



From Fossil Fuels to Renewable Biogas Production from Biomass Based Feedstock – A Review of Anaerobic Digester Systems

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Authors' contributions

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ABSTRACT

Three-quarters of the global energy consumption is expected to come from fossil fuels by 2040 despite many drawbacks to the world's reliance on fossil fuels. The primary drawback of fossil fuels is in procuring, transporting, refining, and combusting them which generates pollution byproducts, global warming, which in turn generate a plethora of associated problems. Biomass as a renewable resource and its conversion into renewable fuel products can offset use and drawback of fossil fuels. Anaerobic digestion is known since the 10th century BC has become today a versatile tool to produce renewable energy in form of biogas from many biomass-based feedstock sources. These sources can be agriculturally based such as livestock waste, energy crops, plant (lignocellulosic) based, forest residues, or industrial and municipal waste such food waste, wastewater treatment sludge, distiller grains and food product residues. Feed stocks can be used in anaerobic fermentation processes as single or co-digest feedstock. Each feedstock represents a challenge on its own for anaerobic digestion processes in order to achieve good operational stability and good biogas production.

Selecting a suitable anaerobic fermentation process from today's available technical sound processes described in this review is essential for future fossil fuel independence.

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1. INTRODUCTION

The world depends on energy sources for the production of electricity, heat, and fuel. Of the various energy sources, fossil fuels were used to produce 82% of the global total primary energy supply in 2014 [1]. Furthermore, the U.S. Energy Information Administration projected a 28% increase in world energy consumption between 2015 and 2040 and more than three-quarters of the global energy consumption in this projection was expected to come from fossil fuels [2]. Despite this projected increase, there are many drawbacks to the world's reliance on fossil fuels. The primary drawback of depending on fossil fuels is the processes of procuring, transporting, refining, and combusting them each generate pollution byproducts, which in turn generate a plethora of problems [3].

1.1 Fossil Fuel Combustion Problems

The burning of fossil fuels generates air and water pollutants including sulfur dioxide, nitrogen oxides, ammonia, particulate matter, carbon monoxide, volatile organic compounds, and ozone; the burning of fossil fuels also releases sequestered mercury into the environment [3,4,5,6,7,8]. Sulfur dioxide is primarily produced from burning coal [3]. Sulfur dioxide aggravates nasal congestion, asthma, pulmonary inflammation, and other respiratory ailments; the presence of sulfur dioxide in the atmosphere also contributes to acid rain and harmful particulate formation [3,6]. Particulate matter, also called soot, can generate haze and produce and exacerbate health conditions such as aggravated asthma, chronic bronchitis and is also associated with an elevated occurrence of premature death [3].

The nitrogen oxides generated from the combustion of any fossil fuel assist in the formation of smog and acid rain [3,8,9]. Exposure to smog can produce burns on lung tissue and increase susceptibility to bronchitis and asthma in addition to other chronic respiratory diseases [3,9]. Acid rain is generated when sulfur dioxide and nitrogen oxides combine with other atmospheric chemicals such as oxygen and water [3,9]. Acid rain increases the acidity of bodies of water, which can harm the aquatic organisms contained within them and the surrounding environment [3,9]. The nitrogen oxides and ammonia generated from fossil fuel combustion

are eventually washed into bodies of water, where they contribute to algal blooms and oxygen-deprived aquatic zones [8].

Coal contains mercury and other heavy metals, which can be released into the environment when the coal is burned [3,9,10]. The released mercury may then enter bodies of water and end up in food chains [3,11,10]. Mercury consumption has been connected neurological and neurobehavioral issues in infants [3,10]. The ash generated from coal combustion can also contain heavy metals; therefore, the ash must be disposed of carefully and the disposal process is generally expensive [3,10].

In addition to chemical pollutants, fossil fuel power plants may utilize water from nearby lakes and rivers for cooling, thereby generating thermal pollution [3,12]. More specifically, changes in ecological water temperature diminish the quality of ecological water [3]. If the water is returned to the ecosystem at a higher temperature, it will have lower dissolved oxygen content, which can put stress on the ecosystem [3]. Overall, the combustion of fossil fuels produces pollution that can lead to environmental and ultimately human health problems. This pollution and pollution-related problems provide motivation to investigate alternative sources of energy.

1.2 Fossil Fuel Global Warming Problems

In addition to the aforementioned pollutants produced from fossil fuel combustion, fossil fuel combustion also generates global warming emissions, which pose potentially irreversible consequences to the Earth's atmosphere [3]. The emission of greenhouse gases leads to global warming, which yields: ground level ozone formation, a rise in sea levels, more severe and frequent natural disasters including flooding, wildfires, drought, and storm surges, an increase in the number of heat-related deaths, an increase in air pollution, an increase in wildlife extinction rates, increased ocean acidity, and ultimately increased mortality and morbidity [3,13,14]. The combustion of coal, oil, and natural gas is the largest source of greenhouse gas emissions globally [15]. All fossil fuels generate carbon dioxide when burned [3]. In 2014 the Intergovernmental Panel on Climate Change (IPCC) determined that approximately 65% of global greenhouse emissions in 2010 came from

carbon dioxide generated using fossil fuels for industrial processes [15]. Furthermore, the IPCC also determined that another 6% of the global greenhouse gas emissions in 2010 came from nitrous oxide, part of which was produced from fossil fuel combustion [15]. Methane is another greenhouse gas that is more effective at trapping heat than carbon dioxide; methane can be released when drilling natural gas wells, oil wells and transporting natural gas via pipelines [3,5,6]. Therefore, the contribution of fossil fuel-related emissions to global warming stimulates the investigation and advancement of alternative fuels.

1.3 Fossil Fuel Extraction Problems

The extraction of solid fossil fuels from the earth yields problems and safety risks, including additional pollution and land degradation [3,6,7]. Solid fossil fuels such as coal are extracted from the ground through mining [3,7]. Surface mining techniques such as mountaintop removal and area strip mining can devastate landscapes; it can also increase the chances of mudslides, landslides, and flashfloods in the surrounding areas and communities [3,7]. Surface mining can also pollute drinking water sources with lead, iron, selenium, arsenic, manganese, hydrogen sulfide, and other toxic chemicals [3,7]. Underground coal mining can result in coal miner injuries and/or death. Coal miners may also develop chronic health disorders such as Black Lung disease (pneumoconiosis) [3]. Underground coal mines can collapse or subside, which can not only result in the injury or death of coal miner(s) but also impact the flow of water on the surface and subsurface [3]. Furthermore, abandoned mines can catch fire or contribute to acid mine drainage [3,7]. During acid mine drainage, water enters the mine and becomes highly acidic; the water may also extract and carry away dangerous heavy metals [3,6,7]. Finally, the mining of coal beds can release methane, which may be harmful to wildlife populations [3]. The hazards and problems associated with fossil fuel extraction are compelling reasons to investigate alternative energy sources.

The investigation into alternative energy sources is also driven by issues caused by the drilling and extraction of liquid and gaseous fossil fuels from the earth [3,16,17]. Extracting oil from shale via hydraulic fracturing or fracking requires a significant amount of water [16,18]. This water usage can prevent water from being used for

other purposes and has an impact on aquatic ecosystems [17,18]. Fracking also requires the use of potentially hazardous chemicals for oil extraction that may be spilled or leak if not handled properly [16,17]. Both fracking and drilling may use chemicals that can cause cancer, mutations, and/or damage to neurological, endocrine, immune and cardiovascular systems [3,15,16]. Drilling for oil and gas also releases water that can be polluted with heavy metals, hydrocarbons, naturally-occurring dissolved solids, and radioactive materials, making it unsafe for consumption and challenging to treat and dispose of safely [3,16,18]. The water that is released is often stored in open-air pits lined with impermeable liner, allowing the water to overflow in heavy rains [3,16]. The wastewater produced from oil and gas extraction in general may contain oil, grease, and/or heavy metals, the presence of which makes it hazardous to the environment and humans [3,16]. In addition to the dangers and risks associated with the drilling process, drilling locations can also yield increased risks. The remote location and intricate engineering associated with offshore oil and gas drilling make it more risky than onshore drilling. Thus, offshore drilling may yield fatalities, injuries, and oil spills [3]. Overall, fossil fuel extraction involves safety risks and can produce pollution that leads to environmental and health problems. These drawbacks of fossil fuel further promote the investigation and advancement of alternative fuels.

1.4 Fossil Fuel Transportation Problems

Transporting fossil fuels also generates problems and safety risks which spur the investigation into alternative energy sources [3,14,19]. Land is required for fossil fuel infrastructure including drilling wells, processing facilities, access roads, pipelines, and others; the land required to accomplish these steps for alternative fuels may be lower [3]. Coal is often transported using trains, trucks, and barges, all of which use diesel fuel [3]. The coal dust and diesel exhaust emitted from this transportation increases surrounding particulate matter concentrations [14,19]. In turn, these transportation exhausts are correlated with adverse birth outcomes, premature death, and cardiovascular and respiratory problems including increased risk of lung cancer, asthma attacks, and hospitalization due to heart and lung disease in the surrounding communities [3,14]. The diesel combustion alone produces nitrogen dioxide and soot, which can be very harmful to

human health [3]. Coal dust also typically contains arsenic, lead, mercury, cadmium, and crystalline silica, which are carcinogens and cause fetal defects and nervous system damage [14]. Coal dust contained in confined spaces can become suspended in air, making it an explosive hazard [14]. The high flammability of natural gas has also led to injuries and fatalities during its transmission and distribution through pipelines [3]. Natural gas leaks in pipelines contribute significantly to methane emissions [3]. The transportation of liquefied natural gas is an additional safety concern. Oil may also be spilled during transportation, which can lead to significant environmental problems [3,19]. The many problems and risks associated with the transportation of fossil fuels further motivate the investigation of less problematic and less risky alternative fuels.

1.5 Fossil Fuel Refinement Problems

Problems associated with the refining of fossil fuels also promote the exploration of alternative energy sources. Fossil fuels typically have to be refined before they are used and the impurities generated from the refining process are often disposed of as waste [3,19,20]. The impurities must be handled and disposed of properly, generating community and environmental challenges [3]. Oil refining involves the removal of sulfur, heavy metals, and nitrogen [21]. The heavy metals, sulfur, and other chemicals contained in coal are removed through crushing and washing, generating a highly toxic slurry [3, 20]. The slurry and ash generated from the coal cleaning and combustion processes are deposited in large reservoir impoundments, which must be properly lined and maintained to prevent the toxic waste from leaching into surrounding water supplies [3,20]. If these heavy metals manage to leach into drinking water, they can lead to reproductive disorders, neurological damage, learning disabilities, cancer, birth defects, and kidney disease [3]. Therefore, the many risks and dangers associated with the refining fossil fuels promote the investigation and advancement of alternative energy sources.

