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ABSTRACT

This paper reviewed the advances and challenges of anaerobic biodigestion technology. The technology is an attractive waste to wealth strategy exploited to proffer solutions to the environmental, energy and agricultural needs. As reviewed, the process is generally considered to be slow and unstable due to strict nature of the anaerobes and difficult to operate. The advances in anaerobic digestion technology considered in this study are attributed to the diversity in bio-sourced feedstock, digester design and variability of process conditions. These highly researchable areas were extensively reviewed. It was found that pretreatment of feedstock, substrate interaction with the novel inoculum and substrate combo which involves mixture of different classes of feedstock that ferment better together than separately due to their enriched microbial load as well as their nutritional requirements, are recent strategies exploited to improve anaerobic biodigestion process. In addition, research on thermal effect, alternating thermophilic, mesophilic and psychrophilic stages while evaluating the impacts of temperature, pH and pressure have been adequately investigated as reviewed. However, the process is challenged by poor biodigester design/configurations, the inhibitory episodes from antagonistic substrate combo and the offensive odor of the effluent on fertilizer application.

Keywords: advances, challenges, anaerobic biodigestion, bio-sourced feedstock.

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This paper reviewed the advances and challenges of anaerobic biodigestion technology. The technology is an attractive waste to wealth strategy exploited to proffer solutions to the environmental, energy and agricultural needs. As reviewed, the process is generally considered to be slow and unstable due to strict nature of the anaerobes and difficult to operate. The advances in anaerobic digestion technology considered in this study are attributed to the diversity in bio-sourced feedstock, digester design and variability of process conditions. These highly researchable areas were extensively reviewed. It was found that pretreatment of feedstock, substrate interaction with the novel inoculum and substrate combo which involves mixture of different classes of feedstock that ferment better together than separately due to their enriched microbial load as well as their nutritional requirements, are recent strategies exploited to improve anaerobic biodigestion process. In addition, research on thermal effect, alternating thermophilic, mesophilic and psychrophilic stages while evaluating the impacts of temperature, pH and pressure have been adequately investigated as reviewed. However, the process is challenged by poor biodigester design/configurations, the inhibitory episodes from antagonistic substrate combo and the offensive odor of the effluent on fertilizer application. The review on these challenges is necessary towards improving the process. On the whole, for improved biodigestion of substrates, these strategies such as pretreatment, co-digestion, etc. should be exploited. Specifically, pretreatment of feedstock facilitates biodigestion and improves the accessibility of the source carbon utilizable by the microbial community, and mixing sources (co-digestion), working together as substrates, provides several advantages that improves biogas yields, methane production, and various other benefits.

Keywords: advances, challenges, anaerobic biodigestion, bio-sourced feedstock.

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I. INTRODUCTION

Anaerobic digestion process is an attractive waste to wealth strategy in which a consortium of microorganisms (anaerobes) produces biogas and bio-fertilizer from biomass in an oxygen-free environment. However, the process was originally developed for waste disposal/treatment several centuries ago. As expected, based on exponential increase in population witnessed globally, huge wastes are generated daily from domestic, industrial and commercial activities (Bamgboye and Ojolo, 2004; Cheng et al., 2010). These wastes are seen to litter the street claiming more lands as number of dumping sites keeps increasing. Waste treatment/disposal is one of the environmental challenges confronting the modern societies globally. Bio-waste (organic waste) constitutes over 60% of these wastes in the advanced nation and even more in the developing nations (Arvanitoyannis et al., 2007; Cheng et al., 2010; Mata-Alvarez et al., 2014). However, these biological material (biomass) includes not only bio-waste but all materials from natural processes which in most cases are nuisance to our environment constituting waste (Babatola and Ojo, 2020; Edenseting et al., 2020).

The technology is not obsolete despite centuries of existence as it is presently an interesting subject in the research community. It proffers solution not only to the environmental issue but also found its applications in both the energy and the agricultural sectors of the economy (Figure 1).

Research shows that the conditions of the process (temperature, pH, and pressure), digester design and substrate characteristics contributed immensely towards the success/failure of the process (Ofoefule and Onukwuli, 2010; Hoefnagels and Germer, 2018; Kalyanasundaram et al., 2020). Specifically, the variability of process conditions, digester design and diversity of bio-sourced feedstock are the key areas exploited to take the anaerobic digestion process this far.

