ANAEROBIC CO-DIGESTION OF FOOD WASTE AND SEWAGE SLUDGE AS A PROMISING ALTERNATIVE FOR WASTE MANAGEMENT AND ENERGY PRODUCTION

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ABSTRACT: Biogas is an economical and environmentally-friendly renewable energy, which can be produced by anaerobic digestion (AD). This biochemical method converts organic compounds (mainly from wastes) into a sustainable source of energy. Anaerobic co-digestion (AcoD) is a method combining more than one substrate to resolve the difficulties faced in a single substrate AD system. Solid wastes increase as the population increases, so do the urbanization and industrial industries. Food waste (FW) and sewage sludge (SS) are examples of one of the solid wastes. Co-digesting of both substrates may improve process stabilization to increase biogas production and overcome the nutrients imbalance. Thus, anaerobic co-digestion has been recognized as a technology that could provide a clean renewable energy source and helps to reduce the landfill problems. The objective of this paper is to depict the essentials of AD together with its fundamental biological process, as well as the important factors affecting the biogas production. This article further discusses the challenges in mono-digestion, benefits of co-digestion and concludes with recent and future issues of biogas production. Traditionally, AD of FW was observed as an auspicious technology; however, there are yet numerous empirical, pecuniary, in addition to social difficulties for the single digestion of food waste. At this time, AcoD is a feasible choice that is widely applied.

KEY WORDS: *Anaerobic co-digestion, food waste, sewage sludge, biogas*

1. INTRODUCTION

The utilization of energy throughout the world is impulsively swelling because of modern industrialization, unrestrained population growth and civilization in both developing and technologically-advanced countries. The necessity of substitute energy sources is now a primary concern for both the researchers and policymakers, which lead to renewable energy. Non-renewable energy bases such as fossil fuel, coal, firewood and petroleum, which directed to worldwide climate change, causes human illness as well as environmental degradation. Marketable production of biogas from industrial sludge, agricultural or domestic waste can be a promising alternative source of energy to overcome such problems. It is anticipated to form sustainable and with no emission of carbon [1], [2].

It has been estimated that roughly 1.3 billion tonnes municipal solid waste is produced annually at present, which is projected to excavate around 2.2 billion tonnes per annum by the year 2025. This signifies a substantial growth for each capita waste production rates, from 1.2 to 1.42 kg per person per day in the next fifteen years. Table 1 represents the generation of waste per capita by region along with average kg per capita per day [3].

Table 1: Current waste generation per capita by region.

Region	**Waste Generation Per Capita (kg/capita/day)**		
	Lower Boundary	Upper Bounday	Average
Sub-Saharan Africa	0.09	3.0	0.65
East Asia Pacific Region	0.44	4.3	0.95
Eastern and Central Asia	0.29	2.1	1.1
Latin America and the Caribbean	0.11	5.5	1.1
The Middle East and North Africa	0.16	5.7	1.1
The Organization for Economic Co-operation and Development countries	1.10	3.7	2.2
South Asia	0.12	5.1	0.45

Biogas is considered as a renewable resource of energy usually originated from biodegradable organic matters such as sewage sludge, domestic wastes, agricultural wastes, food processing and sometimes from animal manure [4]. It is produced by a biochemical process recognized as anaerobic digestion (AD), in which diverse groups of microorganisms participate and the whole process occurs in an anoxic environment [5]. The fundamental end products of biogas are mainly methane (CH_4) and carbon dioxide (CO_2) [6] with some trace elements. The composition of biogas depends on the source of the substrate in addition to the type of biomass digested and the following Table 2 demonstrates the composition of three different substrates [7].

The energy released from the combustion or oxidation of methane, hydrogen and carbon dioxide purified biogas can be utilized as a vehicle's fuel as well as to generate heat and electricity in a gas engine [8], [9]. Anaerobic digestion of food waste can be a possible alternative to handle waste instead of incineration, composting and landfill, which is responsible for the emission of various greenhouse gases. The generation of biogas (purified methane or biomethane) from biomass relies on the amount and properties of the material supply into the system [10].

Table 2: Typical Composition of biogas.

Component	Agricultural waste	Landfills	Industrial waste
Methane (CH_4)	50-80	50-80	50-70
Carbon dioxide (CO_2)	30-50	20-50	30-50
Hydrogen sulphide (H_2S)	.70	.10	.80
Hydrogen (H_2)	0-2	0-5	0-2
Nitrogen (N_2)	0-1	0-3	0-1
Oxygen (O_2)	0-1	0-1	0-1
Carbon monoxide (CO)	0-1	0-1	0-1
Ammonia (NH_3)	Traces	Traces	Traces
Siloxae	Traces	Traces	Traces
Water (H_2O)	Saturation	Saturation	Saturation

2. ANAEROBIC DIGESTION PROCESS

Conversion of organic substrates into biogas through anaerobic digestion consists of a series of five successive steps, which are cross-linked with each other namely: (i) disintegration, (ii) hydrolysis, (iii) acido-genesis, (iv) acetogenesis, and (v) methanogenesis. Anaerobic digestion process and production of biogas is an upshot of complex interactions among several hundred species of microorganisms especially bacteria. These bacteria are classified into the respective four functional groups based on their metabolic reactions: i) fermentative and hydrolytic bacteria, (ii) syntrophic hydrogen-producing bacteria, (iii) acetogenic bacteria, and (iv) methanogenic bacteria. The basic biological reactions of AD, as well as the common bacterial species involved at each stage of AD is shown in table 3.

2.1 Disintegration

Fragmentation is an extracellular process where the complex mixture (such as dead organic matter and particulate organic carbon) to polymeric organic components are converted into soluble monomers by subsequent hydrolytic bacteria. Biomass or organic components are broken down into microscopic weight products by the action of extracellular depolymerization enzymes. Disintegration is also known as an inorganic method, which can mediate the fragmentation, which later leads to the solubilization of large organic compounds to soluble components. These products are usually large complex composite molecules and polymeric carbohydrates, proteins, and lipids, which are then used as a substrate for the hydrolysis process. Other remaining products are inactive particulate and inert dispersible material [10].

Table 3: Chemical reaction and bacteria involved in the anaerobic digestion [11], [12].

