank reactor (CSTR) culture.

Carbon-Nitrogen (C/N) Ratio:-

The relationship between the amount of carbon and nitrogen existing in a particular feedstock is represented by its C/N ratio (Verma, 2002). However, maintaining a proper structure of feedstock for effective plant operation so that the C: N ratio in feed remains within the desired range is essential. It has been found that during anaerobic digestion, microorganisms make use of carbon 25-30 times faster than nitrogen and thus microbes require about 20 to 30:1 ratio of C: N (Sreekrishnan et al., 2004).

Ward et al. (2008) predicted the optimum C/N ratios in an anaerobic digester to be between 20 – 30 and that a high C/N ratio gives an indication of rapid consumption of nitrogen by methanogens resulting in lower gas production. A C/N ratio of 26:1 has also been reported to achieve the maximum biogas yield with various agricultural feedstocks (Deepanraj et al., 2014). Kızılkaya and Bayraklı (2005) observed that C/N ratios can often be considerably lower than what is observed by Ward et al. (2008), for example, sewage sludge with a C/N ratio of approximately 9:1 has also been reported. A condition for good composting is thus a C/N ratio of 25:1 to 40:1 and that anaerobic microbe when given a steady diet at 30:1 ratio decomposes organic materials very quickly. In view of this, a larger percentage of carbon then becomes readily available for degradation (Bardiya, Somayaji, & Khanna, 1996). The microorganism then uses the carbon for energy and nitrogen for protein synthesis (Angima, 2013). A lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5 are toxic to methanogenic bacteria. The optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios (co-digestion of substrates) such as organic solid waste mixed with sewage or animal manure (Deepanraj et al., 2014; Verma, 2002).

Feedstock for Biogas Production:-

The availability of lignocellulosic materials is abundant worldwide as these materials have been found to be estimated to account for approximately 50% of the biomass in the world (Fan et al., 2016). Renewable energy from biomass is one of the most efficient and effective options for the various other alternative sources of energy (Rao, Baral, Dey, & Mutnuri, 2010). It is however available as a domestic resource in the rural areas which are not subject to world fluctuations. Rao et al. (2010) proposed that biomass is a potentially reliable energy resource because of its availability as a sewage sludge, animal manure, industrial waste and agricultural waste. Feedstock has been defined to include any substrate that can be converted to methane by anaerobic bacteria (Steffen, Szolar, & Braun, 1998). This ranges from readily degradable wastewater to complex high-solid waste and that it is required of this given solid waste or wastewater to contain a substantial amount of organic matter which is finally converted mainly to methane (CH₄) and carbon dioxide (CO₂).

Steffen et al. (1998) categorize the sources of substrates for anaerobic digestion as energy crops, agricultural wastes, industrial wastewater and municipal biowaste. Applying different feedstock improvement solutions to feedstocks investigated such as nutrient addition, co-digestion and biomass pretreatment have been demonstrated as effective means of enhancing the methane yield of the feedstock thereby improving the overall anaerobic digestion process (Nges, 2012).

Conclusion:-

Biogas production by anaerobic digestion and the parameters affecting it is reviewed in this paper. These parameters were temperature, mixing, pH, organic loading rate, Carbon to Nitrogen ratio, hydraulic retention time, type of feedstock, pretreatment methods, and anaerobic co-digestion. However, the review clearly defines the pathway of the anaerobic digestion process so as to understand the fundamentals of the process. Process instability and the study of inhibitors in the anaerobic digestion process is warranted to all researchers as these factors have been found to contribute to the lower yield of the biogas as an alternative energy source. The extensive study of ammonia, inhibiting methanogenic bacteria in the anaerobic digestion process is not an exemption to be warranted.

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Conflict of Interest

The authors declare that this article content has no conflict of interest.

Table 1: Different feedstocks with some pretreatment methods applied to produce biogas.

Pretreatment Methods	Feedstocks	References
Thermochemical	Water hyacinth	Patel, Desai, and Madamwar (1993)
Ultrasonic	Activated sludge	Wang, Kuninobu, Kakimoto, Ogawa, and Kato (1999)
Acidic	Newspaper	Xiao and Clarkson (1997)
Steam	Softwood	Söderström, Pilcher, Galbe, and Zacchi (2002)
Carbon dioxide	Sugarcane bagasse	Zheng, Lin, and Tsao (1998)
Lime	Switch grass and corn stover	Chang, Kaar, Burr, and Holtzapple (2001)
Liquid hot water	Wheat straw	Perez, Gonzalez, and Oliva (2007)
Liquid hot water	Corn fibre	Allen, Schulman, and Lichwa (2001)
Liquid hot water	Sugarcane bagasse	Laser, Schulman, and Allen (2002)
Biological	Olive mill wastewater	Dhouib, Ellouz, Aloui, and Sayadi (2006)