1.6 Fossil Fuels Are Non-renewable

In addition to the aforementioned issues, fossil fuels are also considered nonrenewable “because they do not form or replenish in a short period of time” [18]. Fossil fuels take millions of years to be regenerated via geological processes, but humans will deplete these

resources in hundreds to thousands of years, making fossil fuels unsustainable [6,22]. In fact, as the world fossil fuel consumption continues to increase, coal reserves are projected to be depleted by 2112 while the oil and gas are projected to be depleted by the end of 2042 according to the Klass and New models [23]. Problems and risks associated with the combustion, extraction, transportation, refining and non-renewability of fossil fuels including greenhouse gas emissions provide significant motivation for investigating and advancing alternative energy sources.

In contrast to fossil fuel sources biomass is a renewable energy resource because it regrows in a relative short time span by using Carbon Dioxide (CO₂) from the atmosphere and energy from the sun for growth called photosynthesis. After transformation into energy the captured carbon dioxide is released, and the carbon dioxide can be used again for new plant growth. biomass sources can be for example, agriculturally based feedstocks such as livestock waste, energy crops, plant (lignocellulosic) based, forest residues or industrial and municipal waste such food waste, wastewater treatment sludge, as distiller grains, food product residues.

2. BIOGAS FUEL PRODUCTION BY ANAEROBIC DIGESTION

Anaerobic Digestion (AD) technology and the production of biogas for bath water heating purpose may have been in practice in ancient Assyria in the 10th century BC, as well as in ancient China 2000 to 3000 years ago to dispose food waste [24], the history of biogas production began with the discovery of the swamp gas in 1776 by the Italian physicist Alessandro Volta [25]. In the mid nineteenth century biogas was used in India and New Zealand [26]. The first biogas plant on an industrial scale was built in Bombay in 1859 [25]. At end of the 19th century, it was discovered that wastewater can be treated using anaerobic digestion [25]. In the 1890s a digester was used in the United Kingdom to fuel streetlamps using sewage sludge as feedstock [26]. In Ruhr area in Germany wastewater treatment plants were built in Germany in the Ruhr area in 1906 and the produced biogas was mostly used to generate light [25]. By 1937, some German cities had switched their fleets to biogas. After the world War II biogas was produced in the 1950 from agricultural solid manure. The city of Zurich's garbage collection also operated with biogas until the 1973 oil crisis

[25]. In 1955 petroleum became very inexpensive and the use of mineral fertilizer increased extensively [25] which led to a shutdown of existing biogas plants. With the oil crisis in 1973 renewable energy became modern again and biogas produced from agricultural feedstock increased again.

Due to the subsequent low mineral oil prices, the expansion and continuation of biogas technology, in turn, are severely impaired. In the beginning 1990's the new electricity feed-in law was the main cause for a new upswing of AD technology. AD reached a total of 17,783 AD plants in the 28 European member states by the end of 2017 producing a total kg ton of oil equivalent (ktgoe) of 16,820. 540 of these plants are injecting upgraded biomethane with a CH₄ content above 96% into the gas grid. The largest number of AD plants are located in Germany, having 10,971 plants producing 7,845 ktgoe, followed by Italy with 1,655 plants producing 1,898 ktgoe and France with 742 plants producing 899 ktgoe. However, the UK produces 2,733 ktgoe with 613 but larger sized AD plants [27,28].

Today, biogas produced by AD has become and an alternative, carbon-neutral, renewable fuel that can be easily generated from local, low-cost organic materials [4,29,30,31,32].

AD systems today are operated at psychrophilic conditions under 20°C (68°F), mesophilic conditions above 20°C to 45°C (68°F to 113°F), and thermophilic conditions above 45°C to 55°C (113°F to 131°F) [25]. Higher AD operational temperatures result in heat losses of 20% to 30% for mesophilic conditions and 25% to 40% for thermophilic operations. However, heat exchangers can minimize the losses of up to 15% [25] but require larger more costlier systems.

Biogas can be used to generate heat or electricity or be used as a transportation fuel [4, 29, 31, 32]. It is competitive with other alternative energy in terms of efficiency and minimal environmental impact. Biogas is produced from anaerobic digestion [29] (AD), which is a biological process in which microorganisms naturally degrade organic material in the absence of free oxygen [30,33,34]. Some examples of common AD feedstocks are food waste, yard waste, animal manures, food waste, and wastewater solids [35]. Thus, another major benefit to utilizing AD is sustainable waste management [31,36,37]. Feedstock for most of

the European 17,783 AD plants consists of 71% agricultural biomass, followed by sewage with 16% and landfill gas with 8%, the remaining feedstock is 1% unknown and 4% other feedstock [28]. In comparison according to the Environmental Energy Study Institute (EESI) the 2,182 operating AD plants in 2017 in the U.S. produce biogas from 58% from sewage sludge, 30% from landfill gas, and 12% from agricultural biomass [38].

2.1 Background and Benefits of Anaerobic Digestion Technology

Businesses that produce or treat organic wastes such as those in the food and beverage, municipal waste management, wastewater treatment, and agricultural industries seek to capitalize on AD by treating their respective wastes in closed AD reactors [4,35]. AD technology is well-established and mature [33]. Anaerobic digestors may consume little to no energy. AD can work under psychrophilic conditions, requiring the influent not to be heated. AD reactor operation can be by gravity, requiring no additional energy for its operation. [39]. AD technology is advantageous over anaerobic processes due to less or no odor release due to enclosed and sealed AD reactor vessels. Aerobic processes use microorganisms that oxidize with oxygen contained in the air the biological content in the waste stream, whereas anaerobic processes are operated without air.

Fig. 1 shows the organic content (OC) conversion of aerobic and anaerobic processes. Aerobic processes require large amounts of energy. 1 kWh of energy is needed in addition for aeration in contrast to anaerobic processes [40] to convert 1 kg of organic content measured as Chemical Oxygen Demand (COD). During aerobic conversion 50% to 70% of the OC is oxidized to CO₂, whereas 30 to 50% of the OC is assimilated into another wasted call sludge [40, 41]. This requires further treatment such as flocculation, dewatering and or AD [40].

Anaerobic treatment requires less energy input produces about 5-10% sludge through assimilation. Up to 90% of the OC is converted into methane (CH₄) that can be used as fuel source to produce electricity and heat.

From a feasibility perspective, anaerobic digesters are simple and inexpensive to construct, easy to operate and easily scalable, allowing AD to be performed on decentralized biomass sources [31,39,43]. Digesters can be

relatively small if high organic loading rates are used [39]. Some digesters are designed for digesting a single type of feedstock (also called mono-digestion) while others are designed for digesting multiple feedstocks simultaneously (also called co-digestion) [35]. Co-digestion and pretreatment may increase digestion speed and biogas yield from low-yielding or difficult-to-digest feedstocks [21,35]. The biomass contained in anaerobic digesters can also sit for several months during shut down [31,39,43]. The continuous development of AD technologies will lead to increased biogas yield and improved AD efficiency [30].

AD is performed by a consortium of microorganisms within the anaerobic digester [30,33,34]. These microorganisms not only consume organic waste, but reduce odors and pathogens as well [4,30]. The microorganisms grow slowly, causing anaerobic digesters to produce relatively low amounts of sludge and the sludge that is produced is stabilized and has good dewatering characteristics [39]. The high microbial activity of the AD microorganisms present in anaerobic digesters can be preserved, allowing the microorganisms to be used as inoculum for other reactors [39]. The consortia of microorganisms also allow a stable pH to be maintained in anaerobic digestors with little to no additional chemicals or nutrients [39].

In addition to be a method for managing waste, AD provides other major environmental benefits [31,43]. Dependence on biogas and AD rather than fossil fuels can significantly decrease greenhouse gas emissions [44,45]. Furthermore, anaerobically digesting municipal wastes and agricultural and zootechnical products as opposed to combusting them has less of an impact on air quality [36]. Lastly, a biproduct of AD is undigested material that can be used as a

high-value fertilizer for crop cultivation; this fertilizer reduces nutrient runoff and methane emissions [29,31,44,46].

2.2 Problems with Biogas and Anaerobic Digestion

Raw biogas produced from AD is typically comprised of 40-60% methane, 60-40% carbon dioxide, and trace amounts of hydrogen sulfide (H₂S), ammonia (NH₃), nitrogen (N₂), oxygen (O₂), hydrogen (H₂), carbon monoxide (CO), siloxanes, hydrocarbons and volatile organic compounds (VOC) [33]. Methane is the only desired product whereas the other gases and residues are considered pollutants [32]. Thus, a disadvantage of AD is that it generates pollution. However, the biogas can be captured and commercial methods to remove the pollutant molecules and purify the methane gas have been developed; the process of removing these pollutants is called biogas cleaning and upgrading [39,44,47]. The efficiency and yield of the overall biogas upgrading process may further increase as biogas upgrading becomes more developed [39].

Despite the many benefits and positive outlook of AD and biogas dependence, there are also many issues and disadvantages. First, the microbiology and biochemistry of AD are not fully understood [43]. The complexity of the AD process and the ambiguity of optimal reactor operation make development of AD technologies difficult [31]. This lack of understanding can lead to variations in operational parameters, sub-optimal conditions, and volatile fatty acid (VFA) accumulation [47]. In turn, VFA accumulation causes the system's pH to drop, which can inhibit methanogenesis and cause residual soluble COD to be released in the effluent [33,47].

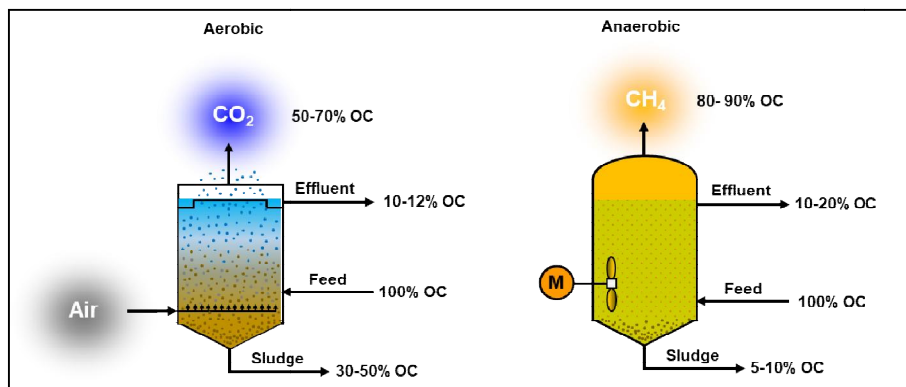


Fig. 1. Organic content conversion for aerobic and anaerobic processes [42]

In addition to not being well understood, the AD process is not ideal for producing a dependable fuel source. The start-up of anaerobic digesters can be slow and long without adapted seed sludge [39]. Throughout the AD process the system is susceptible to organic and hydraulic shock loadings, where VFA accumulation can cause the system to sour and fail [47]. The AD microorganisms can also be inhibited by a large variety of compounds [43]. For wastewater treatment AD may not reduce the amount of organic matter, nutrients, nitrogen, phosphorus, and pathogens in the wastewater to the desired levels, making post-treatment required in some cases [43,46,47]. AD products can also generate bad odors (such as those produced from hydrogen sulfide) and adverse effluents [43]. The generated biogas can contain impurities that can yield increased emissions, corrosion, induce salt accumulation, reduce biogas density, combustibility of fuel gas measured by the Wobbe Index (WI), and even be hazardous or toxic to human health [32,33,39,47,48]. These issues may be resolved as our understanding of AD pathways, systems and technologies continues to grow and develop.