Stage	Type of conversion	Bacteria involved
Stage-I **Hydrolysis** $(C6H10O5)n + nH2O = n(C6H12O6)$	Proteins to soluble peptides and amino acid	*Clostridium, Proteus vulgaris, Vibrio, Bacillus, Peptococcus, Bacteriodes,*
	Carbohydrates to soluble Sugar	*Clostridium, Acetovibrio celluliticus, Staphylococcus, Bacteriodes*
	Lipids to fatty acids or alcohols	*Clostridium, Micrococcus, Staphylococcus*
Stage-II **Acidogenesis** $C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + CO_2$ $C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$ $C_6H_{12}O_6 \rightarrow CH_3CH_2CH_2COOH + 2H_2 + 2CO_2$ $C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$ $C_6H_{12}O_6 \rightarrow 2CH_3CHOHCOOH$	Amino acids to fatty acids, acetate and NH3	*Lactobacillus, Escherichia, Bacillus, Staphylococcus, Pseudomonas, Sarcina, Desulfovibrio, Selenomonas, Streptococcus,Veollonella, Desulfobacter, Desulforomonas*
	Sugars to intermediary fermentation products	*Clostridium, Eubacterium limosum, Streptococcus*
Stage III **Acetogenesis** $CH_3CH_2OH + H_2O \rightarrow CH_3COOH + 2H_2$ $2CH_3CH_2OH + 2CO_2 \rightarrow CH4 + 2CH_3COOH$ $CH_3CH_2COOH + 2H_2O \rightarrow CH3COOH + 3H_2 + CO_2$ $CH_3CH_2CH_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2$ $CH_3CHOHCOOH + H_2O \rightarrow CH_3COOH + CO_2 + 2H$	Higher fatty acids or alcohols to hydrogen and acetate	*Clostridium, Syntrophomonas Wolfeii*
	Volatile fatty acids and alcohols to acetate or hydrogen	*Syntrophomonas wolfei, Syntrophomonas wolinii*
Stage IV **Methanogenesis** $CH_3COOH \rightarrow CH_4 + CO_2$ $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	Acetate to methane and carbon dioxide	*Methanosaeta, Methanosarcina*
	Hydrogen and carbon dioxide to methane	*Methanobacterium formicicum, Methanobrevibacterium, Methanoplanus, Methanospirilum*

Disintegration is included as the first process by the International Water Association (IWA) task group to allow for a diversified application, as well as for the digestion of organic sludge and complex biological compounds. This is particularly significant for waste-activated and essential slime processing, where the deterioration step performs lysis of entire cells and partition of composites [13].

2.2 Hydrolysis

Hydrolysis is considered as the rate-limiting stage of AD of SS [14], [15] as the generation of biogas relies upon hydrolysis of biological substrates. Hydrolysis or liquefaction involves the breakdown of large chains of organic substrates into soluble small molecules into the solution [8]. During this stage, complex organic polymers, for instance, proteins, polysaccharides, and lipids are degraded into soluble amino acids, monomers, and long-chain monomer, respectively [16]. Hydrolytic bacteria produce different types of extracellular enzymes, for instance, proteases, cellulases, amylases, and lipases which perform the breakdown process by binding to the polymeric substrate [17]. Shah *et al* [18] reported that only half of the organic compounds undergo bioconversion during solid wastes digestion and the rest remaining as a major state due to the availability of enzymes involved in their decomposition [19], [20].

The reaction rate of hydrolysis is usually influenced by different parameters, for example, particles size, pH, enzymes production, dispersion, and accumulation of enzyme on the particles of wastes exposed to the digestion process. The anaerobic bacterial group such as *Streptococcus* and *Enterobacterium* are participated to carry out the hydrolysis process [18].

2.3 Acido-genesis

At this stage, water-soluble organic substances, as well as hydrolysis products (monomers, dimers, and long-chain fatty acids), are subsequently transformed into short chains organic acids (formic, acetic, propionic, butyric, and pentatonic), intermediate alcohols (methanol, ethanol), aldehydes, CO_2, and H_2 by acidifying bacteria [18], [21]. By-products produced during the degradation of proteins, amino acids and peptides arise, which is utilized as an energy source for anaerobic microorganisms.

Acidogenesis is a two-directional process comprises both hydrogenation and dehydrogenation owing to the upshot of various groups of microorganisms. Short-chain soluble organic compounds produced during acidiogenesis such as acetate, carbon dioxide, formate, methylamines, methyl sulfide, acetone, and methanol are utilized directly by methanogen. On the other hand, higher intermediate products are transferred to acetate, formate or CO_2 and H_2 by syntrophic acetogens which are used as a substrate for methanogenesis in a bid to maximize methane production. The acidogenic bacteria belonging to a broad diversity of facultative anaerobes consume oxygen unexpectedly introduced into the process, forming favorable environments for the growth of obligatory anaerobes of the respective genera: *Pseudomonas, Bacillus, Clostridium, Micrococcus, or Flavobacterium*. Characteristic of sewage waste determines which bacteria predominates. The following microbial species are isolated from anaerobic digesters: *Clostridium,* *Peptococcus, Bifidobacterium, Desulfovibrio, Corynebacterium, Lactobacillus, Actinomyces, Staphylococcus, Streptococcus, Micrococcus, Bacillus, Pseudomonas, Selemonas, Veillonella, Sarcina, Desulfobacter, Desulfomonas, and Escherichia coli*.

2.4 Acetogenesis

Acidogenesis products (soluble organic particles) are converted into acetates, carbon dioxide, and hydrogen in acetogenesis step, with the help of *Syntrophomonas* and *Syntrophobacte* bacterial genera which later used as a substrate for methanogens [22], [23]. Bacterial species e.g. *Methanobacterium suboxydans* accounted for the breakdown of pentanoic acid to propionic acid, while *Methanobacterium propionicum* is responsible for digestion of propionic acid to acetic acid. Acetogenesis causes the generation of H_2 subsequently, which revels negative effects on the activity of microorganisms that carry out this process. For that reason, symbiosis of acetogenic bacteria with autotrophic methane bacteria is required, hereinafter stated as syntrophy [22], [24]. Syntrophy is defined as a relationship between two distinct types of organisms, in which they digest the substance and sustain energy accomplishing it that neither can decompose individually. In AD process, syntrophic reaction is considered as secondary digestion, where fermentation output of different anaerobic organism is fermented by acetogenic bacteria.

2.5 Methanogenesis

Methanogenesis is the ultimate phase of AD, where methane-producing bacteria perform the transformation of acetate, H_2 in addition CO_2 into methane, carbon dioxide, water, and other products. Different species of methanogens participate in the digestion of complex biological substance into acetate or their organic acids. A cluster of methanogenic archaea together decreases CO_2 via H_2 as an electron donor (autotrophic methanogens) and decarboxylate acetate to form CH_4 and CO_2 (heterotrophic methanogens). Throughout this process, H_2 is absorbed, which establishes a suitable environment for the expansion of acid-forming bacteria that give rise to small molecular weight of organic acids in the acidification stage, and subsequently to the minimum generation of H_2 in the acetogenic phase. As a result of such breakdown, gas produced may be rich in CO_2 since only its irrelevant part will be altered to CH_4 [25], [26].

3. PARAMETERS AFFECTING BIOGAS PRODUCTION

Performance of AD is usually affected by a number of key parameters, therefore it is vital to maintain and provide an appropriate condition for oxygen-free microorganisms. The development and function of the anoxic microbial population are undoubtedly governed by circumstances such as the formation of anaerobic conditions, optimum temperature, pH, nitrogen concentration, as well as the carbon-nitrogen ratio. Thus, change in one factor can adversely affect the efficiency of biogas production. The following factors are responsible for affecting AD.