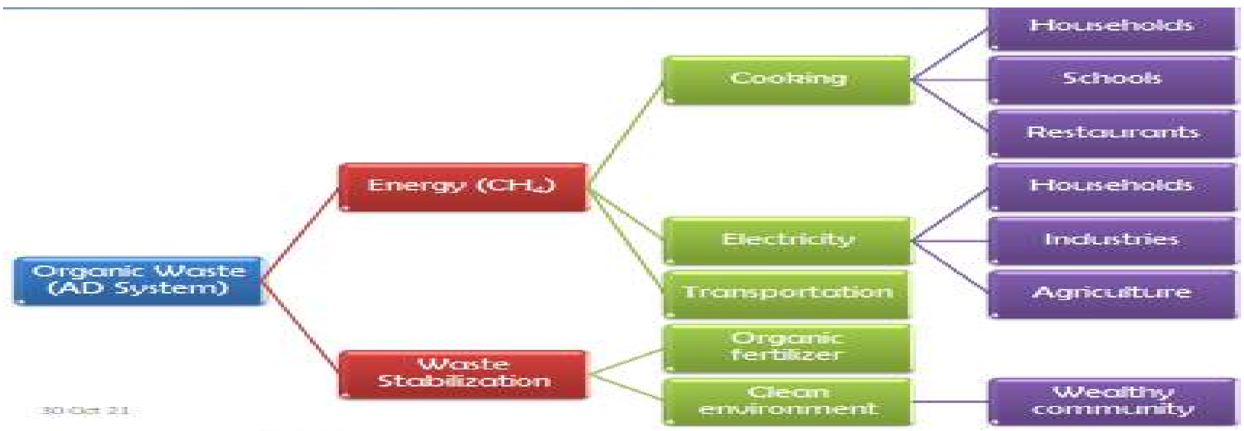

Figure 1: Anaerobic Biodigestion Technology: A waste to wealth strategy

Despite these advances, several researchers have reported that the process is strict and difficult to operate (Kozo et al., 1996; Zuru et al., 1998, Uzodinma et al., 2007; Ofoefule and Uzodinma, 2009). One of the challenges is the difficulty associated with substrate digestion making the process slow and unstable. Specifically, most of the substrates combo exploited has antagonistic /inhibitory effects resulting in low/delayed or termination of biogas production when exploited (Uzodinma et al., 2007; Ofoefule and Uzodinma, 2009). The strict nature of the anaerobes is another challenge as they can be inactive (lethargic) if there is a deviation in process condition. The sensitivity of these anaerobes leads to early termination of the process. Moreover, scum builds up due to poor digester design which eventually becomes strongly bonded to the wall and bottom of the biodigester resulting in a reduced digesting capacity is equally a challenge to this technology. A review of these advances as well as the challenges confronting the technology is necessary. Specifically, the current study presents these advances in terms of diversity of feedstock, biodigester design and and variability in process conditions. However, the challenges encountered are presented with the aim of achieving more from the process while addressing the challenges.

1.1 Advances in Anaerobic Biodigestion Technology: Diversity in Bio-sourced Feedstock

Digestion is a biology term relating to eating of food and biodigestion connotes a special type of eating by microbes. In view of this, digestion is a biological process in which a consortium of micro-organisms converst biological material (organic matter) into volatile components (biogas) and water resulting to mass loss and perhaps destruction of pathogens. Biodigestion technology was originally formulated for waste treatment/disposal to address one of the global issues posed by its counterparts: pyrolysis, gasification and thermal incineration (combustion) with respect to greenhouse effect (Arvanitoyannis et al., 2007; Cheng et al., 2010). Hence, it is also known as sludge digestion.

Biomass (biological material) constitutes the feedstock exploited for anaerobic biodigestion operation. The diversity of bio-sourced feedstock (Edenseting et al., 2020) cheaply sourced domestically and industrially has drawn the interest of several researchers to the technology. The organic substrate varies in degradable effluents and complex solids waste and it is generally made up of complex chemical substances which vary in proportion (Steffen et al., 1998). These include: as carbohydrates, proteins, lignin, water and traces of inorganic matter. These bio-Sourced feedstocks are classified based on residues and as well by the products they produce, etc. (Ben-Iwo et al., 2016; Hoefnagels and Germer, 2018; Edenseting et al., 2020).

1.1.1 Bio-Sourced Feedstocks Based on Residue

In this category, there are primary, secondary and tertiary residues (Hoefnagels and Germer, 2018). Figure 2 indicates the sources and the products derived from this class of bio-sourced feedstocks and its application.

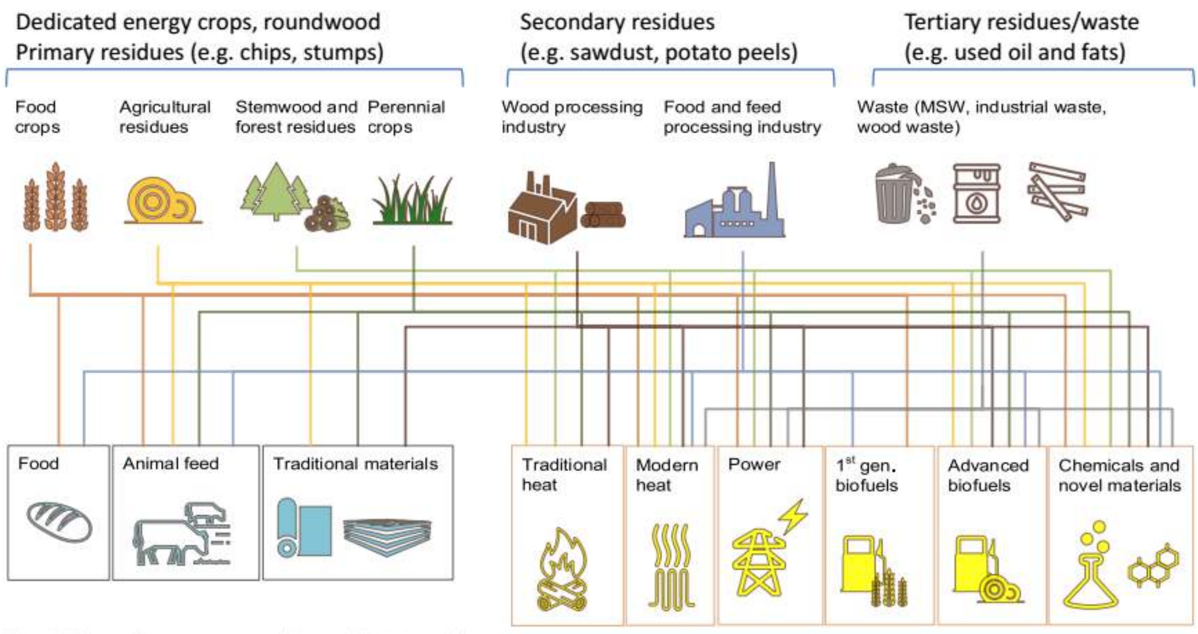

Figure 2: Bio-sourced feedstocks and application

Sourced: Hoefnagels and Germer (2018)

1.1.1.1 Primary Residues

Biomass from this category can be exploited mainly for animal feed and other traditional materials. They include: chips, stumps and other residues from food crops, agricultural wastes and forest tree residues (Zhu et al., 2010).