2.3 Definition of Anaerobic Digestion

AD is a sequence of biological processes used to degrade organic material and produce mainly biogas under anaerobic conditions [37,40,49,50, 51,52]. The biogas produced by AD consists primarily of a mixture of methane and carbon dioxide [40,51]. Other products of AD include bacterial biomass, sludge, and ions [40,52]. Very little sludge is produced by AD and the sludge that is produced is well stabilized [40]. Ions produced by AD include ammonium, phosphate anions, and sulfur anions [40]. AD also produces

hydrogen sulfide, water, ammonia, and new bacterial cells [40,43].

2.4 Four Stages of Anaerobic Digestion

AD consists of four stages: (i) hydrolysis, (ii) acidogenesis, (iii) acetogenesis/dehydrogenation, and (iv) methanogenesis [33,37,40,43,52]. The overall process proceeds by the syntrophic interaction of various combinations of archaeal-bacterial consortia [33,37,40,49,50,51]. A simplified diagram of the different AD pathways is shown in Fig. 2. This diagram shows the reactants, the biogas end product, the intermediate products, the four reaction stages, and the types of microorganisms involved in each reaction stage [40,43].

2.4.1 Hydrolysis

The first step in AD is usually the enzymatic hydrolysis of polymers, which allows the microorganisms involved in AD to assimilate the particulate organic matter [40,43,50,52]. Hydrolysis may be preceded by biomass death and lysis, physico-chemical treatment and/or comminution [40]. In the hydrolysis step, hydrolytic and fermentative bacteria secrete exoenzymes at the bacteria surface that hydrolyze proteins, carbohydrates, and lipids to form amino acids, monosaccharides, and long chain fatty acids, respectively [31,40,43,49,50,52]. Alcohols are also produced from this process [40]. These product compounds are smaller and more water-soluble than their polymer counterparts, allowing them to pass through the cell membranes of the acidogens and be used as substrates [43,40,49, 52]. Fig. 3 shows the hydrolysis of the lipid triacylglycerol into glycerol and long chain fatty acids [40].

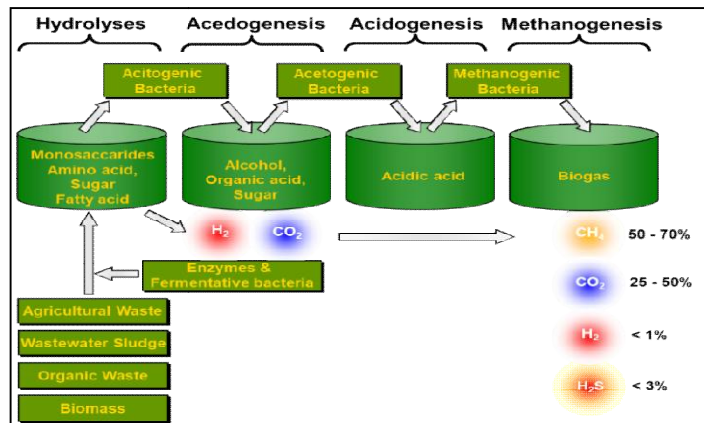


Fig. 2. Simple anaerobic digestion pathway [53]

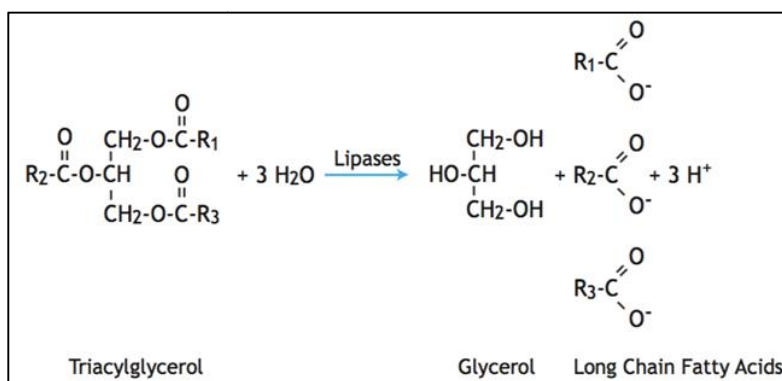


Fig. 3. The hydrolysis of triacylglycerol [40]

Polymers are usually hydrolyzed slowly under anaerobic conditions [43]. The rate and degree to which a polymer is hydrolyzed depends on: reactor operating temperature, substrate residence time, substrate composition, particle size, pH of the medium, $\text{NH}_4^+\text{-H}$ concentration, and hydrolysis product concentration [43]. The rate of hydrolysis in wastewater depends heavily on temperature and temperature fluctuations [40]. When dealing with wastewater, hydrolysis is the rate-limiting step of the overall AD process in most cases, especially if the wastewater contains (semi-) solid substrates or a high suspended solid to chemical oxygen demand (SS/COD) ratio [40,54]. Hydrolysis may even be the rate-limiting step for the AD of low temperature domestic sewage or other dilute wastewaters [40]. Hydrolysis is often rate-limiting due to a lack of accessible surface area and/or the structure of the solid substrates or particles in the wastewater [40,54]. Since hydrolysis is often the rate-limiting step when treating wastewater via AD, the designing of anaerobic digesters used to treat high SS/COD ratio wastewaters, dilute wastewaters, and/or (semi-) solid substrates is usually derived from the characteristics of the hydrolysis step [40].

2.4.2 Acidogenesis

Acidogenesis starts with the amino acids, monosaccharides, long chain fatty acids, and alcohols (produced during hydrolysis) diffusing into the fermentative bacterial cell(s) [40,43,55]. These small, dissolved compounds are then fermented or anaerobically oxidized into simpler compounds, mainly VFAs (i.e. acetate or larger organic acids) but also CO_2 , H_2 , H_2S , NH_3 , lactic acid, alcohols (i.e. ethanol), and new cell material [31,43,40,49,55]. Lastly, these products are excreted from the fermentative bacteria [40,43].

In acidogenesis, amino acids undergo de-ammonification (also known as the Stickland reaction) in groups [40,55]. First, one amino acid is anaerobically oxidized via de-ammonification to form ammonia, VFA(s), and H_2 [40]. The H_2 produced during this conversion is utilized for reductive de-ammonification of other amino acid(s) [40]. The reductive de-ammonification reaction also produces ammonia, VFA(s), and H_2 ; the ammonia molecules produced from these coupled reactions accept free protons, which helps to mitigate pH drop within the reactor [40]. AD may be inhibited by this ammonia if the ammonia concentration is sufficiently high within the reactor [55].

Acidogenesis is considered acidifying because sugars, proteins and other neutral compounds are converted into carbonic acid and VFAs in this step [40]. Hence, fermentative microorganisms are also considered to be acidogenic or acidifying [40]. Rapid acidogenesis can inhibit methanogenesis due to low pH generated from the accumulation of VFAs [33].

The conditions of the reactor medium determine the composition of the acidogenesis products generated in the reactor [40,55]. Some examples of acidogenic reactions that use sucrose as a reactant are presented in Fig. 4 [40]. Each reaction generates a different amount of H_2 , H^+ , HCO_3^- , and VFAs [40]. Less energetic acidogenic reactions that contain sucrose as a substrate have Gibbs free energy (ΔG^0) values that depend heavily on the H_2 concentrations present in the reactor. If methanogens or other H_2 scavenging organisms are present in the reactor and effectively remove H_2 , the primary end product will be acetate [40]. If H_2 accumulates in the reactor, then the acidogenesis will yield more reduced end

products. The reduced end products could include propionate or butyrate, or even more reduced compounds such as alcohols or lactate [40,55]. Anaerobic reactors that are overloaded, perturbed, or acidifying in design often yield effluents containing these reduced products [40].

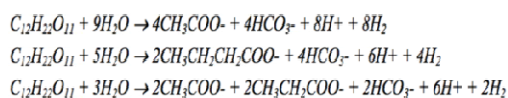


Fig. 4. Acidogenic reactions that use sucrose as a substrate [40]

Acidifying reactions have the largest ΔG^0 values of all AD reactions. As a result, acidogenesis is the fastest conversion step in AD [40]. The large ΔG^0 values of acidifying reactions give rise to ten to twenty times greater bacterial growth rates, five times greater conversion rates, and five times greater bacterial yields than methanogenesis reactions [40,55]. The high reaction rate can also cause a sudden pH drop (also known as souring) in the anaerobic reactor and perturbation or overloading of the reactor with toxic compounds [40,55]. As the pH in the reactor drops, the concentration of VFAs and the degree of methanogenesis inhibition both increase [40]. This increase in methanogenesis inhibition promotes quicker pH drop and VFA accumulation. Acidifiers remain active at a pH as low as 4, so anaerobic reactor contents can reach pH values between 4 and 5 [40].

The group of fermentative bacteria that perform acidogenesis is diverse and large [43]. Also, a large variety of hydrolytic and non-hydrolytic microorganisms are capable of performing acidogenesis [40]. Certain anaerobes including *Clostridium*, *Paenibacillus*, *Ruminococcus*, and *Streptococci* convert soluble monomers into VFAs, CO_2 , H_2 , alcohols and other gaseous and soluble products while other microorganisms such as *Aminobacterium*, *Acidaminococcus*, and *Desulfovibrio* convert monomers into H_2 and acetic acid [33]. Common species are from the clostridia group and the Bacteroidaceaea family [43]. The clostridia group are anaerobic, form spores, and can endure adverse conditions [43]. The Bacteroidaceaea family are known for degrading sugars and amino acids and are often found in digestive tracts [43].

2.4.3 Acetogenesis

The overarching concept of acetogenesis is further oxidation of the acidogenesis products

[43]. In acetogenesis, the excreted VFAs, H_2 , CO_2 , and other acidogenesis products are ingested by acetogenic bacteria [40]. After ingestion, the large chain fatty acids (CFAs) must undergo β -oxidation via specific acetogenic bacteria to form acetate moieties from the aliphatic chain [40]. At least 50% of the acidogenic products are converted into butyric and propionic acids during this process; the butyric and propionic acids are then converted into small CFAs [43]. Oleate, linoleate, and other unsaturated large CFAs are saturated with H_2 and then undergo β -oxidation [40]. If an uneven number of carbon atoms is present in the large CFA being β -oxidized, propionate is formed [40]. The acetogenic bacteria ultimately convert the short chain fatty acids (CFAs) and other compounds into acetic acid/acetate, new cell material, H_2 , and CO_2 [31,40,43,49]. Acidogenesis products such as ethanol, methanol, CO_2 , H_2 , and lactate may be homoacetogenically interconverted at this stage as well [40]. Back reactions may also occur such as the conversion of acetate or propionate to volatile fatty acids or alcohols [40]. The acetogenic bacteria later convert these products to acetic acid and hydrogen so they can be utilized by the methanogens [43].