3.1 Slurry

In order to produce biogas through the utilization of substrate over the course of AD, a favorable atmosphere for the growth and ideal metabolic reaction of microbes have to be ensured, which took part in the system. In the case of domestic waste, the ratio of appropriate liquefaction between solid and water should be 1:1. Most importantly, the decomposition medium should be free from certain inhibitors for microorganisms (such as heavy metals, detergents, antibiotics, antiseptics) but the presence of a decomposable biological substance with a pH between 6.8 and 7.3 is needed.

3.2 Temperature

Temperature is considered as one of the most essential parameters of AD as the growth of methanogens, activities of enzymes, substrate solubilization and overall production of methane are influenced by temperature. In anaerobic rector, the most common periodical obstacles are the capability of heat loss and optimum temperature maintenance in the digester throughout the process. Depending on the temperature, three major groups of methanogenic microbes participate in the AD process which is categorized as follows; (i) psychrophilic: cryophiles works at an extremely low temperature ranging from 0 to 15^{o}C, (ii) mesophiles: which are able to function at a temperature around 15-40^{o}C, and (iii) thermophilic, which are relatively effective at high temperature of 40-60^{o}C [27]. Instead of mesophilic temperature used in traditional fermentation process [28], thermophilic AD has several advantages, such as enhanced specific microbial growth rate, faster metabolic activity, elimination of pathogens and ultimate higher yield of biogas [29-31]. A study conducted by Li *et al.* [32] stated that at an upper temperature (55°C), the co-digestion activity of FW and activated sewage sludge was excellent and biogas generation rate was also 1.6 and 1.3 times greater than a mesophilic temperature of 35°C and 45°C, respectively.

3.3 Hydraulic Retention Time (HRT) and Organic Loading Rate (OLR)

These two inversely proportional parameters have equal importance on the insights of the construction of the fermenter and treatment process [33]. HRT is defined as the typical range of time that the biomass settles in the anaerobic reactor where OLR designates the number of organic compounds stated in Chemical Oxygen Demand (COD) concentration of feed (g COD/L) or in terms of Total Solids (g TS/L) or Volatile Solids (g VS/L) supplemented to the fermenter per reactor volume (L) per day. If the system operated by long HRT, it can lead to a shortage of nutrients and can cause microorganisms to be decreased, while operated at short HRT will cause microbes washout [34]. The solid content of substrate, temperature and reactor type applied for treatment determines the HRT.

On the contrary, an unexpected rise in OLR results the operation failure imposed to reduce COD deduction efficiency, as well as biogas production and pH [35]. Moreover, Rincòn *et al*. [36] reported that the microbial community is influenced by a higher OLR inside the digester system; for example, *Clostridium* is effective at minimum OLR and the classes and phyla; *Gammaproteobacteria*, *Deferribacteres*, *Actinobacteria*, and *Bacteroidetes* respectively, prevailed at high OLR.

3.4 pH and free ammonia

Although pH value is regarded as one of the major features of AD, it is difficult to control a steady pH in the reactor due to the complexity of the substrates, in addition to several microorganisms which require different optimum pH value for their metabolic activity [37]. Meanwhile, pH governs the enzymatic activity of microorganisms [38], and many researchers agreed that maximum biogas production occurs when maintaining at neutral or slightly alkaline pH conditions (between 6.8 to 7.2) [39]. The temperature kept inside the fermenter regulates the pH [7].

On the contrary, an excess amount of free NH_3 inhibits the growth of bacteria, and thereby lowers biogas production. Besides, it may generate H^+ imbalances and K^+ shortage, leading to cell lysis. Despite the fact that it is validated that the concentration of high NH_3 brings about operational complexity in digesters, it is additionally conveyed that microbes can adjust to higher free alkali concentration with time. That is the reason why it is hard to predict the exact NH_3 concentration, in which system failure or any uncertainty may occur [27], [40].

3.5 Carbon-nitrogen (C: N) ratio

The carbon to nitrogen (C/N) percentage of biological constituents offers necessary supplements for microorganisms that affect the entire anaerobic co-digestion process [41]. High ammonia concentrations will be accumulated when the C/N proportion is smaller and large amounts of VFAs will be produced if the C/N ratio is greater [42]. Therefore, maintaining the right C/N ratio during biogas generation is a challenge. The optimum C: N at which maximum fermentation occurs is between 20:1 and 30:1.

3.6 Water Content

Water content must be around 90% of the mass of the total substance. Too much water content can restrict the optimum utilization of digester, hereby reduce the production rate per unit volume in the pit. In case water content becomes too low, acetic acid will increase, repressing the assimilation procedure and subsequently, less generation of biogas and thick foam will be developed on the surface. The water content fluctuates according to the crude material used for digestion.

4. CHALLENGES IN MONO ANAEROBIC DIGESTION (AD)

Research and application on AD has been extensively increased over the last few decades [43]-[45], because of its numerous benefits, particularly its feasibility to treat any sort of biodegradable waste, such as FW or municipal waste, for the necessity of sustainable and renewable energy production, as well as waste management that are not quite the same as landfilling [46]. Mono fermentation of FW poses critical difficulties in terms of both biological and technical process in the interior anaerobic digestion. For the AD process, FW can be a favorable substrate, owing to its energy-rich content, abundant quantity as well as ample availability [47]. FW also has high biodegradability and rapid hydrolysis [48].

Conversely, most of FW provides the acidic condition, which will later destroy the reactor alkalinity that has negative impacts to adopt AD as well as restricting the methanogenic bacterial activity [49]. Some challenges to face, such as accumulation of volatile fatty acids (VFAs) and instability of the process, inhibitory levels of ammonia and hydrogen sulfide, nutrient deficiency or cause digester foaming [50]-[52] resulted in reduced permanence of the digester, in addition to low biogas yield. Therefore, co-digestion with another substrate like SS is recommended to provide the alkalinity and trace elements required for the AD system.

5. CO-DIGESTION WITH SEWAGE SLUDGE

Anaerobic co-digestion (AcoD) is the digestion of two or more substrates together, which have complementary characteristics between each other to improve the fermentation efficiency and enhance biogas production. The combination between co-substrates led to positive impacts to AD system, such as balance (C/N ratio, pH and moisture), dilutions of potentially toxic compounds and supplement of trace elements [52]. Thus, studies on AcoD has the potential efficiency to solve the limitations occur during mono AD.

AD was frequently utilized for FW management during the most recent decades because of unsuitable constituents, (for example, more sodium (Na+) content) and amazingly high biodegradability [53]. Amongst diverse waste sources, the rate of municipal solid waste (MSW) generation is expanded consistently (2–3%), due to gradual populace growth and their rising expectations for everyday comforts [54]-[56]. The FW is a noteworthy part of MSW that differs from 20- 50% in various nations, which signify to the crude/cooked food materials before/after food preparation in domestic level, also from production/manufacturing and nourishment provision sector [57]. The greatest challenge for MSW is its strong dampness content and promptly decomposable nature of FW [58], [59]. FW chiefly made of starch (10.7-13.7%), protein (2.4-3.6%), lipids (1.4-6.5%), nutrients and minerals with 16.7-30.9% of total solids and 15.3-26.4% unstable solids [60], [61]. The breakdown of the lipid portion improves the CH_4 production likely 0.7-1.01 g L-1 VS, yet it needed longer fermentation time (50-65 days), owing to their structural intricacy [53],[62], while proteins and starch processing requires relatively lower maintenance time of around 15-25 days. However, the CH_4 generation rate testified as 0.42-0.50 gL-1 VS also established a 50% lower amount that of the lipid assimilation. The AcoD of salad rich FW and SS will increase potassium (K^+), thereby restrain the AD procedure. The AcoD of protein-rich with FW will contribute to the alkaline capacity, and sugar-rich FW can adjust the C/N proportion of the reactor, which could limit the risk of NH_3 inhibition [61]. Additionally, it was found that higher level of FW than SS can maintain a strategic distance from the ammonia restriction, as a result of the accessibility of more carbon in the fermenter [53].