1.1.1.2 Secondary Residues

This category of bio-sourced feedstock constitutes industrial wastes from wood, feed and food processing industries. They are: sawdust, potato peels and others exploited for animal feed, heating and power generation (Bamgboye, 2012; Bruni et al., 2010; Pisutpaisal et al., 2014; Patel, 2017).

1.1.1.3 Tertiary Residues

These bio-sourced materials are mainly wastes from sewage and industries such as: used oil and fats that are converted to biofuels and bio-chemicals (Gelegenis et al., 2007).

In terms of the products, biological materials are classified into four generations: first generation, second generation, third generation and fourth generation. More on these class of bio-sourced feedstock can be found in Dutta et al. (2014); Edenseting et al. (2020).

1.2 Advances in Anaerobic Biodigestion Technology: Variability in Process Conditions

The impact of anaerobic biodigestion technology in several sectors of the economy is attributed to the variability of the process conditions in which the anaerobic biodigestion can be operated. In this section, the essential parameters that influence anaerobic digestion are discussed. These include the pre-treatment of bio-sourced feedstock (section 2.2.1), activators/innocula (section 2.2.2), temperature (section 2.2.3), pH (section 2.2.4), and pressure (section 2.2.5).

1.2.1 Pre-treatment Bio-Sourced Feedstock

These are mainly the biomaterial in which the anaerobes digest as substrates. Generally, any biodegradable material can be used as bio-sourced feedstock for energy production. In view of this, several biological materials (bio-sourced feedstock) have been exploited for biogas production via anaerobic digestion. There are myriads of biologically digestible materials (substrates) exploited for anaerobic digestion classified as first generation (food mostly energy crop), second generation (residue, grasses mostly lignocelluloses and wastes), third generation (sea weed algae) and genetically modified biomass constituting fourth generation substrates (Demirel et al., 2009; Wall et al., 2014; Edenseting et al., 2020).

About a decade ago, Germany has over 6000 digesters exploiting mainly energy crops anaerobically (Allen, 2015). Similar developments were reported in Brazil, China, USA, Ireland etc., where energy crops like sugar cane, cassava, maize (first generation) were utilized as bio-sourced feedstock (Mitchell, 2008; Edenseting et al., 2020). However, with the hike in food prices globally, there is much concern over the use of energy crops for biogas production. This has shifted the onus for exploitation of second, third and fourth generation substrates eliminating competition between food and agricultural land. Akinbami et al. (2001) reported feasible substrates for anaerobic process to include: water lettuce, water hyacinth, cattle dung, cassava leaves, urban refuse, agricultural residue, sewage and industrial waste. Table 1 shows some of these feedstocks as well as their yield.

Table 1: Bio-sourced Feedstock and Potential

Materials and their main components	Yield of Biogas m^3/kg TS	Methane content (%)
Animal barnyard manure	0.260 ~ 0.280	50 ~ 60
Pig manure	0.561	
Horse droppings	0.200 ~ 0.300	
Green grass	0.630	70
Flax straw	0.359	
Wheat straw	0.432	59
Leaves	0.210 ~ 0.294	58
Sludge	0.640	50
Brewery liquid waste	0.300 ~ 0.600	58
Carbohydrate	0.750	49
Liquid	1.440	72
Protein	0.980	50

Source: Ampomah-Benefo (2018)

Potentially, all biological material can be exploited by anaerobes for production of biogas and organic fertilizer. This is attributed to the presence of essential nutrient in these materials to support growth and metabolic activities of anaerobic bacteria for biogas production (Duku et al., 2011). Research has shown that chemical composition and biological availability of the nutrients in these materials differ with species as well as factors affecting growth and the age of the biological material (Ofoefule and Onukwuli, 2010). The energy stored in these materials can be extracted when digested. The choice of conversion method is usually influenced by the physical properties (moisture content, calorific value, and particle size) and chemical content (alkali metal content Na, K, Mg, P and Ca,) of the feedstock.

Biomaterials with low moisture content (< 15 %) are considered dry and are suitable for direct combustion, gasification, or pyrolysis, while those with high moisture content is suitable for anaerobic digestion. If wet digestion is desired, water has to form the highest proportion (> 70 %). Consequently, when feedstock with low moisture content has to be used in an anaerobic digestion, large quantities of water have to be added for optimum biogas yield, especially if wet digestion is being considered. The bio-sourced feedstock is mixed with a proportional amount of water and seeded with a consortium of microbes to form slurry.

Recently, various studies have been conducted with co-digestion and the results have seen improvement over single feedstock digestion (Gashaw, 2014; Li et al., 2015; Jena et al., 2017; Tasnim et al., 2017; Dahunsi et al., 2017). Specifically, simultaneous digestion of a mixture (blending) of two or more substrates is referred to as co-digestion. In co-digestion, the feedstock is mixed with other biomaterial that contains relevant microbes. The co-existence of different types of substrates in the same geographical area promotes integrated management offering considerable environmental benefit such as energy saving, recycling of nutrients back to the land and reduction of greenhouse gas GHG emission (Kacprzak et al., 2010). Co-digestion is expected to enhance the performance of the anaerobic digestion process as different properties of the constituent substrates are exploited due to positive synergism established in the digestion medium by providing a balanced nutrient supply and sometimes by suitably increasing the moisture content required in the digester (Darwin et al., 2014).