The acetogenic bacteria that convert large CFAs are obligate hydrogen producers [40] (van Lier, Mahmoud, & Zeeman, 2008). Thus, the generation of the acetic and propionic acids during this stage also yields a large amount of hydrogen, which drives the pH of the aqueous medium down [43]. The presence of this hydrogen can inhibit the ability of acetogenic bacteria to metabolize the large CFAs; thus, it is desirable to minimize the amount of hydrogen present in the AD reactors in order to promote acetogenesis [40]. The hydrogen produced during this step can either be consumed by the hydrogen-utilizing methanogens, which generate methane from hydrogen and carbon dioxide, or it can react with carbon dioxide and a smaller organic acid such as acetic acid to form a larger organic acid [43]. The partial pressure of hydrogen can remain extremely low if methanogens and/or sulfate reducing bacteria effectively uptake and utilize the hydrogen while stabilized digestion conditions are maintained [40]. Thus, there is a narrow association between acetogenic bacteria that produce H_2 and methanogenic bacteria that consume H_2 [40]. Methanogenic bacteria alone usually keep the partial pressure of hydrogen in the anaerobic digester below 10^{-4} atm, which ensures that the

acetogenic reaction and hydrogen production are sustained (van Lier, Mahmoud, & Zeeman, 2008). This low partial pressure of hydrogen also makes ethanol, propionate, and butyrate degradation exergonic so acetogens can gain energy from degrading these compounds [40].

2.4.4 Methanogenesis

In methanogenesis methane, carbon dioxide, and new cell material are generated from acetate/acetic acid, carbonate and hydrogen, methanol, or format [40]. There are three pathways through which methanogenesis occurs: the hydrogenotrophic pathway (also called the Wood Ljungdahl or CO₂ reduction pathway), the acetotrophic/aceticlastic pathway and the methylotrophic pathway [33]. The substrate's nature and the energy source determine which pathway will be used [33,49]. In the acetotrophic/aceticlastic pathway aceticlastic methanogenic bacteria convert acetic acid, acetate, or methanol to methane, carbon dioxide, and new cell material [43,43,49]. In the hydrogenotrophic pathway hydrogenotrophic methanogenic bacteria convert hydrogen and carbon dioxide into methane [33,40,43,49]. Finally, in the methylotrophic pathway methylamines, methanol, and other C-1 compounds are used as both energy and carbon sources for the production of methane [28]. The generated methane is a gas that does not dissolve in water, which enables the removal of organic carbon from the AD medium [43,49].

Methanogens are microorganisms that belong to the group of archaea [31,43]. They have the slowest growth rate among the anaerobic digestion microbial groups, making methanogenesis another rate-limiting step of the overall AD process [31,43]. Out of the microorganisms that make up the four AD stages, methanogens are also the most responsive to changes in temperature, pH, redox and the presence of inhibitors [31].

In an AD system, the few methanogenic species that use the aceticlastic pathway make up the majority of methanogens and produce 60-70% of the methane [43,49]. Aceticlastic methanogens also grow very slowly; it takes several days or longer for their population to double [49]. As a result, anaerobic reactors containing unadapted seed material have very long start-up times and demand highly concentrated sludge for optimum treatment at start-up [49].

The remaining 30-40% of the methane generated from methanogenesis is primarily derived from the hydrogenotrophic pathway [40,49]. The hydrogenotrophic pathway is the most ubiquitous and metabolically efficient pathway reported among microorganisms; it has the most efficient carbon fixation mechanism and thus produces the most energy [33]. Hydrogenotrophic methanogens have a much greater maximum growth rate than aceticlastic methanogens and only take 4 to 12 hours to double in population [40]. The remarkable stability of anaerobic high-rate reactors, even under varying conditions, is attributed to the hydrogenotrophic methanogen's high growth rate [49]. The hydrogenotrophic methanogen's consumption of H₂ plays a key role in this system's stability as it serves to keep the partial pressure of H₂ low in the surrounding environment, allowing for the continued production of oxidized soluble products including acetic acid [43].

Of the two genera that produce methane from acetate, *Methanosarcina* dominate above 10⁻³ M acetate and *Methanosaeta* dominate below it [43]. *Methanosarcina* grow faster than *Methanosaeta*; however, *Methanosaeta* can operate at lower acetate concentrations, albeit longer retention times are required [43]. *Methanosaeta* only utilize acetate and have a higher affinity for it than *Methanosarcina*, whereas *Methanosarcina* can utilize acetate, hydrogen, and methylamines [43]. Ultimately, all hydrogenotrophic and aceticlastic methanogens serve to consume hydrogen generated during the previous stages of AD, which allows acidogenesis and acetogenesis to proceed [43]. Furthermore, almost all well-known methanogenic species can utilize hydrogen and carbon dioxide to produce methane [43].

3. FEEDSTOCK FOR ANAEROBIC DIGESTION

Feedstock for farm-based AD comes from livestock manure is the main feedstock, but there are important other feedstocks that can be utilized by AD technologies to generate biogas [56]. Common AD feedstocks include energy crops, plant biomass, agricultural residues such as animal manure and crop residues, industrial residues particularly from the food and beverage industries, wastewater treatment and sewage sludge, municipal organic waste, biowaste such as that from paper processing, and other organic waste sources [33,43,56,57]. Table 1 displays

various types of AD feedstocks utilized in Europe and their approximate biomethane yields [25, 58]. It should be noted that a feed stock content above 15% is the upper limit for sufficient pumping and mixing [25].

Biomethane values are approximate and can fluctuate vary widely [59], based on plant size, operation and feed stock quality and need to be reviewed, tested and evaluated for each possible commercial application. Manure and slurry, sewage sludge, municipal solid waste, and food waste are the most common forms of waste used for biogas production by the European energy industry [56]. The type of AD feedstock and how readily it can be degraded plays a critical role in the biogas production rate, efficiency and economic impact of any AD system [43,48]. Substrate digestibility and resulting biogas composition depend on carbon-to-nitrogen ratio, loading rate, mineral composition, volatile fatty acid composition, salinity, hydraulic retention time (HRT), pH and temperature [34].

AD feedstocks are comprised of carbohydrates, cellulose, hemicellulose, proteins, and fats, all of

which can be anaerobically digested to generate biogas [56]. The rate of conversion for proteins and carbohydrates are higher than fats but fats have been shown to generate more biogas [56]. The continued AD of crop residues, food waste, sewage sludge and other organic waste streams could increase biogas production [58]. Lastly, as pre-treatment technologies continue to develop, the increase in feedstock biodegradability may warrant the use of other feedstocks such as those with greater cellulose content [58] or a combination of feedstock stocks, called co-substrates) to achieve higher biogas yields.

3.1 Co-substrates

Substrates can be combined and co-digested to increase organic content, biogas yield and ultimately improve the performance of any anaerobic digester [56,58,60,61]. Some organic wastes that are commonly co-digested include food wastes, municipal biowastes, and/or agriculture-related industrial wastes [56]. The types of substrates being co-digested determines the biogas composition and biogas yield [56]. The biogas and methane production and yield

Table 1. Selected anaerobic digestion feedstocks and their biomethane yields

Feedstock	TS [%]	VS [%]	Biogas [l/kgVS]	CH ₄ [l/kgVS]
Livestock manure				
Cow liquid	6 - 12	68 - 85	317	192
Cow solid	15 - 25	65 - 85	311	200
Pig liquid	2.5 - 9.7	60 - 85	580	350
Pig solid	20 - 25	75 - 90	590	360
Poultry liquid	10 - 29	75 - 77	460	300
Poultry Solid	32 - 45	70 - 80	458	307
Sheep	25 - 40	80	660	350
Horse	25	75	550	350
Biomass				
Corn	17 - 38	92 - 95	750	480
Gras	26 - 30	90	515	350
Gras silage	26 - 40	67 - 98	567	400
Oat straw	86	90 - 93	330	198
Potato	22	94	500	300
Rye straw	86	92 - 94	284	170
Wheat straw	86	60 - 90	336	202
Industrial Waste				
Apple pomace	2 - 3.7	94 - 95	500	330
Bread	85	95	920	550
Food waste	9 - 37	74 - 98	700	500
Vegetable waste	15 - 25	76 - 90	540	350
Brewer's spent grain	24	95 - 96	557	380
Municipal Waste				
Clippings	15	87-93	588	320
Leaf	85	82	453	300
Organic waste	35	70	520	350
Sewage sludge	5 - 10	75	480	300

from the anaerobic co-digestion of various biological wastes has been assessed through several studies.

Yusuf and Ify co-digested wastepaper, Cow Manure (CM), and Water Hyacinth (WH) anaerobically [62]. Using 5 different digesters at room temperature, they only varied the amount of wastepaper feedstock and measured the resulting biogas yield. The presence of wastepaper in the digestion improved the biogas yield but the biogas yields also decreased as the quantity of wastepaper increased. A first order kinetic model was generated for each digester to estimate the maximum biogas yield generated from each set of biomass feedstock. Based on these results, 0.5% waste paper was assumed to generate the maximum biogas yield, producing 340 L biogas/kg VS and 204 L methane/kg VS. Another researcher used a paper to manure ratio of 2:1 which produced biogas of 82 mL biogas/g VS [63].

Priya et al. examined (i) the co-digestion of WH with food waste and (ii) the co-digestion of WH with waste activated sludge (WAS) derived from sewage treatment [64]. The WH were combined with food waste in a 1:1 ratio and WH were also combined with WAS in a 1:1 ratio. These mixtures were generated in triplicate and each mixture was inoculated with a seed inoculum. Tests were performed in 1000 mL batch reactors simultaneously. The WH and WAS generated 148 ± 5 L biogas/kg VS while the WH and food waste generated 394.6 ± 12 L biogas/kg VS. This result could be due to the WH and food waste mixture having a higher solids content.

Abdoli et al. investigated the co-digestion of cow dung and maize waste at two different ratios; the cow dung/maize waste ratios were 10:1 and 10:5 [61]. The digestion took place in a 5 L batch reactor operated under mesophilic conditions ($36 \pm 1^\circ\text{C}$). The 10:1 ratio yielded 250 L biogas/kg VS and 130 L methane/g VS whereas the 10:5 ratio yielded 480 L biogas/kg VS and 300 L methane/kg VS.

4. TYPES OF ANAEROBIC DIGESTION REACTORS

Many types of AD reactors are designed for treating wastewater. These reactor designs attempt to maximize substrate-to-biomass contact and biomass retention simultaneously [51]. However, these desirable qualities can counteract each other [51]. For example, maximizing contact between substrate and

biomass generates increased mixing and biogas production, which promotes the washing out of the biomass unless countermeasures are deliberately incorporated into the reactor's design [51].