Because of excessive alkalinity and micronutrient content, SS becomes a broadly studied co-substrate with FW [63]. Other than that, SS was also reported having a large number of active microbes, which had an advantage during the AD process for the development of different groups of microorganisms [64]. Usually, FW is manifested with more C/N proportion (11.1 - 36.4), whereas the SS is exposed with less C/N ratio (6-9), that can be increased up to 6-15 by subsequent mixing [53]. Biogas produced by the addition of FW in SS fermenter enhanced the C/N ratio in addition to kinetic reaction consequently marks AcoD tasks financially achievable and realistic [62], [65], [66].

The ideal C/N percentage around 20-30 is appropriate for digester operation and C/N proportion ≥30 inverted the digester, because of nutrients inadequacy, which influences microbial action and shows the insufficient substrate evacuation rate. Nevertheless, if the C/N proportion ≤ 6, it adversely influences the procedure, which consequently produces moderate carbon level in addition to excessive ammonia concentration that represses the development of hydrogenotrophic methanogenic bacteria [53], [62], [67], [68]. Rattanapan *et al* [69] have observed the ideal C/N ratio of 29.72 for the highest production of biogas through co-digestion of canteen FW and household wastewater at mesophilic temperature. For beneficial AcoD, the steady supplement supply, upgraded C/N proportion and operation buffering efficiency can bolster the steady digester performance.

The mixing ratio between FW and SS vary across the literature. An examination indicates the highest of 215 mLCH_4 g-1 VS following the FW and SS amount of 1:4, which is 85.3% higher CH_4 yield contrasted to single fermentation of FW only [70]. It was likewise reported that 1:1 blending ratio (v/v) of the organic fraction (chiefly FW) of municipal solid waste (OFMSW) and SS enhanced the methane generation up to 47.2% (365 mLCH_4 g-1 VS), mostly because of upgraded C/N proportion [71]. In spite of the substrate ratio, supplementation of trace elements legitimately or through leachate origin were additionally found catalytic for improved procedure efficiency. A few investigations exhibited that addition of iron enhances the procedure soundness and methane production rate up to 18-39% both in mono-and co-digestion of FW [72]-[74]. Furthermore, the co-digestion effectiveness was developed by subtraction of Fe, Co, Mo, and Ni through an amalgamation of suitable dump leachate in FW processing [75]. It was appreciated that the addition of the above components help to attain stable AcoD process by enhancing enzymatic action [73]-[75], [76], [77]. Liu et al. [78] have reported that optimum mixing ratio of FW: SS at 85:15 (%) presented to achieve methane production of 353.5 ml/ g- volatile solids (VS) at the mesophilic condition. While research by Wang et al. [79] indicated that mixing ratio of FW: SS was 1:3 (w/w, VS) under mesophilic environment enhanced high biogas generation of 435.5 ml/g-VS. Other than that, enhancement in organic loading rate (OLR) or reduction in hydraulic retention time (HRT) of a mixture between FW and SS were more deleterious to methanogenesis than hydrolysis/acidogenesis, which led to the decreased methane production and reducing the effectiveness of VS.

Over the last few years, co-digestion of domestic waste and SS has been applied extensively and several studies have shown enhanced methane (CH_4) generation and watering down toxic substances [80]-[83]. The constraints that affect the sum of these amenities are of equally significant when it appears to develop the co-digestion efficiency. Generation of methane yields has been augmented through the addition of SS to the food waste illustrated by various literatures [81], [83], [84]. One of the major concern in this research is SS might contain a high concentration of light and heavy metals that may inhibit the AcoD process.

Previous investigations reported that the process of AD exhibited better viability with a co-digestion strategy in lieu of mono digestion method, particularly for FW and SS. Notwithstanding, there are still debates about the best favorable ratio for the highest process performance, various studies revealed various ratio as ideal for AcoD. For that reason, to figure out the ideal feed ratio, more research is necessary and recommended to characterize either absolute solids substance or C/N ratio of the feed is the greatest standards for proportion assurance, which must be examined for every particular situation.

6. Current issues related to biogas production

6.1 The gap between biotech research and commercialization

Conversion of the massive lignocellulose to biogas has cabalistic efficiency, and research endeavors toward its ulterior advancement have as of now been done. These procedures ordinarily have methodological difficulties that originate from a low comprehension of ideal fermenter operation. Enhancement of AD is mainly influenced by the multifaceted nature of AD and the likelihood that is associated with an investment in novel technologies [85].

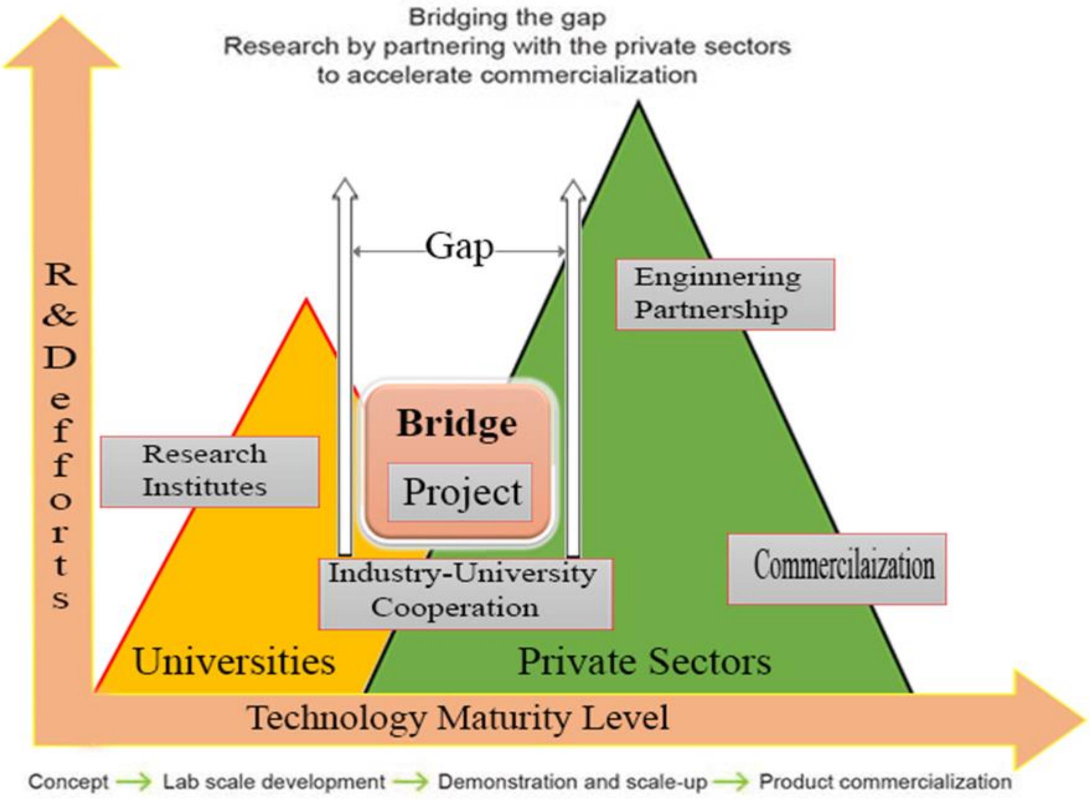

Fig.1. A schematic diagram showing the gap between bioindustry and research [85].