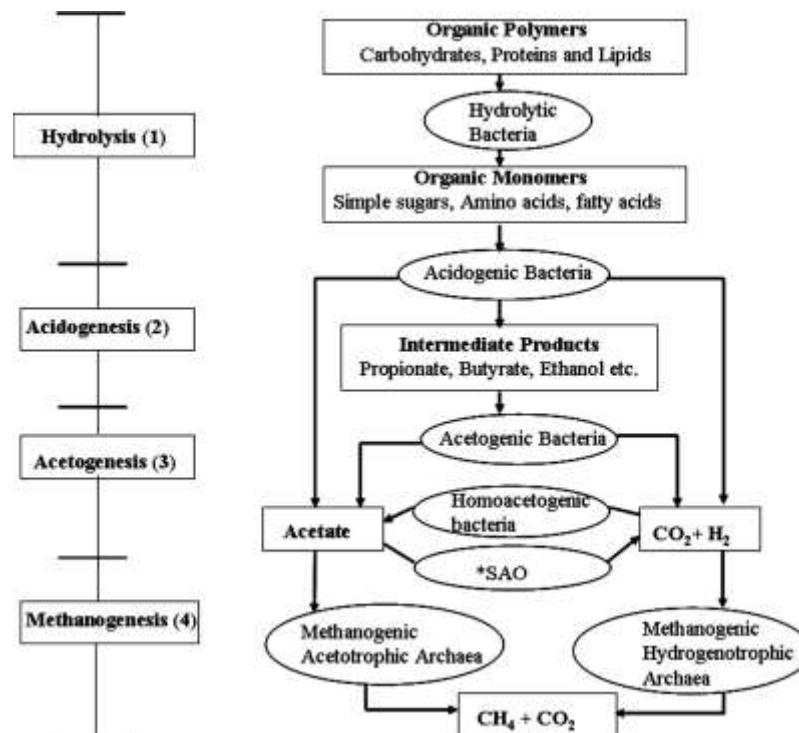


Fig. 1:- The Anaerobic Digestion Pathway according to Björnsson (2000). *SAO refers to Syntrophic acetate-oxidizing bacteria.

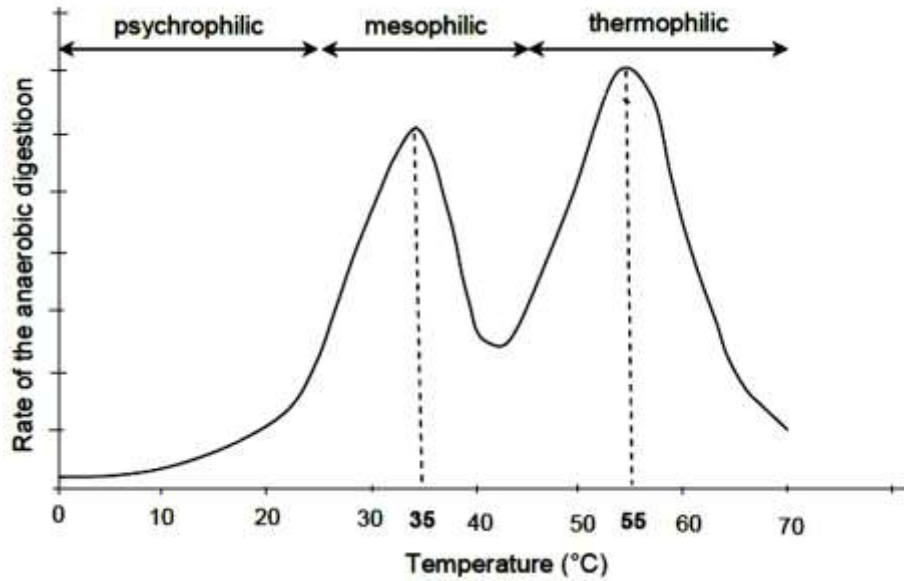


Fig. 2:- The impact of temperature on the rate of anaerobic digestion (Ortega et al., 2004)