Based on AD reactor research and experience, balanced microbial communities must be immobilized in AD systems for AD intermediates to be maintained at low concentrations and effective anaerobic wastewater treatment to be achieved [65]. This immobilization allows anaerobic wastewater treatment systems to be categorized as either suspended-growth or attached-growth systems [51]. In suspended-growth systems, microorganisms grow while suspended in the reactor solution, typically in the form of 'granular' and/or 'flocculent' sludge [51]. In attached-growth systems microorganisms grow in the form of fixed film, possibly on liquid-suspended carrier media [51].

Suspended-growth systems retain and immobilize large quantities of biomass and sludge, allowing these contents to become highly concentrated and form granules [40,51]. As a result, suspended-growth systems have high activity rates and settling velocities, making them often classified as high-rate systems [51]. Suspended-growth systems can achieve long Solids Retention Times (SRTs) and short Hydraulic Retention Times (HRTs) [66]. Solids and hydraulic retention times are the average amount of time activated-sludge solids and soluble compounds remain in each reactor or system, respectively. The large amount of biomass assists the reactor in retaining sludge when relatively short hydraulic retention times are used [40]. The large amount of retained biomass also allows for greater sludge stabilization, higher organic loading rates, and smaller reactor volumes than other anaerobic digesters [40,51,66]. The maximum loading rate for high-rate anaerobic reactors is based on the maximum amount of contact that can be achieved between wastewater constituents and the anaerobic bacteria or biocatalysts [40].

Fixed-film processes and expanded/fluidized bed reactors are two types of attached-growth systems [51]. In fixed film processes, bacteria adhere to fixed media (such as crossflow media, rocks, or plastic rings) [51]. Expanded/fluidized bed reactors possess suspended carrier media (sand, porous inorganic particles, etc.) and over time an attached film grows on these carriers [51]. The most effective, efficient, stable, and/or

economical wastewater treatment system depends of the quality of the wastewater and may incorporate multiple types of anaerobic treatment processes [51].

High-rate reactors are often used in sewage treatment applications [66]. The quality of the granular sludge in these systems depends on the wastewater quality, the reactor's loading conditions, and the system's configuration [51]. The high-rate reactors in wastewater treatment often retain granular sludge via gas-liquid-solids separation devices [51]. Some examples of high rate granular sludge-based systems used in wastewater treatment are up flow anaerobic sludge blanket (UASB) reactors, internal circulation (IC) reactors, anaerobic filter (AF) reactors, anaerobic baffled reactors, expanded granular sludge bed (EGSB) reactors, anaerobic migrating blanket reactors, anaerobic hybrid reactors, hybrid up flow anaerobic sludge blanket reactors, sequencing batch reactors, and fully mixed liquid reactors including continuous-stirred tank reactors [51,66].

Low-rate suspended-growth anaerobic wastewater treatment systems generally possess lower organic loading rates and hydraulic loading rates than high-rate systems [51]. This makes low-rate systems able to retain flocculent, non-granular sludge more effectively than high-rate systems [51]. Unlike high-rate systems, low-rate suspended-growth systems have their hydraulic retention times (HRTs) and sludge retention times (SRTs) coupled [40,67]. Low-rate systems are often used to treat wastewater with poor granulation ability or too poor or too great of granule retention at high loading rates (possibly due to the presence of substances such as high fat, oil, grease, or total suspended solids content, salts, calcium, and more) [51]. Some examples of low-rate suspended-growth anaerobic systems are the anaerobic contact process (ACP) and ADI-BVF® reactor [51].

4.1 Continuously Stirred Tank Reactor

An example diagram of a continuously stirred tank (CST) reactor process schematic is displayed in Fig. 5 incorporating a hydrolyses step Fig. 5a. Fig. 5b shows the CST reactor with internal mixing and optional internal recirculation. Fig. 5c shows optional recirculation with optional biomass recovery. Biogas Generated I the hydrolyzation step and CST reactor is collected and can be forwarded to energy conversion technologies. CST reactor can be built in various

shapes. Most common is the cylindrical tank form. For sludge applications in a Waste Water Treatment Plant (WWTP) egg shaped reactors with 46.74 m height, 29.60 m in diameter and 16,700 m³ of volume provide good mixing and sludge circulation [68].

The specific design of the CST reactor depends heavily on the substrate's characteristics and other nontechnical considerations [70]. Anaerobic CSTRs are simple in design, easy to operate, economical and may be classified as either high or low-rate anaerobic reactors [66,67, 70,71]. The temperature, pH, gas supply rate, and gas removal rate are all conditions that can be easily controlled within the CSTR and mixing keeps these conditions relatively uniform throughout the reactor [70,71,72]. Parameters such as chemical and substrate concentration, temperature, and mixing are more uniform in CSTRs than other reactor types (Usack, Spirito, & Angenent, 2012). Basic parameters and design features are shared by all reactor types, making the CSTR an appropriate preliminary assessment method in most cases and commonly used in research [70]. However, solid settling in tubing and the plugging of lab-scale pumps often prevents lab-scale CSTRs from being fed with influent stream(s) containing relatively high solids concentrations [70]. In these cases, the lab-scale bioreactors are fed at regular intervals and are thus called continuously stirred anaerobic digesters (CSADs) [70].

The mixing in the CSTR promotes adequate contact between the active biomass and substrate, allowing for AD to proceed [70]. Mixing in CSTRs is often accomplished through either mechanical agitation, gas injection or hydraulic recirculation [70]. The mixing will disperse the biomass and substrate, preventing short-circuiting, sludge stratification, heavy particles from settling on the bottom of the reactor, and minimizing dead space [70]. However, the continuous mixing of the CSTR puts a heavy demand on the CSTR's energy consumption [70]. Furthermore, the impact of mixing intensity, regime, and characteristics on the anaerobic bacteria and overall AD process is still unclear [70].

Anaerobic CSTRs are often preferred when product activation or substrate inhibition are involved [71]. They are also frequently used when an enzyme inhibitor is present in the substrate stream [71]. CSTRs are used for hydrolyzing solids and fats in effluents with high

solid and fat concentrations and for promoting acidification [73]. They are not preferred for treating effluents with too high (e.g. up to 80 g COD/L) or too low (e.g. 2 to 10 g COD/L) of COD concentrations [73,74]. Studies have explored incorporating media into CSTRs to promote methane production and reduce biomass washout [74]. CSTRs are frequently used for anaerobic wastewater treatment prior to the 1970's [67]. A major reason they are not used anymore nowadays is, that they required large reactor volumes in order to achieve the desired biomass concentration [40,67].

4.2 Anaerobic Fixed Bed Reactor

A diagram of an Upflow Anaerobic Fixed Bed (UAFB) process is displayed in Fig. 6, incorporating a hydrolyses step Fig. 6a. Fig. 6b shows the UFAB reactor with internal mixing and optional internal recirculation. The black circles represent the fixed bed coated with AD microorganisms. Fig. 5c shows optional recirculation with optional biomass recovery. Biogas Generated in the hydrolyzation step and UAFB reactor is collected and can be forwarded to energy conversion technologies.

AD microorganisms are immobilized on a support in anaerobic fixed bed reactors [76]. The immobilization of microorganisms on the support allows anaerobic fixed bed reactors to maintain stability, high cellular residence times, large microorganism retention capacities and achieve short hydraulic retention times [76,77]. Anaerobic fixed bed reactors are relatively compact, strong and robust towards toxic shocks, easily acclimated and can overcome variations in influent and shock loads [76,77]. Also, the construction, maintenance, and operation costs

are relatively lower for anaerobic fixed bed reactors than other high-rate reactors [76]. Furthermore, few suspended solids are found in the effluent of anaerobic fixed bed reactors; thus, separation and recycle of solids is not required in anaerobic fixed bed reactors, attributing them with short startup times [76]. As a result of these qualities, anaerobic fixed bed reactors are commonly used to treat medium- and high-strength wastewaters; in particular, anaerobic fixed bed reactors are suitable for treating wastewaters between 1,000 and 20,000 mg/L COD [76,77].

A variety of natural and synthetic support materials have been utilized in anaerobic fixed bed reactors and it has been determined that the characteristics of a fixed-bed reactor's support material(s) significantly affects the reactor's organic matter removal efficiency [76,77]. Better organic matter removal efficiencies have been obtained from high porosity supports than non-porous ones in all cases [76]. When choosing a support medium for the anaerobic fixed bed reactor, cost and specific surface area are the most important factors to consider; reducing bed size can increase specific surface area of the reactor bed, thus increasing organic matter removal [76].

An Anaerobic fixed bed reactor can also be operated as a downflow reactor. This reactor is shown Fig. 7, incorporating a hydrolyses step Fig. 7a. Fig. 7b shows the Upflow Anaerobic Fixed Bed (UAFB) reactor with internal mixing and optional internal recirculation. The black circles represent the fixed bed coated with AD microorganisms. Fig. 5c shows optional recirculation with optional biomass recovery. Biogas generated in the DAFB reactor travel

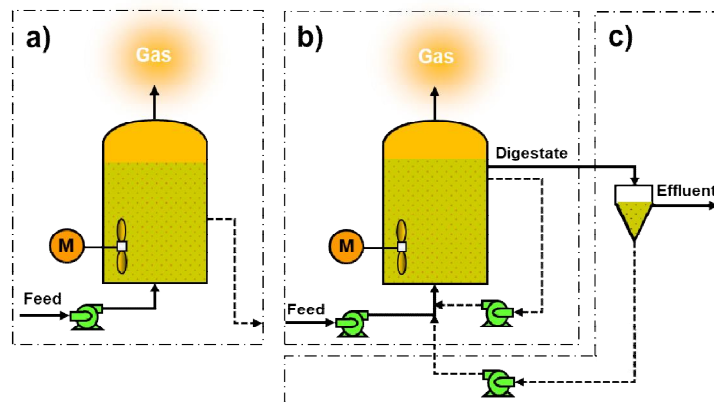


Fig. 5. Diagram of continuously stirred tank (CST) reactor with a) Hydrolyses, b) CST reactor, c) Recirculation with anaerobic biomass recovery [69]