The R&D division related to this area focusing on the development of AD innovation so as to simplify the usage of purified methane among the transportation industry. The way to distinguish the life science industry and exploration gap (Fig. 1) relies on considering the science, innovation as well as assessing the effects of essential technical, beneficial, and biological boundaries. Welfares and expenditures need to be dissected. For instance, in order to reduce cost, identification of significant technological steps is necessary (for example the expense of numerous stages of AD application or the utilization of enzymes) that have the best impact on the total finance. The investigation of such advances will give basic data for assessing research precedency for improvement [86].

Classification and measurement of microorganisms in addition to enzymes, which are chosen for the breakdown of natural waste, influence the transformation rates and stability of the process. If the production expense is high, the cost of biogas production will also expand. Production of biocatalyst with an extensive scope of utilization and better action during enzymatic disintegration are the targets of companies. In this way, on-going research activities emphasis on the advancement of microbes or potentially biocatalysts with broad application, better features, in addition to minimum production cost [87], [88]. AD technology likewise demands utilities, for example, electricity and heat. Optimum utilization of these utilities is considered as a technical issue that can be enhanced in industrial scale, which later can move process productivity.

Table 4: Current issues and prospective R&D efforts to address the main research gaps.

Issues	**Focus of R&D efforts**
Use of enzymes, bacteria, or catalyst	• Large area of applications • High production cost
Utility requirements	• Consumption of electrical power • Excess O_2 and H_2 • High pressure and heat
Technology	• Pre-treatment • Multi-stage technology • Advanced techniques (high pressure) • Microscale technology
Fuel properties	• Enriched-methane biogas • Less H_2S

Furthermore, digestion of lignocellulosic squander to biogas in combination with fertilizer can promote market antagonism through by-product (i.e., digestate) incomes. Current research aims at fitting together processing technologies, for example, various steps or else high-pressure advances [87]. The biogas generation incorporates technical as well as financial factors, for example, microbial species, pre-treatment and purifying technology, properties of the substrate, and ideal digester environments. For economically- feasible biogas production, optimization of these determinants with a proper combination is the fundamental factor. Research can assume a reactant job to fill up the gap among engineering and science/biotechnology (Table 4) to give imaginative and sustainable technological options for the biogas area [89], [90].

6.2. The future of biogas in a sustainable economy

The economy of biogas is identified with variables, for example, waste accessibility and coordination, process productivity, and properties of the end product. AD process has been illustrated and has strong business accessibility. Because of minimum cost and immense availability, biowaste can be served as biogas production. Certification of biofuel (i.e., biomethane) in the green economy is regarded as another essential issue for trade and use according to renewable fuel criterion. Business collaborator has anticipated that consolidation of government project owing to research funds and also personal industrial ventures could speed up the initiation of these powers to the market at a reasonable expense. Nevertheless, biogas based motors are not yet sufficiently grown to cope with the technological points of biogas application; along these lines, the need to adjust engine for biogas burning have to be considered [88].

When the cost of fossil fuel is decreased, biogas plays a crucial role among European bio-based economy since it gives vital points of view to worldwide producers. The EU's Renewable Energy Order requires a 10% expansion in the utilization of green vehicle fills by 2020. European strategy is intending to build up ecological maintainability criteria for biofuel, and European nations are urged to put resources into biogas establishments.

In accordance with a lately printed EBA Biogas Report, there are more than 15 000 biogas plants in Europe [85] already, and this figure is proceeding to develop. Table 5 [85] demonstrates the number of biogas plants in the major European biogas-generating nations.

Table 5: Biogas plants in the top five biogas producers in Europe [92].

Country	Number of biogas plants
Germany	8000
Italy	1491
UK	813
France	736
Switzerland	633

In the most recent decade, the biogas division developed inside Europe, compelled by various parameters, for example, the feed-in tariffs in Germany, the liability registration for energy sustainability in the UK, and the expense arrangement (i.e. economy exclusions) in Sweden [90]. A large portion of the electric power in Germany originates from biogas because governmental activities help energy production from wastes. At present, nearly all biogas generation is dependent on SS; yet, it is anticipated that by 2030, a rising sum of biogas (around 224 TW•h) will be formed from damp manure, landfill, undigested SS, and food processing residue [91].

7. CONCLUSION

Interests in AD are required to prevail because of the minimal effort of accessible feedstocks and the wide range of biogas applications (i.e., for heating, power grid, and fuel). Numerous lignocellulosic sources, such as excrement, organic product, and vegetable squanders can be utilized for biogas formation, and AD can be connected on a little or substantial scale. This adaptability permits the production of biogas anywhere on the planet. Current research activities meant to improve AD control and in this way its proficiency. Microbial action during AD is a significant parameter for procedure steadiness and biogas yield and along these lines, further investigation is required. Biogas generation is developing in the European energy market; in a couple of decades, it will offer an efficient option for the generation of bioenergy.

Most of the mono anaerobic digestion of food waste as a substrate is facing a problem in the accumulation of VFAs (high acidity) and ammonia inhibition. Anaerobic co-digestion may solve the problems by offering stability and compliments of trace elements that lack in mono anaerobic digestion of food waste. Sewage sludge had high alkalinity that can complement the anaerobic digestion process with the food waste. The findings among researchers also vary, depending on the characteristics of food waste and sewage sludge itself. Therefore, more research can be done across these topics to improve biogas production. Besides that, the anaerobic co-digestion process will be an environmentally-friendly process to recycle wastes as well as energy production.

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REFERENCES

[1] Latinwo, G, & Agarry, SE. (2015) Modelling the kinetics of biogas production from mesophilic anaerobic co-digestion of cow dung with plantain peels. Int. Journal of Renewable Energy Development (IJRED), 4(1), 55–63.

[2] Yusuf, MOL, Debora, A, & Ogheneruona, DE. (2011) Ambient temperature kinetic assessment of biogas production from co-digestion of horse and cow dung. Res. Agr. Eng, 57(3), 97–104.