However, a successful co-digestion involves more than simultaneous digestion of multi-feedstock/substrates for biogas production. In essence, the composition of these substrates, the process conditions and the activity of microbial community in the system are equally important as they are linked to biogas production and stability of the process. In addition, there are other locally found lignocellulosic materials and organic wastes that have received considerable research attention recently (Okoroigwe and Agbo, 2007; Ofoefule and Onukwuli, 2010; Eze and Agbo 2010; Fang, 2010; Ezekoye et al., 2011; Eze and Ojike, 2012). Meanwhile, plant materials mostly lignocellulosic materials such as crop residues are more difficult to digest than animal waste as special bacteria found in the stomach of these ruminant animals had initiated biomaterial fermentation (i.e., hydrolysis) prior to anaerobic digestion (Itodo et al., 1992; Eze, 2003).

The organic substrate varies in degradable effluents and complex solids waste (Steffen et al., 1998). During AD process, the raw material decomposition occurs at different kinetics. AD may occur more rapidly, if the substrates are short-chain hydrocarbons or simpler sugars. On the other hand, process could be slow if substrates are quite complex such as cellulose and hemicellulose (Bhatia 2014). Alkaline pretreatment of the feedstocks, nutrient addition, and co-digestion have increased biogas yield and productivities, eventually affecting the overall process performance (Ivo Achu 2012). Figure 3 shows the role of feedstock on the rate of AD.

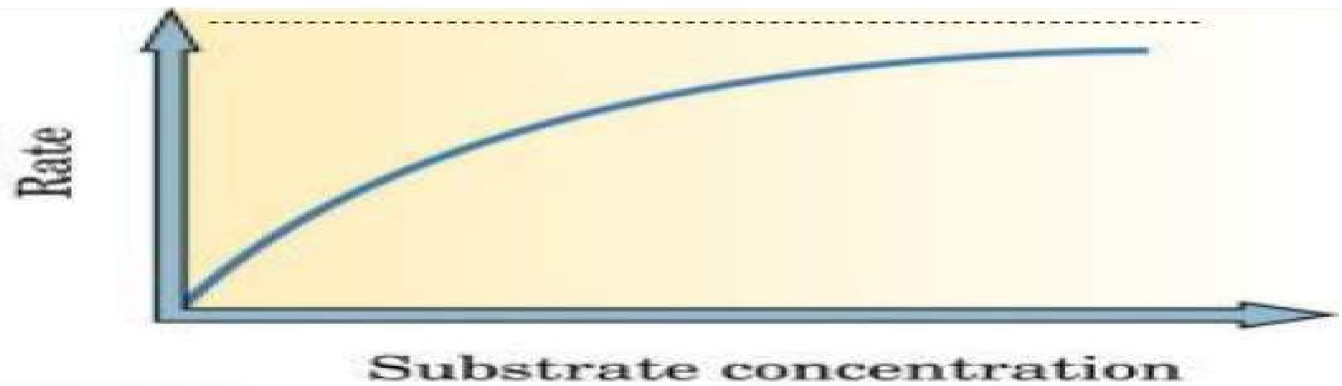

Figure 3: Impact of substrate concentration on rate of AD

However, the challenge for the use of this type of feedstock is its structure. Hydrolysis of insoluble complex organic material in soluble monomers and oligomers is the first step in biogas generation from lignocellulosic material. For this, it is necessary that the responsible enzymes be produced by the microorganisms and that there is direct interaction amongst the enzymes as well as the substrate (Chandel et al., 2019). However, pretreatment of lignocellulosic biomass is necessary for using them further in biogas production via AD. Pretreatment removes or breaks the lignin as well as hemicellulosic portion of the biomass, thereby enabling the cellulosic material accessible to the microorganisms during the AD process (Karp et al., 2013; Fan et al., 2016).

1.2.2 Activator/Inoculum

It is the seed of microbes added to the feedstocks to initiate anaerobic digestion process. It is also called inoculum or starter. It can be sourced from an existing active digester or from animal dung (droppings) which contain large quantities of consortium of microbes. The inoculum can also be extracted in the laboratory from a pure culture of microbes. The role of enzyme in anaerobic digestion process is critical especially initiating the hydrolysis and as well catalyze other stages.

Microbe is needed to secrete enzymes to initiate the process. Immediate production of biogas within a short period is a function of the quantity of inoculum and how quickly they can adjust and populate. Research showed that they are sensitive environmental conditions such as temperature, pH and nutrients/substrates (Ezeonu et al., 2005; Filmax, 2009; Zhang, 2017; Vivekanandan, 2017). The medium (slurry) in which the inoculum is introduced must be maintained with the optimal conditions to achieve optimal microbial activities (Figure 4).