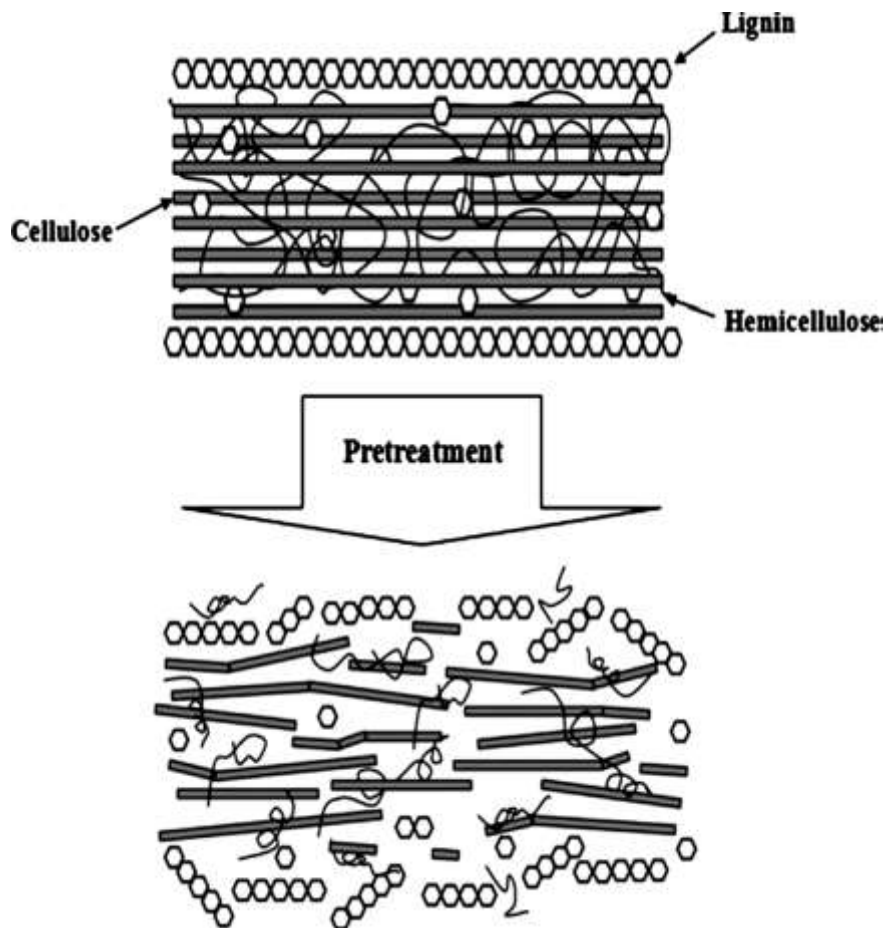


Fig. 3:- Schematic diagram for the pretreatment of lignocellulosic materials by Mood et al. (2013)

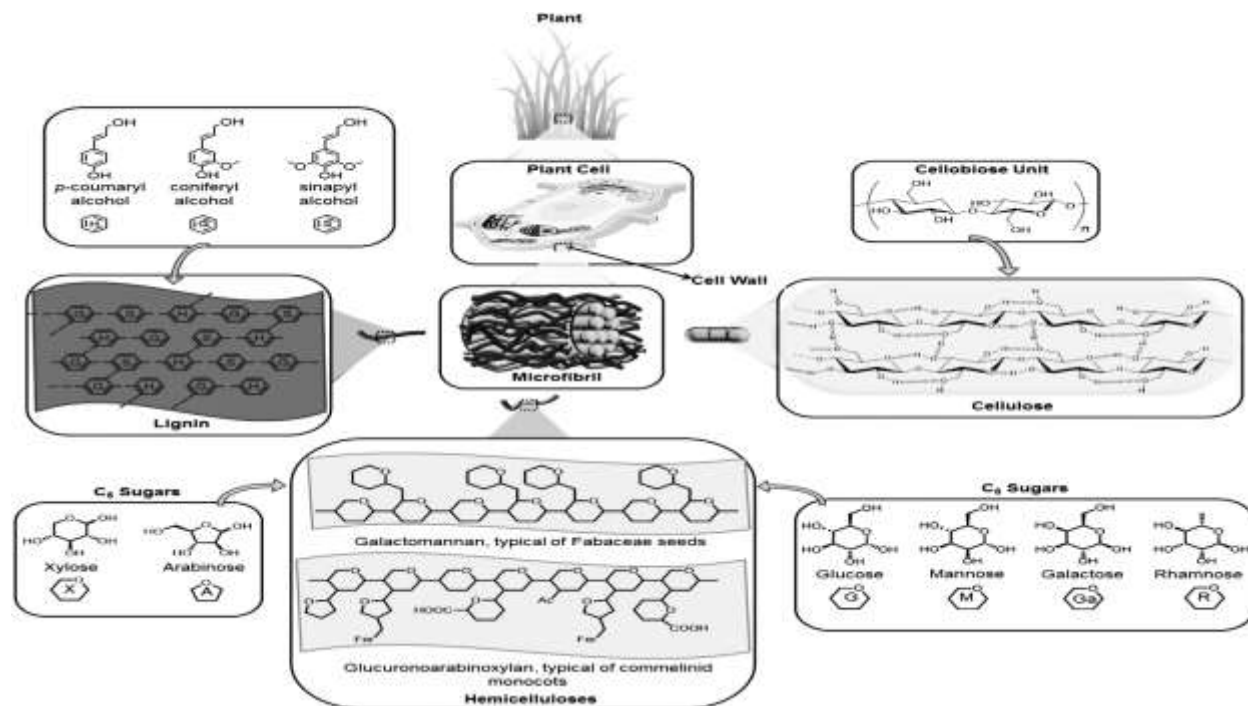


Fig.4:- The Biochemical structure of lignocelluloses showing the various monomers of cellulose, lignin, and hemicellulose

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