[3] Carley, J, Pasternack, G, Wyrick JR, Barker JR, Bratovich PM, Massa DA, Reedy GD, Johnson TR (2012) Significant decadal channel change 58–67 years post-dam accounting for uncertainty in topographic change detection between contour maps and point cloud models. Geomorphology, 179, 71–88.

[4] Matheri, A, Ntuli, F, Belaid, M, & Seodigeng, T. (2016) Modified gompertz model of biogas production from co-digestion of sewage sludge and food waste. In Proceedings

of IAENG transactions nn engineering sciences: special issue for the international association of engineers conferences.

[5] Prabhu, MS, & Mutnuri, S. (2016) Anaerobic co-digestion of sewage sludge and food waste. Waste Management & Research, 34(4), 307–315.

[6] Adeoti, O, Ilori, MO, Oyebisi, TO, & Adekoya, LO. (2000) Engineering design and economic evaluation of a family-sized biogas project in Nigeria. Technovation, 20(2), 103-108..

[7]. Hagos, K, Zong, J, Li, D, Liu, C, & Lu, X. (2017) Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives. Renewable and Sustainable Energy Reviews, 76, 1485–1496.

[8] Teklehaimanot, T. (2018) Biogas Generation and Main Factors Affecting in the Production of Biogas. International Journal of Advsnced Technology and Innovative Research, 10(01), 0022–0025.

[9]. Babel, S, Sae-Tang, J, & Pecharaply, A. (2009) Anaerobic co-digestion of sewage and brewery sludge for biogas production and land application. International Journal of Environmental Science and Technology, 6(1), 131-140.

[10] Chanakya HN, Ramachandra TV, Vijayachamundeeswari M. (2006) Anaerobic digestion and reuse of digested products of selected components of urban solid waste. Center for Ecological Sciences & Centre for Sustainable Technologies.

[11] Nayono, S. (2010) Anaerobic digestion of organic solid waste for energy production (Vol. 46). KIT scientific Publishing.

[12] Abbasi, T, Tauseef, SM, & Abbasi, SA. (2012) Anaerobic digestion for global warming control and energy generation - An overview. Renewable and Sustainable Energy Reviews, 16(5), 3228-3242.

[13] Batstone, DJ, Keller, J, Angelidaki, I, Kalyuzhnyi, SV, Pavlostathis, SG, Rozzi, A, … Vavilin, VA. (2002) The IWA anaerobic digestion model no 1 (ADM1). Water Science and Technology, 45(10), 65-73.

[14] Dohányos, M, Zabranska, J, Kutil, J, & JeniEek, P. (2004) Improvement of anaerobic digestion of sludge. Water Science and Technology, 49(10), 89–96.

[15] Mottet, A, François, E, Latrille, E, Steyer, J, Déléris, PS, Vedrenne, F, & Carrère, H. (2010) Estimating anaerobic biodegradability indicators for waste activated sludge. Chemical Engineering Journal, 160(2), 488–496.

[16] Henze, M, & Comeau, Y. (2008) Wastewater characterization. Biological wastewater treatment: Principles modelling and design. 33-52.

[17] Song, H., Clarke, W. P., & Blackall, L. L. (2005) Concurrent microscopic observations and activity measurements of cellulose hydrolyzing and methanogenic populations during the batch anaerobic digestion of crystalline cellulose. Biotechnology and Bioengineering, 91(3), 369–378.

[18] Shah, FA, Mahmood, Q, Shah, MM, Pervez, A, & Asad, SA. (2014) Microbial ecology of anaerobic digesters: The key players of anaerobiosis. The Scientific World Journal, 2014.

[19] Parawira, W, Read, J, Mattiasson, B, & Björnsson, L. (2008) Energy production from agricultural residues: high methane yields in pilot-scale two-stage anaerobic digestion. Biomass and Bioenergy, 32(1), 44–50.

[20] Conrad, R. (1999) Contribution of hydrogen to methane production and control of hydrogen concentrations in methanogenic soils and sediments. FEMS Microbiology Ecology, 28(3), 193–202.

[21] Lozano, CJ, Mendoza, MV, de Arango, MC, Monroy, EF. (2009) Microbiological characterization and specific methanogenic activity of anaerobe sludges used in urban solid waste treatment. Waste management, 29(2), 704-711.

[22] Rev, BS. (1997) Energetics of syntrophic cooperation in methanogenic degradation. Microbiol. Mol. Biol. Rev, 61(2), 262-280.

[23] Canas, EMZ. (2010) Technical Feasibility of Anaerobic Co-digestion of Dairy Manure with Chicken Litter and Other Wastes (Doctoral dissertation, University of Tennessee, Knoxville).

[24] de Bok, FAM. (2005) The first true obligately syntrophic propionate-oxidizing bacterium, Pelotomaculum schinkii sp. nov., co-cultured with Methanospirillum hungatei, and emended description of the genus Pelotomaculum. International Journal of Systematic and Evolutionary Microbiology, 55(4), 1697–1703.

[25] Griffin, ME, McMahon, KD, Mackie, RI, & Raskin, L. (1998) Methanogenic population dynamics during start-up of anaerobic digesters treating municipal solid waste and biosolids. Biotechnology and Bioengineering, 57(3), 342–355.

[26] Karakashev, D, Batstone, D, & Angelidaki, I. (2005) Influence of environmental conditions on methanogenic compositions in anaerobic biogas reactors. Applied and Environmental Microbiology, 71(1), 331–338.

[27] Vintila, T, Dragomirescu, M, Croitoriu, V, Vintila, C, BARBU, H, & Sand, C. (2010) Saccharification of lignocellulose-with reference to Miscanthus-using different cellulases. Romanian Biotechnological Letters, 15(4), 5498–5504.

[28] Forster-Carneiro, T, Pérez, M., & Romero, L. (2008) Influence of total solid and inoculum contents on performance of anaerobic reactors treating food waste. Bioresource Technology, 99(15), 6994-7002.

[29] Kim, H, Nam, J, & Shin, H. (2011) A comparison study on the high-rate co-digestion of sewage sludge and food waste using a temperature-phased anaerobic sequencing batch reactor system. Bioresource Technology, 102(15), 7272-7279.

[30] El-Mashad, H, Zeeman, G, Loon, W. Van, Bot, GP, & Lettinga, G. (2004) Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure. Bioresource Technology, 95(2), 191–201.

[31] Campos Pozuelo, E, Palatsi Civit, J, & Flotats Ripoll, X. (1999) Codigestion of pig slurry and organic wastes from food industry. In n Proceedings of the II International symposium on anaerobic digestion of solid waste, 192–195.

[32] Li, C, Champagne, P, & Anderson, BC. (2013) Biogas production performance of mesophilic and thermophilic anaerobic co-digestion with fat, oil, and grease in semi-continuous flow digesters: effects of temperature, hydraulic retention time, and organic loading rate. Environmental Technology, 34(13–14), 2125–2133.

[33] Bolzonella, D, Pavan, P, Battistoni, P, & Cecchi, F. (2005) Mesophilic anaerobic digestion of waste activated sludge: influence of the solid retention time in the wastewater treatment process. Process Biochemistry, 40(3–4), 1453–1460.