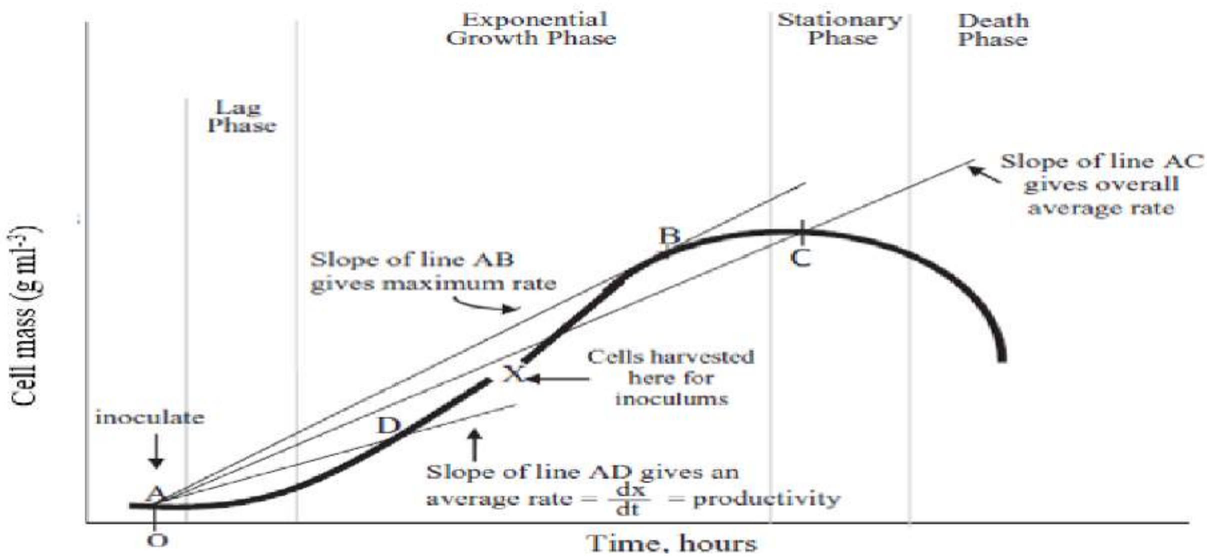

Figure 4: Growth phases of typical microbes in an anaerobic system

Source: Ampomah-Benefo (2018)

The microbial activities of the inoculum in the slurry as well as growth rate are summarized in four growth phases (Ampomah-Benefo, 2018). These include: lag phase, exponential growth phase, stationary phase and the death phase (Mosier and Ladisch, 2009). The lag phase is the time it takes the inoculated microbe to adapt to the new environment. This phase is also known as the incubation period. The duration of the lag phase is greatly influenced by the source of the inoculum and how quickly it can adjust to its new environment. Inoculum taken from an active digester with the same kind of slurry as the new digester usually have minimal lag phase period as it adjust easily with negligible adaptation period. After the lag phase, then exponential growth phase sets in.

This is the period of highest microbial activity as the microbe begins to populate at an exponential rate. At this period, substrate is consumed rapidly because of the population growth of microbes. Substrate consumption rate remains constant at maximum microbial growth. As substrate gets depleted, the microbial activity remains constant as the substrate is depleting (Stationary growth phase). As the substrate gets exhausted, the microbe has nothing to feed on and goes to extinction (death phase).

However, during anaerobic digestion processes various microbes play specific roles in a sequential manner. The anaerobes which are generally fermentative bacteria comprise: acidogens, acetogens and methanogens. Each of them has different regeneration time as acidogenic anaerobes spent less than an hour to about 36 hours to regenerate. Acetogenic anaerobes spend about twice as much of time (3.3 days to 3.75 days) used by acidogenesis to regenerate.

Methanogenic anaerobes, which are the final microbes to convert substrate to biogas, spend between 5 days and 16 days to regenerate (Deublein and Steinhauser, 2008). A correct balance of time for regeneration of all these anaerobes is necessary for optimization of biogas generation. It therefore suggests that in an anaerobic digestion system biogas production can be expected between 5 days to 16 days. In the case where lag time is minimized, biogas can be realized within a day (Ampomah-Benefo, 2018). This work will exploit inoculum from different sources and the varieties in the feedstocks offered by co-digestion for improved biogas production.

1.2.3 pH of the Slurry

It is a measure of performance and stability of chemical reaction taking place in the digester. Each stage in anaerobic digestion processes requires a particular pH range for optimal microbial activities (Figure 5) Several researchers reported that acidogenesis stage occurs around a pH of 5.0, whereas methanogenesis occurs at pH of 7.0 (Ann et al., 1996; Lin et al., 2013).

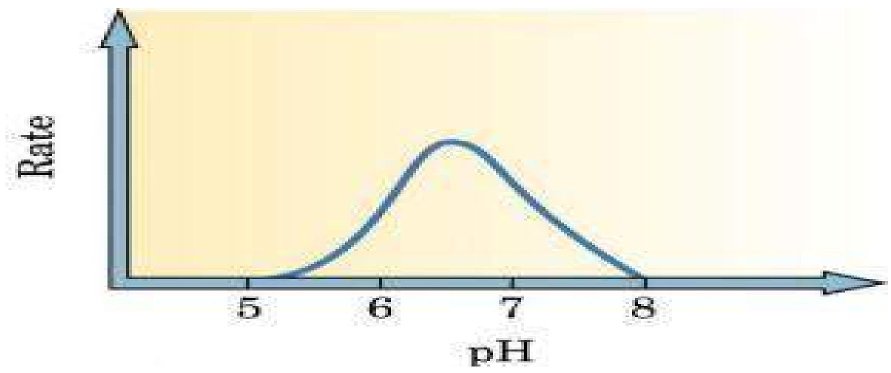

Figure 5: pH and Rate of biodigestion dependency

In a single stage anaerobic digester, where all the various digestion stages take place in a single tank, the system acts like a combined culture with pH range of 6.8 – 7.4, with neutral pH being the optimum (Boone and Luying, 1987). The rate of CH_4 production may decrease if the measured pH is either lower than 6.3 or higher than 7.8 (Kim et al., 2004). For low pH, acidogens populate and increase the production of volatile fatty acids and H_2 (Ann et al., 1996; Chen et al., 2008). If the process is not corrected it could lead to failure of the anaerobic processes to produce biogas. This can be corrected by first reducing the organic loading rate and then the introduction of chemicals such as $NaHCO_3$, NaOH, or Na_2CO_3 to adjust the pH to neutral.

The process condition in a single stage may promote a particular reaction at the expense of the other and the overall process efficiency is relatively low. To optimize biogas production, it is necessary to create favorable environmental condition by dividing the reactions into stages such that effluent of the previous reactor becomes a substrate in the next reactor and ensuring that the process condition in each of the stages is favorable for optimal yield.