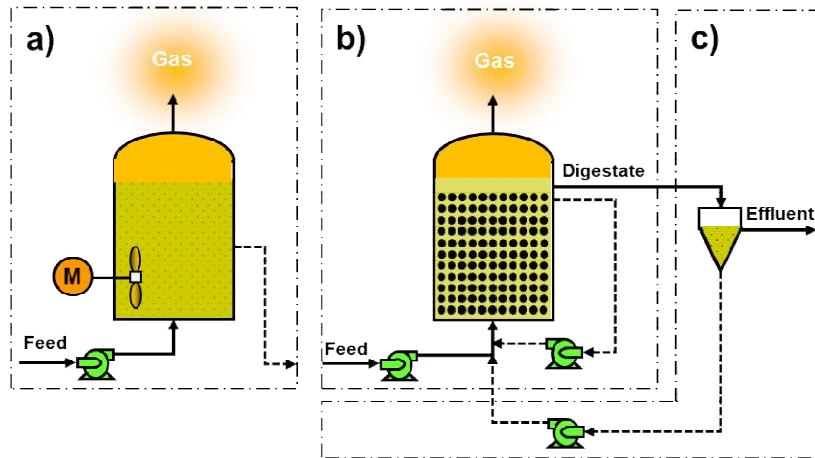


Fig. 6. Diagram of Upflow Anaerobic Fixed Bed (UAFB) reactor with a) Hydrolyses, b) UAFB reactor, c) Recirculation with anaerobic biomass recovery [75]

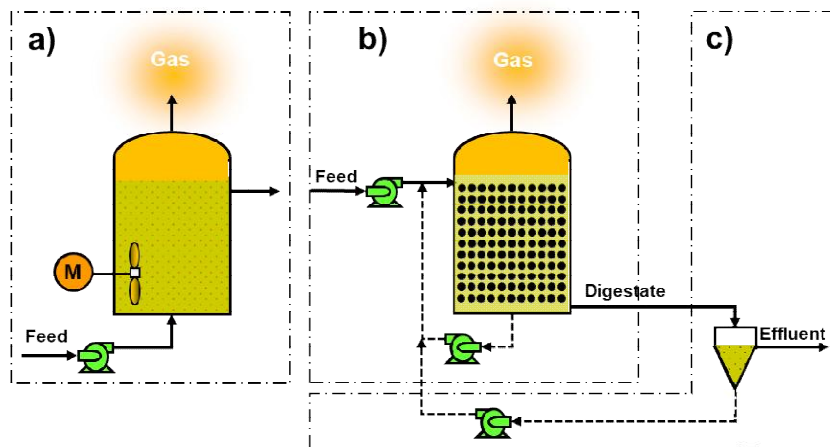


Fig. 7. Diagram of Downflow Anaerobic Fixed Bed (DAFB) reactor with a) Hydrolyses, b) DAFB reactor, c) Recirculation with anaerobic biomass recovery [78]

against the flow of the biomass suspension. Biogas both from the hydrolyzation step and DAFB reactor is collected and can be forwarded to energy conversion technologies.

4.3 Anaerobic Sludge Bed Reactor

Anaerobic sludge blanket reactors are the most common anaerobic wastewater treatment systems [40]. Anaerobic sludge bed reactors retain sludge by generating sludge aggregates such as flocs or granules [40]. Sludge granulation leads to highly concentrated biomass, a high solids retention time, extensive microbial diversity, a higher tolerance to changes in inhibitors and temperature, and reduced operating costs and reactor volume [67]. Gentle

mechanical mixing and correct reactor operating conditions are needed for the sludge aggregates to develop excellent sedimentation and settling properties [40,67]. Granular, highly active and well settleable sludge in the sludge bed yields optimum sludge bed performance, even allowing for high liquid velocities to be utilized in the reactor without appreciable sludge wash-out [40, 67]. High-rate anaerobic sludge bed reactors possess high loading rates and small footprints [50]. Anaerobic sludge bed reactors have been successfully implemented in a variety of industries [6]. However, not every type of industrial wastewater is able to form granulated sludge in the anaerobic sludge bed reactor [67]. A schematic of a UASB reactor is displayed in Fig. 8 with optional external recirculation. Biogas

generated in the reactor is collected and can be forwarded to energy conversion technologies.

The UASB reactor consists of a gas-liquid-solid (GLS) separator surrounded by a rectangular or cylindrical column and is made up of the following systems: influent distribution, an anaerobic (and/or anoxic) sludge bed, an anaerobic (and/or anoxic) sludge blanket of active microorganisms, effluent collection and discharge, gas collection, and a settling compartment [66, 80, 81]. Within Fig. 8 the lighter colored circles represent biogas bubbles, the darker colored circles represent sludge particles, the bottom layer is the sludge bed, the layer above that is the sludge blanket, and the top layer is the settling compartment [82]. UASB reactors are initially inoculated with activated sludge and/or digested, granular, anaerobic flocculent [66]. Influent wastewater then enters through the influent distribution system at the bottom of the reactor and flows upward; the entering wastewater is usually dispersed evenly onto the reactor bed in order to achieve good contact between wastewater and sludge [40, 66, 81]. Heavier sludge components are retained in the reactor while light and dispersed sludge particles are washed out [66]. Over time, flocs and granules of inert organic and inorganic matter form from these heavier sludge components [66]. The sludge aggregates filter out the smaller particles present in the influent wastewater [83]. At the same time, small bacterial aggregates form and grow in the seed sludge [66]. A dense sludge bed consisting of

granular or flocculent sludge with excellent settling properties develops after a period of time, usually 2-8 months [66]. The sludge bed development time depends on the properties of the seed sludge and wastewater and the operating conditions [66].

The sludge blanket is located above the sludge bed [66]. The flow of wastewater through the sludge blanket causes it to expand [80]. While the influent wastewater passes through the sludge blanket, the microorganisms in the blanket filter and treat the wastewater by anaerobically digesting the organic matter present [66, 80, 82]. Over time, heavier components form and settle in the sludge bed [80, 82, 83]. The ratio of the sludge blanket cross-sectional area to sludge blanket depth determines the influent distribution across the sludge bed; the smaller the ratio, the more uniform the distribution but also the greater the pressure resistance [80]. Generally, the upflow velocity through the sludge bed must be maintained at 0.7 to 1 m/h for the sludge bed to remain in suspension [83].

The sludge blanket has diffused growth and particles in the sludge blanket have lower settling velocities than those in the sludge bed [66]. Due to the anaerobic environment and presence of COD in the wastewater, microorganisms within the blanket anaerobically digest the COD and grow and multiply [66,80]. The species of anaerobic microbes form granular beads that assimilate into the biomass solids, which

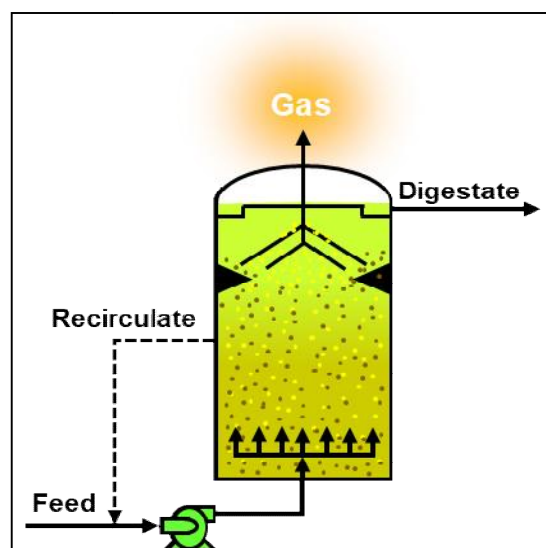


Fig. 8. Diagram of an Upflow Anaerobic Sludge Bed (UASB) reactor [79]

are retained in the reactor by the effluent weir and their weight [80, 83]. The remaining lighter-weight species are carried over the weir and leave the UASB as effluent [80]. The UASB and sludge blanket eventually become dominated by the microbes that form the dense, granular, bead-like solids; It may take several months for this granulated sludge to develop [80, 83]. If the effluent recycle is used to control the upflow velocity through the sludge blanket when wastewater influx diminishes, the microbial granular solids within the sludge blanket will abrade each other via rubbing and rolling, thus keeping the beads within the desired size range [80]. The abrasion also ensures that a high ratio of active microorganism to organic matter is maintained within the UASB reactor, allowing the system to maintain its high performance [80].

The biogas generated in the sludge bed and sludge blanket is released in the form of bubbles [66]. Some biogas bubbles may be entrapped in the sludge, which buoys the sludge internally, while the free gas bubbles rise through the sludge to produce external buoying and mixing within the UASB reactor [66, 83]. The upper section of the reactor contains a settling zone and a gas collection zone [82]. In the settling compartment, solids settle and are channeled back to the reactor body [82]. The submerged GLS separator at the top of the column separates the effluent, biogas, and buoyed sludge; it is usually shaped in the form of an inverted cone or pyramid [51,65,66,82]. The GLS separator also serves as a biogas collection dome to collect the biogas at the top of the reactor [40, 82, 83]. The gas effluent exits the settling zone and accumulates in the gas collection zone while solid biomass becomes more concentrated in the settling zone [82]. The GLS separator additionally serves to mitigate liquid turbulence found in the settling compartment, retain sludge particles, limit sludge bed expansion, and polish the wastewater effluent [40]. The minimization of turbulence assists in sludge aggregate retention [40]. The GLS separator may need to be customized to promote proper separation of these phases within the UASB reactor [65]. Organic matter and sludge approaching the top of the tank may be deflected downwards via sloped walls and/or coalesce at the top of the reactor [65,83]. After biogas entrapped in the buoyed sludge and organic matter escapes, the sludge and organic matter in the settling zone will settle back to the digester compartment via gravity [65,82,83].

Baffles are used to prevent floating granular sludge and viable bacterial matter from washing out of the reactor; the baffles also direct settling solids back to the sludge bed and sludge blanket [39,65]. The gravity-directed settling mechanism retains and concentrates biomass in the reactor [82]. This reactor design produces relatively clarified water at the top of the tank above the sloped walls [64]. The clarified water at the top of the tank is either extracted as effluent or recycled to increase the upflow velocity in the UASB reactor [65,83]. The clarified effluent leaves the reactor via submerged exit(s) along with a small portion of the biomass [82].

Anaerobic sludge bed reactors can require high height-to-diameter ratios; when treating low strength wastewaters, the reactors can be 20-25 meters high [40]. The low surface area promotes the feeding of the reactor [40]. Wastewater generally flows upward in these reactors and the height in conjunction with biogas accumulation assists in generating a turbulent flow [40, 84]. The vertical flow present in UASB reactors increases the contact between the influent and the accumulated sludge compared to horizontal flow-based reactors, thus also improving suspended solids removal [84]. The accumulated upward flow velocity in tall reactors also fosters better contact between the sludge and pollutants [40]. A recirculation flow is applied to the reactor to provide more thorough mixing and minimize stratification of the reactor contents [40].

UASB reactors are high-rate suspended-growth reactors that are compact and easy to operate [40,66,67,80]. They possess a high concentration of biomass, making their required volume lower than other reactors while allowing them to treat wastewater at organic loading rates as high as 10 kg BOD/m³/d [66,82,83]. The generation of flocculant or granular sludge in UASB reactors allows them to achieve high organic matter removal efficiencies without additional support material and the rising of biogas bubbles within UASB reactors eliminates the need for external mixing and the associated cost [66]. UASB reactors can achieve low hydraulic retention times (generally 6 to 10 hours) and high solids retention times [66,82]. The blanketing and granulation in UASB reactors allow the SRT and HRT to be altered independently and effectively, allowing the reactor to be designed and specified based on the biomass's degradation properties; this reduces treatment times from days to hours [66].