[34] Dareioti, M., & Kornaros, M. (2015) Anaerobic mesophilic co-digestion of ensiled sorghum, cheese whey and liquid cow manure in a two-stage CSTR system: effect of hydraulic retention time. Bioresource Technology, 175, 553-562.

[35] Babaee, A, & Shayegan, J. (2011) Effect of Organic Loading Rates (OLR) on Production of Methane from Anaerobic Digestion of Vegetables Waste. In Proceedings of the World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden.

[36] Rincón, B, Borja, R, González, JM, Portillo, MC, Sáiz-Jiménez, C. (2008) Influence of organic loading rate and hydraulic retention time on the performance, stability and microbial communities of one-stage anaerobic digestion of two-phase. Biochemical engineering journal, 40(2), 253-261.

[37] Sunny, S, & Joseph, K. (2018) Review on factors affecting biogas production. International Journal For Technological Research In Engineering, 5(9), 2347–4718.

[38] Neshat, S, Mohammadi, M, Najafpour, G, & Lahijani, P. (2017) Anaerobic co-digestion of animal manures and lignocellulosic residues as a potent approach for sustainable biogas production. Renewable and Sustainable Energy Reviews, 79, 308–322.

[39] Lemmer, A., Merkle, W., Baer, K., & Graf, F. (2017) Effects of high-pressure anaerobic digestion up to 30 bar on pH-value, production kinetics and specific methane yield. Energy, 138, 659–667.

[40] Banks, C., Chesshire, M., Heaven, S., & Arnold, R. (2011) Anaerobic digestion of source-segregated domestic food waste: performance assessment by mass and energy balance. Bioresource Technology, 102(2), 612–620.

[41] Reilly, M, Dinsdale, R, & Guwy, A. (2016) The impact of inocula carryover and inoculum dilution on the methane yields in batch methane potential tests. Bioresource Technology, 208, 134–139.

[42] Siddique, M, Production, & Wahid, Z. (2018) Achievements and perspectives of anaerobic co-digestion: A review. Journal of Cleaner, 194, 359–371.

[43] Pham, T, Kaushik, R, Parshetti, G, & Mahmood, R. (2015) Food waste-to-energy conversion technologies: current status and future directions. Waste Management, 38, 399–408.

[44] Zhang, R, El-Mashad, HM, Hartman, K, Wang, F, Liu, G, Choate, C, Gamble, P. (2007) Characterization of food waste as feedstock for anaerobic digestion. Bioresource technology, 98(4), 929-935.

[45] Garcıa, A, Esteban, M, Marquez, M, & Ramos, P. (2005) Biodegradable municipal solid waste: Characterization and potential use as animal feedstuffs. Waste Management, 25, 780–787.

[46] Chiu SL, Lo IM, Woon KS, Yan DY. (2016) Life cycle assessment of waste treatment strategy for sewage sludge and food waste in Macau: perspectives on environmental and energy production performance. The International Journal of Life Cycle Assessment, 21(2), 176–189.

[47] Paritosh, K, Kushwaha, S, Yadav, M, Pareek, N, Chawade, A, & Vivekanand, V. (2017) Food waste to energy: an overview of sustainable approaches for food waste management and nutrient recycling. BioMed Research International, 2017.

[48] Ren, Y, Yu, M, Wu, C., Wang, Q, Gao, M, Huang, Q, & Liu, Y. (2018) A comprehensive review on food waste anaerobic digestion: Research updates and tendencies. Bioresource Technology, 247, 1069–1076.

[49] Xu, F, Li, Y, Ge, X, Yang, L, & Li, Y. (2018) Anaerobic digestion of food waste– Challenges and opportunities. Bioresource Technology, 247, 1047–1058.

[50] Grimberg, S, Hilderbrandt, D., Kinnunen, M, & Rogers, S. (2015) Anaerobic digestion of food waste through the operation of a mesophilic two-phase pilot scale digester– assessment of variable loadings on system performance. Bioresource Technology, 178, 226–229.

[51] Subramanian, B, & Pagilla, K. (2015) Mechanisms of foam formation in anaerobic digesters. Colloids and Surfaces B: Biointerfaces, 126, 621–630.

[52] Xu, F, Li, Y, Wicks, M., Li, Y, & Keener, H. (2018) Anaerobic Digestion of Food Waste for Bioenergy Production. Adv Food Process Technol: AFPT, 112(10), 1–8.

[53] Awe, OW, Zhao, Y, Nzihou, A, Pham Minh, D, & Lyczko, N. (2018) Anaerobic co-digestion of food waste and FOG with sewage sludge – realising its potential in IrelandA critical review on anaerobic co-digestion achievements between 2010 and 2013. Renew. International Journal of Environmental Studies, 75(3), 496–517.

[54] Ariunbaatar, J, Panico, A, Esposito, G, & Pirozzi, F. (2014) Pretreatment methods to enhance anaerobic digestion of organic solid waste. Applied Energy, 123, 143–156.

[55] Karthikeyan, O, Trably, E, Mehariya, S, & Bernet, N. (2018) Pretreatment of food waste for methane and hydrogen recovery: A review. Bioresource Technology, 249, 1025–1039.

[56] Valero, D, Montes, J, Rico, J, & Rico, C. (2016) Influence of headspace pressure on methane production in Biochemical Methane Potential (BMP) tests. Waste Management, 48, 193–198.

[57] Lee, D, Bae, J, Kang, J, & Kim, K. (2016) Potential methane yield of food waste/food waste leachate from the biogasification facilities in South Korea. Journal of Material Cycles and Waste Management, 18(3), 445–454.

[58] Girotto, F, Alibardi, L, & Cossu, R. (2015) Food waste generation and industrial uses: a review. Waste Management, 45, 32–41.

[59] Xie, S, Wickham, R, & Nghiem, L. (2017) Synergistic effect from anaerobic co-digestion of sewage sludge and organic wastes. International Biodeterioration & Biodegradation, 116, 191–197.

[60] Xu, S, Selvam, A, & Wong, J. (2014) Optimization of micro-aeration intensity in acidogenic reactor of a two-phase anaerobic digester treating food waste. Waste Management, 34, 363–369.

[61] Chiu, SL, & Lo, IM. (2016) Reviewing the anaerobic digestion and co-digestion process of food waste from the perspectives on biogas production performance and environmental impacts. Environmental Science and Pollution Research, 23(24), 24435-24450.

[62] Koch, K, Helmreich, B, & Drewes, J. (2015) Co-digestion of food waste in municipal wastewater treatment plants: effect of different mixtures on methane yield and hydrolysis rate constant. Applied Energy, 137, 250–255.

[63] Kim, HW, Shin, HS, Han, SK, & Oh, SE. (2007) Response Surface Optimization of Substrates for Thermophilic Anaerobic Codigestion of Sewage Sludge and Food Waste. Journal of the Air & Waste Management Association, 57(3), 309–318.