1.2.4 Pressure

High biogas pressure above the slurry (gas cavity) in a biodigester causes CO_2 to dissolve in the slurry. This dissolved CO_2 increases the acidity of the digestate (Lemmer et al., 2017). As a result of increasing pressure, the rate of biogas formation is consequently reduced (Hamad et al., 1983; Mateescu, 2016). Mateescu (2016) presented the result of the study on the variation of hydrostatic pressure with percentage yield of biogas conducted. The maximum biogas yield was achieved at 0 kPa (gauge pressure), which was above 60 % of CH_4. At 600 kPa, CH_4 production was generally less than 20 %. To reduce the effects related with CO_2 solubility, large increase of pressure is avoided by regularly withdrawing and combusting the gas yield or by venting the accumulated gas regularly as will be exploited in this study.

1.2.5 Temperature

Anaerobic digestion can occur at three different ranges of temperature: (i) psychrophilic < 20 oC, (ii) mesophilic 20 - 40 oC, and (iii) thermophilic 45 - 60 oC. These temperature ranges are suitable for specific microbes. Beyond these ranges the respective microbes are not able to withstand the temperature changes, hence are destroyed, or become inactive (Ryckebosh, 2011; Evans and Furlong, 2003). Generally, an increase in temperature increases the activities of the microbes, hence an increase in the rate of conversion of slurry to biogas. Studies show that the growth rate of the microbes (in each temperature range) increases exponentially with temperature. This growth continues until an optimum temperature is attained. Beyond this optimum temperature, further increase in temperature will impede the growth and result in the death of microbes (Diamantis, 2010).

Generally, advances in anaerobic digestion technology as presented (Table 2) is attributed to the diversity in feedstock, digester design and variability of process conditions. Specifically, studies have been carried out on pretreatment of bio-sourced feedstock, novel inocula and their interaction with bio-sourced feedstock as well as their nutritional requirements (Tchobanoglous et al., 2003; Fekadu, 2014; Cestonaro et al., 2015; Fu et al., 2015). In addition, research on thermal effect on the AD process, alternating thermophilic, mesophilic and psychrophilic stages while evaluating the productivity, kinetics, and net energy balance have been adequately investigated (Ampomah-Benefo, 2018; Velazquez-Marti et al., 2019). For best degradation of substrates, methods such as pretreatment and co-digestion are used. Pretreatment facilitates the digestion and improves the accessibility of the source carbon utilizable by the microbial community, and mixing sources (co-digestion), working together as substrates, provides several advantages that improves biogas yields, methane production, and various other benefits.

Table 2: Advances in Anaerobic Digestion Process

Researcher	Bio-Sourced Feedstock	Process Condition	Gas Potential (m^3/kgSV)
Bayrakdar *et al.*2018	Chicken manure	Mesophilic	0.272
Franco *et al.*2018	Wheat straw + inoculum	Mesophilic	0.229
Franco *et al.*2018	Wheat straw + glucose + ac. Formic + inoculum	Mesophilic	0.276
Guo *et al.*2018	Excessively withered corn straw + glucose	Mesophilic	0.282
Li *et al.*2018	Parton + sheep manure	Mesophilic	0.152
Li *et al.*2018	Paper + sheep manure	Mesophilic	0.199
Mancini *et al.*2018	Lignocellulose in general	N-methylmorpholine N-oxide	0.304
Martín *et al.*2018	Microalgae + pig manure	Alkaline pretreatment with NAOH	0.377

Mustafa *et al.*2018	Bagasse of sugarcane + inoculum*	Hydrothermal pretreatment	0.318
Vazifehkhoranet *al.*2018	Wheat straw + sewage	Mesophilic	0.314
Xu *et al.*2018	Corn straw + Bacillus Subtilis	Microaerobic mesolithic	0.270
Zahan *et al.*2018	Gallinaza (sawdust, wood shavings, and rice or straw husk) with yogurt serum	Mesophilic	0.670
Aboudi *et al.*2016	Dry sediment of sugar beet tails + pig manure	Mesophilic	0.260
Dennehy *et al.*2016	Food waste and pig manure	Mesophilic	0.521
Glanpracha and Annachhatre, 2016	Cassava pulp with pig manure	Mesophilic	0.380
Marin *et al.*2015	Vinasse and chicken manure (chicken dung)	Mesophilic	0.650
Aboudi *et al.*2015	Dry beet granules of sugar beet + cow dung	Mesophilic	0.280
Belle *et al.*2015	Fodder radish with cow dung	Mesophilic	0.200
Cestonaro *et al.*2015	Sheep litter (mixture of rice husk with feces and urine) + cattle manure	Mesophilic	0.171
Di Maria *et al.*2015	Sludge from wastewater with fruit and vegetable waste	Mesophilic	0.216
Fu *et al.*2015a	Corn straw + inoculum	Thermophilic microaerobic	0.326
Fu *et al.*2015b	Corn straw + inoculum	Secondary thermophilic microaerobic	0.381
Agyeman and Tao, 2014	Food waste + livestock manure	Mesophilic	0.467

Source: Velazquez-Marti et al. (2019)

II. CHALLENGES CONFRONTING ANAEROBIC BIODIGESTION PROCESS

Anaerobic biodigestion process, though an age-long process, is unattractive, difficult and highly unstable process due low methane yield. In addition, its effluents are not suitable for direct discharge to the environment due to offensive odor. In this section, these challenges are discussed. The challenges are generally based on biodigester design/configurations (section 3.1), the inhibitory episodes from antagonistic substrate combo (section 3.2) and the offensive odor of the effluent on fertilizer application (section 3.3). The review on these challenges is necessary towards improving the process. However, in each of these challenges, the author proffers the way out towards addressing them.