UASB reactors effectively treat a vast variety of industrial effluents, including those where inhibitory and/or toxic compounds are present [65]. UASB reactors have been used to treat agro-industrial wastewater, chemical industry wastewater, sewage, food processing waste, pulp and paper waste, brewery waste and distillery waste [40,83]. UASB reactors are the most robust type of high-rate anaerobic reactor used in sewage treatment [66]. UASB reactors are able to treat wastewaters as low as 2000 mg/L and achieve up to 80 to 90% COD removal using eight to ten-hour hydraulic retention times [80,83].

On the other hand, UASB reactors are susceptible to organic shock loads and their performance depends on the operating temperature [65,65,83]. Furthermore, it can be difficult to control sludge bed expansion, lowering the maximum organic loading rate [66]. Granular sludge can also disintegrate, float, and/or wash out of the UASB reactor [66]. In addition, the UASB reactor is not effective at treating low strength wastewaters because the lack of biogas generation yields a lack of mixing within the reactor [83,84]. The UASB reactor is also not effective at treating low-temperature wastewaters due to the high liquid viscosity and lack of biogas generation (and hence a lack of mixing) [66,83, 84]. The UASB reactor is also not effective at treating wastewaters that contain high concentrations of proteins, fats, or solids [83, 84]. The organic matter, pathogen, and nutrient (e.g. NH_4^+ , PO_3^- , S_2) levels of some wastewaters may not be lowered to sufficient levels, while other treated wastewaters may generate high sulfate concentrations within the UASB reactor, requiring effluent post-treatment [66]. Finally, BOD removal efficiency for UASB reactors is limited to around 70%, which is lower than most other systems [82]. However, post-treatment processes can be used to achieve greater BOD removal efficiencies [82].

4.4. Expanded Granular Sludge Bed (EGSB) Reactor

The Expanded Granular Sludge Bed (EGSB) reactor is another suspended-growth reactor that generates granular sludge [51]. An example of an EGSB reactor is displayed in Fig. 9, with optional external recirculation. Biogas generated in the reactor is collected and can be forwarded to energy conversion technologies. It operates using the same principles as the UASB reactor; however, the geometry, construction materials,

and process parameters usually differ from the UASB reactor [51]. EGSB reactors are usually 12 to 18 meters high, have a significantly smaller footprint than UASB reactors, and are usually made of stainless steel or fiberglass-reinforced plastic (FRP) [51]. Typical loading rates for EGSB reactors generally range from 10 to 25 kg COD/m³/day [51].

EGSB reactors are usually used to treat wastewaters containing poorly biodegradable or inert particles or low strength, soluble wastewaters [86]. EGSB reactors can contain a distribution system at the bottom [86]. As wastewater flows up through the several-meter-thick granular bacteria bed, the large flux causes the bed to expand [68]. This promotes wastewater-sludge contact as the biomass converts the organic matter in the wastewater to biogas [86]. The large flux also assists in preventing small, inactive particles from settling in the sludge bed [86]. The upflow produced by the distribution system and biogas generation yields thorough mixing throughout the reactor [86]. A GLS separator is located at the top of the reactor [86]. As biomass aggregates at the top of the reactor, higher-density biomass returns to the sludge bed [66].

4.5 Internal Circulation (IC) Granular Sludge Bed (ICGSB) Reactor

Another high-rate reactor that operates based on granular sludge formation is the internal circulation (IC) reactor [51]. A diagram of this reactor is located in Fig. 10, with optional external recirculation. Biogas generated in the reactor is collected and can be forwarded to energy conversion technologies [88]. Similar to the EGSB reactor, this reactor is tall and possesses a small footprint [51]. Wastewater containing a strong community of AD microorganisms and low concentrations of TSS and FOG can be treated in as little as a few hours via this reactor [51]. The IC reactor is often used to treat wastewater from brewery, beverage, and paper industries [51]. Loading rates generally range from 15 to 35 kg COD/m³/day [51].

First, the influent is pumped from the distribution system into the ICGSB reactor [51]. Upon entering the reactor, the influent is mixed with recycled sludge [51]. An expanded granular sludge bed is present in the first compartment of the IC reactor, which is used to convert a majority of the entering COD into biogas [51]. A

lower level separator collects this biogas from this compartment to form a gas lift [51]. The lift carries water and sludge through the “riser” pipe and up to the gas/liquid separator, which is located on top of the reactor [51]. At this point the biogas and water/sludge mixture are separated and the biogas is collected via the three-phase separator [51]. The water/sludge mixture is directed through the concentric “downer” pipe towards the bottom of the reactor [51]. The rising and falling flows in the system constitute the internal circular flow of the system [51]. Any remaining biodegradable COD from the first compartment’s effluent is removed in the low-loaded second compartment, which is located above the first [51]. The effluent from the second compartment exits the reactor through overflow weirs [51].

4.6 Anaerobic Fluidized Bed Reactor (AFBR)

A diagram of an anaerobic fluidized bed reactor (AFBR) is displayed in Fig. 11 with optional external recirculation. Biogas generated in the reactor is collected and can be forwarded to energy conversion technologies. The darker circles represent suspended particles and the line towards the top of the AFBR represents the

wastewater level and discharge. When a fluid passes upward through a bed of solid particles at a high enough velocity, the particles will be suspended and behave similar to a fluid; this process is called fluidization [89, 90]. If fluid enters the static bed at a low superficial velocity, well below a minimum fluidization velocity, the bed remains fixed and the fluid passes through void space between the solid particles [89]. As the superficial velocity increases, the average distance between the particles in the bed increases and the bed expands; the extent of the expansion depends on the superficial velocity of the fluid flow, the fluid’s viscosity, particle size and particle density [89]. The minimum fluidization velocity is the superficial velocity at which the particles in the bed become suspended; it is also the point at which the buoyance force balances the gravitational and drag forces on the particles within the bed [89]. In other words, the particles become suspended when the minimum fluidization velocity is reached because the pressure difference across the bed and the weight of the particles negate each other [89]. Fluidization promotes excellent particle mixing, a high rate of mass transfer, large contact area, and uniform temperature and particle distributions in fluidized bed reactors [89, 90].

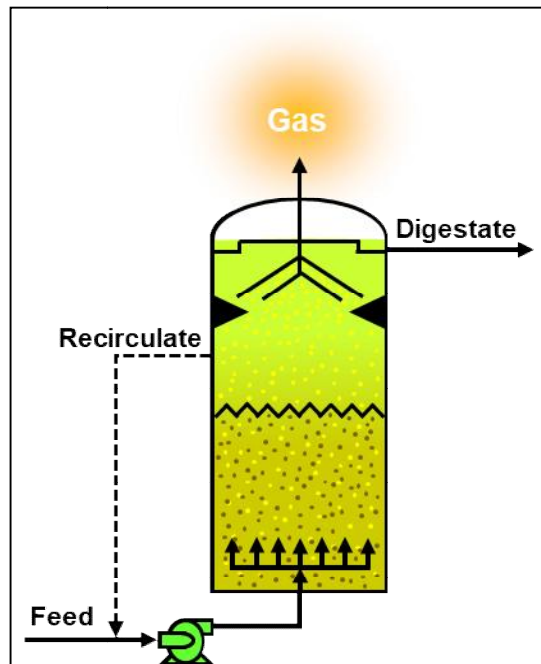


Fig. 9. Diagram of an expanded granular sludge bed (EGSB) reactor [85]

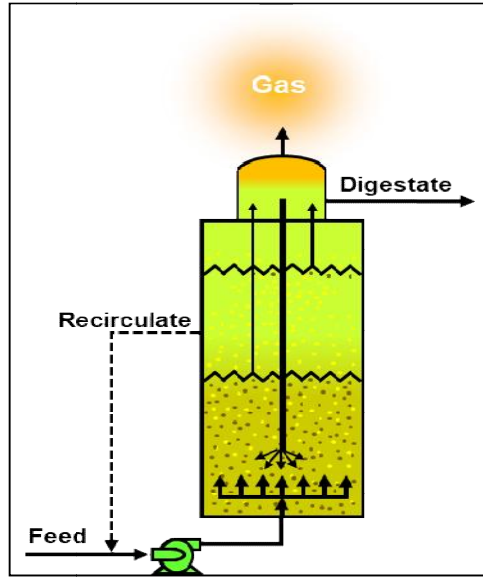


Fig. 10. Diagram of an Internal Circulating Granular Sludge Bed (ICGSB) reactor [87]

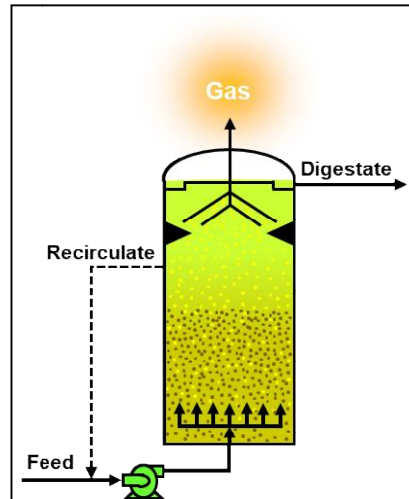


Fig. 11. Diagram of an Anaerobic Fluidized Bed (AFB) Reactor [88]

For anaerobic fluidized bed reactors used in biological-based wastewater treatment, microorganisms form biolayers on small, heavy particles, which are kept fluidized by the upward flow of wastewater in the reactor [89,91]. The small, heavy particles (typically 0.2-0.8 mm in diameter) provide settling velocities around 50 m/h, which allows for high superficial wastewater velocities around 10-30 m/h to be used in the reactor [91]. This high superficial wastewater velocity prevents inert sediment found in the wastewater from settling in the reactor, thus promoting higher sludge activity [91]. The small, heavy particles also promote a high attachment

surface area (more than 2000 m²/m³) within the reactor, generating a high biomass concentration typically around 40 kg/m³ [91]. The high sludge activity and biomass concentration allow AFBRs to obtain very high treatment capacities [91]. As a result, AFBRs are also relatively smaller and more compact than conventional biological wastewater treatment reactors [91].

The AFBR treatment process begins with wastewater entering the reactor and being evenly distributed across the reactor particle bed via a distributor [89]. The particle bed is composed of a variety of support media and/or catalysts such

as sand or another kind of inorganic carrier with extremely large and specific surface(s) [51,89]. The carrier particles provide weight and serve as anchors for AD microorganisms to attach to and grow [51,89]. The wastewater enters the reactor bed at a superficial velocity and if the wastewater's superficial velocity is sufficiently high, it will put the microorganism-coated particles into suspension and the bed will become fluidized [89]. Fluidization maximizes contact between pollutants and microorganisms, allowing anaerobic fluidized bed bioreactors to treat wastewaters more quickly than conventional biological treatment methods [89]. A separator is located at the top of the AFBR to separate the liquid, solids and biogas [45]. The solids return to the reaction chamber [51]. The liquid leaves the reactor as effluent and is often recycled in AFBRs used in wastewater treatment [89]. The high fluidization and recirculation rates in AFBRs promote gas-liquid mass transfer, oxygen transfer, sludge fluidization, and maximize biomass-substrate contact [51,81].