[64] Razaviarani, V, Buchanan, I, Malik, S, & Katalambula, H. (2013) Pilot-scale anaerobic co-digestion of municipal wastewater sludge with restaurant grease trap waste. Ournal of Environmental Management, 123(26–33).

[65] Mata-Alvarez, J, Dosta, J, & Romero-Güiza, M. (2014) A critical review on anaerobic co-digestion achievements between 2010 and 2013. Renewable and Sustainable Energy Reviews, 36, 412–427.

[66] Ng, BJH, Mao, Y, Chen, CL, Rajagopal, R, & Wang, JY. (2017) Municipal food waste management in Singapore: practices, challenges and recommendations. Journal of Material Cycles and Waste Management, 19(1), 560–569.

[67] Fotidis, IA, Wang, H, Fiedel, NR, Luo, G, Karakashev, DB, & Angelidaki, I. (2014) Bioaugmentation as a Solution To Increase Methane Production from an Ammonia-Rich Substrate. Environmental Science & Technology, 48(13), 7669–7676.

[68] Wang, H, Fotidis, I, & Angelidaki, I. (2015) Ammonia effect on hydrogenotrophic methanogens and syntrophic acetate-oxidizing bacteria. FEMS Microbiology Ecology, 91(11)

[69] Rattanapan, C, Sinchai, L, Tachapattaworakul Suksaroj, T. Kantachote, D, & Ounsaneha, W. (2019) Biogas Production by Co-Digestion of Canteen Food Waste and Domestic Wastewater under Organic Loading Rate and Temperature Optimization. Environments, 6(2), 16.

[70] Kim, HW., Han, SK, & Shin, HS. (2003) The optimisation of food waste addition as a co-substrate in anaerobic digestion of sewage sludge. Waste Management & Research, 21(6), 515–526.

[71] Cabbai, V, Ballico, M, Aneggi, E, & Goi, D. (2013) BMP tests of source selected OFMSW to evaluate anaerobic codigestion with sewage sludge. Waste Management, 33, 1626–1632.

[72] Ariunbaatar, Javkhlan, Esposito, G, Yeh, DH, & Lens, PNL. (2016a) Enhanced Anaerobic Digestion of Food Waste by Supplementing Trace Elements: Role of Selenium (VI) and Iron (II). Frontiers in Environmental Science, 4(8).

[73] Zhang, W, Wu, S, Guo, J, Zhou, J, & Dong, R. (2015) Performance and kinetic evaluation of semi-continuously fed anaerobic digesters treating food waste: role of trace elements. Bioresource Technology, 178, 297–305.

[74] Cheong, D, & Hansen, C. (2007) Feasibility of hydrogen production in thermophilic mixed fermentation by natural anaerobes. Bioresource Technology, 98, 2229–2239.

[75] Zhang, W, Zhang, L., & Li, A. (2015) Enhanced anaerobic digestion of food waste by trace metal elements supplementation and reduced metals dosage by green chelating agent -EDDS via. Water Research, 84, 266–277.

[76] Ariunbaatar, Javkhlan, Esposito, G, Yeh, DH, & Lens, PNL. (2016b) Enhanced Anaerobic Digestion of Food Waste by Supplementing Trace Elements: Role of Selenium (VI) and Iron (II). Frontiers in Environmental Science, 4, 8.

[77] Zhang, L, & Jahng, D. (2012) Long-term anaerobic digestion of food waste stabilized by trace elements. Waste Management, 32, 1509–1515.

[78] Liu, X, Li, R, Ji, M, & Han, TL. (2013) Hydrogen and methane production by co-digestion of waste activated sludge and food waste in the two-stage fermentation process: substrate conversion and energy. Bioresource Technology, 146, 317–323.

[79] Wang, T, Yang, P, Zhang, X, Zhou, Q, Yang, Q, Xu, B., … Zhou, T. (2018) Effects of Mixing Ratio on Dewaterability of Digestate of Mesophilic Anaerobic Co-Digestion of Food Waste and Sludge. Waste and Biomass Valorization, 9(1), 87–93.

[80] Appels, L, Lauwers, J, Degrève, J, Helsen, L, & Dewil, R. (2011) Anaerobic digestion in global bio-energy production: potential and research challenges. Renewable and Sustainable Energy ReviewsSustainable Energy, 15(9), 4295–4301.

[81] Edelmann, W, Engeli, H, & Gradenecker, M. (2000) Co-digestion of organic solid waste and sludge from sewage treatment. Water Science and Technology, 41(3), 213–221.

[82] Heo, N, Park, S, Lee, J, & Kang, H. (2003) Solubilization of waste activated sludge by alkaline pretreatment and biochemical methane potential (BMP) tests for anaerobic co-digestion of municipal organic waste. Water Science and Technology, 48(8), 211-219.

[83] Sosnowski, P, Wieczorek, A, & Ledakowicz, S. (2003) Anaerobic co-digestion of sewage sludge and organic fraction of municipal solid wastes. Advances in Environmental Research, 7(3), 609–616.

[84] Lemmer, A, Merkle, W, Baer, K., & Graf, F. (2017) Effects of high-pressure anaerobic digestion up to 30 bar on pH-value, production kinetics and specific methane yield. Energy, 138, 659–667.

[85] Achinas, S, Achinas, V, & Euverink, GJW. (2017) A Technological Overview of Biogas Production from Biowaste. Engineering, 3(3), 299–307.

[86] Lynd, L, Zyl, W, Van, McBride, J, & Laser, M. (2005) Consolidated bioprocessing of cellulosic biomass: an update. Current Opinion in Biotechnology, 16(5), 577–583.

[87] Schwietzke, S, Ladisch, M, Russo, L, Kwant, K, Mäkinen, T, Kavalov, B, Maniatis, K, Zwart, R, Shahanan, G, Sipila, K, Grabowski, P.. (2008) Analysis and identification of gaps in the research for the production of second-generation liquid transportation biofuels (No. ECN-O--08-022). Energy research Centre of the Netherlands ECN.

[88] Weber, C, Farwick, A, Benisch, F, Brat, D., Dietz, H, Subtil, T, & Boles, E. (2010) Trends and challenges in the microbial production of lignocellulosic bioalcohol fuels. Applied Microbiology and Biotechnology, 87(4), 1303–1315.

[87] Achinas, S, Achinas, V, & Euverink, GJW. (2017) A Technological Overview of Biogas Production from Biowaste. Engineering, 3(3), 299–307.

[89] Banerjee, S, Mudliar, S, Sen, R, Giri, B, Satpute, D, Chakrabarti, T, & Pandey, RA. (2010) Commercializing lignocellulosic bioethanol: technology bottlenecks and possible remedies. Biofuels, Bioproducts and Biorefining, 4(1), 77–93.

[90] Blanch, HW. (2012) Bioprocessing for biofuels. Current Opinion in Biotechnology, 23(3), 390–395.

[91] Åhman, M. (2010) Biomethane in the transport sector—An appraisal of the forgotten option. Energy Policy, 38(1), 208–217.

[92] Wiesenthal, T, & Mourelatou, A. (2006) How much bioenergy can Europe produce without harming the environment? http://worldcat.org/isbn/929167849X.