2.1 Challenges Attributed to Biodigester Design and Configuration

The bioreactor's design and configurations is one of the keys to successful anaerobic digestion operation. It is the chamber in which the anaerobes digest the substrates and as a result produce biogas and the nutrient-rich biol for plant growth. As stated earlier, maintaining an air-tight chamber is difficult in practice and failure to maintain this condition leads to oxidization of most of the methane forming compounds as more ammonia gas, CO2 are produced at the expense of methane as methanogens (methane-forming anaerobes) are very sensitive to oxygen and die when they are exposed to oxygen. This is aerobic digestion which as reviewed is more thermo-dynamic feasible with stable products than anaerobic digestion. The effect is low methane yield as the process has deviated to aerobic digestion.

Furthermore, it is reported that anaerobic digestion comprises of four stages (hydrolysis, acidogenesis, acetogenesis and methanogenesis) requiring a synchronized action of four groups of microbes. In each of these stages, individual group of anaerobes require different process conditions for optimum microbial activity as acidogens thrive in acidic medium while acetogen and methanogens need relatively high pH (7-7.4) to explore effectively (Ampomah- Benefo et al.,2013). Most digesters are operated as a single stage where all the anaerobes are lumped together in one chamber (stage), regardless of their disparities; it would be a case of 'survival of the fittest'. Sadly, the most important pathway in methanogenesis, acetoclastic methanogenesis, where acetoclastic methanogens (methanosarcina and methoanosaeta) formed more than 60% of the methane, the most valuable constituent of biogas is not thermodynamically favorable as its Gibb's free energy is comparatively near positive (-31.0kJ/mol) than the other methanogenesis pathways, hydrogenotrophic methanogenesis and homoacetogenesis, with - 135.0kJ/mol and -104. 00kJ/mol respectively (Ampomah - Benefo, 2018). The outcome is better imagined as production of methane would be suppressed.

However, the challenge of primary concern to this study is the problem of scum. It is attributed to solid accumulation when biodigester's design is inadequate (Anonymous, 2020). Scum originated from the substrate as suspended solids like straw, grass, stalk, dried dung, feather, etc., tend to be floating to the surface. These eventually may become a problem when they are not digested as they form a thick scum layer which blocks the surface. This posed a danger of blocking the gas by the rising scum. The trapped gas may cause CO_2 to dissolve which reduces the pH of the slurry to acidic which inhibits methanogens resulting low methane yield. The surface scum has to be removed and that leads to shutting down of the digester for cleaning translating to economic loss and down time.

Solid and mineral materials like sand and earthed material may be picked up by animal during feeding and egested undigested by animals. Such particles are usually seen in poultry birds, cow or pig dung. Based on their weight, gravitational pull on these heavy undigested particles settle/sink to the bottom and eventually pile up to scum which block the outlet pipe or reduce the active digester capacity. Scum is not brittle but very filthy and tough. It can become so strong within a short time that needs heavy equipment to break it (Wang et al., 2009). To destroy it, it is either the scum must be watered from the top or pushed down into the liquid. Both operations demands costly apparatus and the plant have to be shutdown accounting to huge economic loss and downtime.

However, when scum is fully developed, stirring is not a viable solution for breaking scum (Budiastuti and Rahayu, 2016). The only solution is to avoid scum formation by ensuring that the digester content is sufficiently/perfectly or by carefully selecting suitable substrates. However, as far as the substrate involve animal manure, the presence of sand, stone and other debris in the animal dung is inevitable as such sufficient mixing operation is the only way forward. As reviewed, the challenge of sufficient mixing irrespective of types is an issue currently investigated as the mechanical, hydraulic and pneumatic approaches to mixing have peculiar challenges. Therefore, the low methane yield, poor effluent quality, instability and early termination of gas production are related to digester's design and configuration. Designing a multi-stage with improved mixing efficiency will address these issues.

2.2 Challenges Attributed to Substrates

Researchers have exploited several biomaterials for biogas production. These materials include among others animal wastes (Zuru et al., 1998), industrial waste (Uzodinma et al., 2007), plant waste (Bori et al., 2007; Ofoefule et al., 2009), food processing wastes (Arvanitoyannis et al., 2007). However, animal wastes (manure) are readily digested than plant materials. The difficulty posed by digesting plant materials especially crop residues is associated with its high cellulosic and ligninic content which is difficult to be broken during hydrolysis (Itodo et al., 1992; Garba and Uba, 2002; Kozo et al., 1996; Dioha et al., 2006; Eze, 2003; Okoroigwe, 2005) coupled with attendant acidity in the biogas system leading to reduction if not termination of biogas production (Uzodinma et al., 2007; Ofoefule and Uzodinma, 2009). Meanwhile, all organic materials contain enough nutrients essential to support the growth and metabolism of anaerobic bacteria in biogas production (Ofoefule and Onukwuli, 2010). The choice of substrates for biogas production is critical as it can mar or promote the process.

Several optimization techniques for enhancing biogas production has been reported to including blending (co-digestion), size reduction, inoculation, chemical treatment, addition of metals and others (Batstone et al., 2007; Ofoefule and

Uzodinma, 2006; Ofoefule and Uzodinma, 2009). Co-digestion involves the digester with a blend of substrates combo to exploit its synergistic effects by provision of balanced micro and macro nutrients for optimum microbial activity. It involves enhancement of digestion of biomass (mostly plants) due to the addition of easily degradable substrates (mostly animal waste).

However, impact of co-digestion can be adverse as several inhibitory episodes have been reported of co-digestion involving a mixture of two or more substrates resulting in low methane yield, instability and even poor effluent quality (Oparaku et al., 2013; Teng 2014; Forgacs et al., 2019). The inhibitory episode from antagonistic substrate combo is one of the challenges and many researchers seek to unmask (Agyeman et al., 2014; Fu et al., 2015; Di Maria et al., 2015; Belle et al., 2015; Aboudi et al., 2015; Glanpracha and Annachhatre ,2016; Dennehy et al., 2016; Aboudi et al., 2016; Li et al., 2017; Zahan et al., 2017; Mancini et al., 2018; Franco et al., 2018; Guo et al., 2018; Martín et al., 2018; Mustafa et al., 2018; Vazifehkhoran et al., 2018; Xu et al., 2018). The task is finding two or more substrates with complementary characteristics so that methane yield, effluent quality and process stability are enhanced through their joint treatment. This portrays co-digestion process as a trial and error technique whose impact can be positive or negative.

However, organic materials harnessed for biogas production is limited and new substrates should be sought to meet the ever-increasing energy demand. Further research on many locally available wastes especially plant residues as potential feedstock for biogas production is still ongoing. In view of this, several researchers have reported that biogas production as well as the stability of the process is dependent on several factors such as pH of the digesting medium, total solids, volatile solids, ambience and slurry temperature, nature (especially composition) of waste, organic loading rate, retention (residence) in the biodigester and mixing ratio of substrates, and others (Garba and Sambo, 1992; Carl and Lamb, 2002; Dioha et al., 2005; Ezeonu et al., 2005; Anonymous, 2020).

2.3 Challenge Attributed to Effluent as Bio-Fertilizer

In the course of conducting anaerobic digestion process especially using second generation constituting crop residue and organic waste, it is of concern that the process too would not generate waste to the community especially as the effluents from anaerobic digestion are of poor quality than that of aerobic digestion (Babatola and Ojo, 2020). Generally, oxidizing agents such as O2, NO3, SO4, and CO2, destroy cells by oxidizing various cell components. The reaction releases energy in the form of heat. This is why air should be avoided as the slurry in the presence of O2 undergoes oxidation referred to as aerobic digestion, in which the reaction releases energy. Table 3 shows the oxidization of glucose where free energy of ΔGo =-2840 kJ mol-1 is released with the production of CO2 and H2O. In this reaction no CH4 is formed. This is because methanogens, which forms CH4, are very sensitive to oxygen and die when they are exposed to O2 (Ampomah-Benefo, 2018).

Table 3: Aerobic reaction of biomass

Component	Aerobic reaction
Reaction	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
Energy released	ΔG^0= -2840kJ/mol
Energy balance	60% biomass, 40% heat released

Source: Ampomah-Benefo (2018)

Moreover, odorous substances include high concentration of ammonia, light metal ions (Na, K, Mg, Ca, and Al) and heavy metals (Cr, Fe, Co, Cu, Zn, Cd, and Ni) in the digester (Cheng, 2008). Ammonia is produced from urea and proteins biodegradation and causes microorganisms to cease growth. The light and heavy metals may form salts, which may dehydrate microbial cells due to osmotic pressure. The digester effluent when used as fertilizer on land often creates serious environmental problem as the odor bothers neighboring residents (Filmax, 2009).

The most important problem in substrate management is that associated with the scum (sludge) while in the digester and when disposed.

A protocol to exploit the scum anaerobic treatment gives the same high effluent quality as aerobic treatment. Studies are currently conducted to evaluate the effluent sludge in order to assess not only its fertilizing effect but also environmental impact (Anonymous, 2020). In view of this, the author suggests the effluent can be filtered and its residue pyrolysed to create biochar and it absorption property can be investigated. The biochar can be soaked with the effluent filtrate while evaluating its fertilizing effect as well as odor emission.

III. CONCLUSION

Anaerobic biodigestion process is generally considered to be slow and unstable due to strict nature of the anaerobes and difficult to operate. However, the process is promising as it applications cut across several sectors of the economy including the energy, agricultural and environmental sectors. The advances and challenges confronting the anaerobic digestion technology have been extensively reviewed. The advances are attributed to technological innovations with regards to the diversity in bio-sourced feedstock, digester design and variability of process conditions. A variety of bio-sourced feedstock such as: animal manure, agro-residues, lignocellulosic biomaterials, food waste and municipal refuse/sewage exploited in a closed reactor/tank or bioreactor so-called anaerobic biodigester of various classes. Typically, the AD process may be categorized into four phases, i.e., hydrolysis, acidogenesis, and acetogenesis followed by methanogenesis. Pretreatment of feedstock is an unavoidable process to make the lignocellulosic substrate amenable for consortium of microorganisms (anaerobes).

It was found that pretreatment of these feedstocks, substrate interaction with the novel inoculum and substrate combo, mixture of different classes of feedstock that ferment better together than separately due to their enriched microbial load as well as their nutritional requirements, are recent strategies exploited to improve anaerobic biodigestion process. In addition, research on thermal effect, alternating thermophilic, mesophilic and psychrophilic stages while evaluating the productivity, kinetics, and net energy balance have been adequately investigated as reviewed. However, the process is challenged by poor biodigester design/ configurations, the inhibitory episodes from antagonistic substrate combo and the offensive odor of the effluent on fertilizer application. The review on these challenges is necessary towards improving the process.

On the whole, for improved degradation of substrates, several strategies such as pretreatment and co-digestion, etc. have been exploited. Specifically, pretreatment of feedstock facilitates biodigestion and improves the accessibility of the source carbon utilizable by the microbial community, and mixing sources (co-digestion), working together as substrates, provides several advantages that improves biogas yields, methane production, and various other benefits.

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