AFBRs are often used to treat wastewaters with low concentrations of total suspended solids (TSS), low concentrations of fat, oil, and grease (FOG), and strong AD communities [51]. They have been successfully utilized in treating hardly to readily degradable wastewaters [92]. Unlike conventional wastewater treatment technologies, AFBRs also show potential for treating wastewater containing hydrophobic and frequently high molecular weight recalcitrant pollutants [89]. AFBRs are highly resistant to system disturbances and shocks, low cost to operate, uniformly mixed and transfer mass quickly [89]. AFBRs treat wastewater at relatively high rates and low hydraulic retention times [89, 92]. Loading rates of 60 kg COD/m³/day or more can be achieved by these reactors if an acidogenic stage is used to pretreat the wastewater [51]. Similar to other granular sludge-based reactors, these reactors are tall and cylindrical [51]. They are also stable, easy to operate, and highly efficient [89]. AFBRs have higher settling rates, higher biomass concentrations, higher superficial liquid velocities, and lower area requirements than conventional biological treatment methods [91]. Inert sediment flows through an AFBR, whereas it ends up being stored in the sludge in conventional biological treatment methods [91].

4.7 Upflow Anaerobic Filter (AF) Reactor

Anaerobic filter (AF) reactors contain a stationary packing media that forms a fixed bed [40,43,51,

82,83]. As biomass enters the reactor with the wastewater, it attaches and grows on this stationary media to form a biofilm [43,40,51,83]. Anaerobic organisms efficiently adhere to proper inert carriers, allowing AF systems to start up rapidly [40]. As the biofilm grows over time, a large amount of biomass gets trapped within the packing media, forming suspended flocs within the interstices of the support medium [43]. Thus, microorganisms in anaerobic filter reactors have a high average residence time [43]. The combination of biofilm and flocs in the filter causes wastewater particles to become trapped; the active biomass attached to the filter surface degrades the organic matter present in the particles [83]. Anaerobic filter reactors typically remove 50-80% and sometimes as much as 90% of suspended solids and BOD present in wastewater [83].

Based on this information, the support material's size, shape, weight and surface characteristics are critical to biofilm and sludge formation [43, 40]. Additionally, the reactor bed should maintain a large void fraction for optimal treatment performance [43, 40]. Commonly employed media types include pall rings, cross-flow, random pack, stones, crushed rocks or bricks, cinder, gravel, pumice, specially formed plastic pieces, and others [51,82,83].

A variety of AF reactor configurations have been utilized for wastewater treatment such as upflow, downflow, and hybrid, with upflow being the most common [43,51]. Anaerobic filter reactors are often operated in upflow mode to reduce the chance that the fixed biomass will be washed out of the reactor [83]. Fig. 12 displays a diagram of an upflow Anaerobic.

Filter (UAF) reactor. The black circles represent packing material. The wastewater is pumped in from the left the left and exits on the right top. The sludge is withdrawn from the bottom. Biogas generated in the reactor is collected and can be forwarded to energy conversion technologies. In upflow mode, wastewater is distributed at the bottom of the tank to provide a homogenous, upward flow through the filter's support medium; this also helps to avoid short-circuiting flow [43, 94]. As wastewater passes through the fixed bed, the microorganisms comprising the biomass on and in the support medium anaerobically degrade the soluble organic compounds present in the wastewater [43]. Due to the upflow design, anaerobic filter reactors biomass may also be found below the anaerobic filter in the form of granules or flocs [43]. AD activity in UAFRs

primarily occurs in this non-attached biomass [40]. Upon reaching the top of the reactor, the clarified wastewater is separated from the generated biogas using a free board and the clarified wastewater is discharged as effluent [43]. In downflow, liquid enters the top of the tank and is distributed above the support medium. The liquid then passes through the support medium, which can be either submerged or non-submerged, before being collected at the bottom of the tank [43]. Effluent recirculation is more common in the downflow configuration than the upflow [43].

There are many disadvantages of anaerobic filter reactors. Their filter beds can become obstructed and clogged, the inert packing material comprising the filter bed makes the required reactor volume very large, their effluents can contain large amounts of pathogenic organisms and mineral salts, and anaerobic filter reactors usually only remove up to 15% of total nitrogen [43,40,83]. Sludge aggregates form in the UAFRs during operation that possess excellent settling abilities, causing them to become trapped in the packing material [40]. This clogging hinders the contact between wastewater and sludge and the clogging is especially common when treating partly soluble wastewaters [40]. Biomass also accumulates at the bottom of UAFRs, which can result in hydraulic short circuiting and blockage [43]. Thus, downflow anaerobic filter reactors may be

preferred for treating wastes with higher suspended solids concentrations [51].

Downflow anaerobic filter reactors are designed such that the downflow helps to prevent sludge from accumulating and clogging the filter [40]. However, the primary mechanism for biomass retention in this system is its physical adherence to the packing material's surface [40]. Only a very low amount of biomass can be retained in these down-flow fixed film reactors, which significantly limits this reactor's organic loading rate [40]. Therefore, down-flow fixed film reactors are unlikely to be employed in full-scale anaerobic reactor settings [40].

Anaerobic filter reactors tend to have solids retention times of at least 20 days, whereas their hydraulic retention times are relatively short (usually a 12-36 hour HRT is recommended) [43, 83]. These characteristics make anaerobic filter reactors excellent candidates for treating low-concentration wastewater [43]. In fact, anaerobic filter reactors are more appropriate for post-treatment of wastewater but may be used as the main method for wastewater treatment as well [43]. Loading rates for anaerobic filter reactors typically range from five to 15 kg COD/m³/day [51]. The wastewater treated using this reactor must have FOG and TSS concentrations of < 100 mg/L and < 15% COD, respectively [51]. Submerged anaerobic filter reactors should possess a water level at least 0.3 m above the

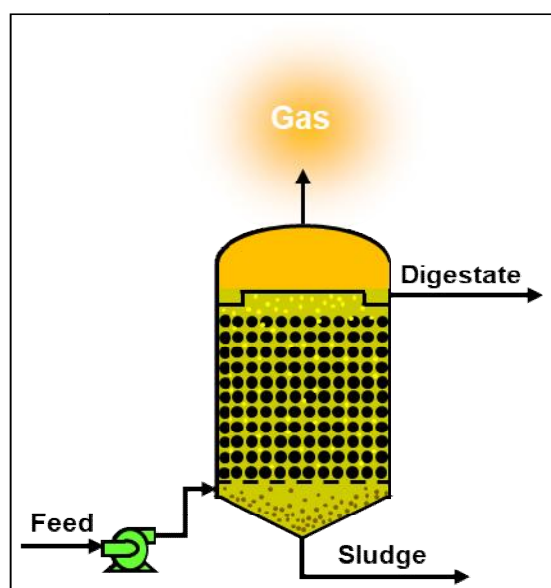


Fig. 12. Diagram of an up flow anaerobic filter (UAF) Reactor [93]

filter media to ensure an even flow regime [83]. The filter media should also possess a large surface area to maximize the quantity of adhered bacteria while maintaining large enough pores to prevent filter clogging [83]. The large surface area maximizes the contact between the biomass and organic matter and thus the amount of AD occurring at a given time [83].

4.8 Anaerobic Hybrid Reactor

A diagram of an anaerobic hybrid reactor is displayed in Fig. 13. This reactor employs both suspended-growth in the lower part of the reactor and fixed-film processes packing material represented by the black circles with optional external recirculation. Biogas generated in the reactor is collected and can be forwarded to energy conversion technologies. The darker circles represent suspended particles and the line towards the top of the AFBR represents the wastewater level and discharge. Cross-flow plastic media is used to generate a fixed-film zone in the upper section (top 50% to 70%) of the reactor while suspended growth takes place in the lower section (bottom 30% to 50%) [51, 96]. The top section is often referred to as the anaerobic filter section while the bottom section is referred to the UASB section [51, 96]. Typical organic loading rates range from five to 15 kg COD/m³/day for this reactor and they have FOG and TSS limits similar to those of the anaerobic filter and UASB reactors [51]. This reactor is particularly suited for treating wastewaters that have difficulty developing granular sludge, such as those from some chemical industries [51]. The hybrid setup promotes a more stable environment for granular sludge formation by concentrating biomass [51]. Biomass is further retained within the system by the gas-liquid-solid

separation achieved by the cross-flow media [51, 96]. One example of a commercially available anaerobic hybrid reactor is the ADI-Hybrid reactor [51].

4.9 Low-Rate Anaerobic Reactor

Low-rate anaerobic reactors use a suspended-growth system with a low loading rate (0.5 to 3 kg COD/m³/day) [51]. The low loading rate allows non-granular flocculent biomass to be retained in the reactor [51]. The low loading rate also allows this type of reactor to treat wastewaters with higher COD, FOG, and TSS than those treated using high loading rate reactors [51]. The larger the volume of the low-rate anaerobic reactor, the more robust and stable the system [51]. This reactor can also operate at lower temperatures and it generally produces less waste sludge (by dry weight) than other types [51]. Pretreatment clarification is often not required when using this reactor [51]. Fig. 14 shows a low rate reactor. This reactor employs suspended-growth. Biogas generated in the reactor is collected and can be forwarded to energy conversion technologies. Digestate or treated wastewater is discharged on top of the reactor through an effluent structure.

The ADI-BVF® reactor [98] is one type of commercially available low-rate anaerobic reactor [51]. BVF® reactors can be constructed above or below ground using an insulated geomembrane cover [51]. In addition to possessing the aforementioned characteristics of low-rate anaerobic reactors are utilized these reactors can be used to digest activated sludge generated from downstream aerobic processes [51]. This ultimately simplifies and lowers the operating cost of the cumulative sludge handling and disposal process for aerobic treatment [51].

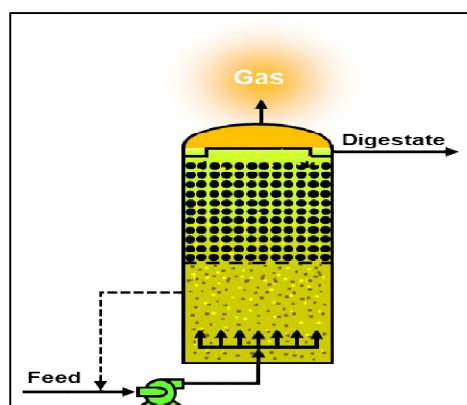


Fig. 13. Diagram of an anaerobic hybrid (AH) reactor [95]

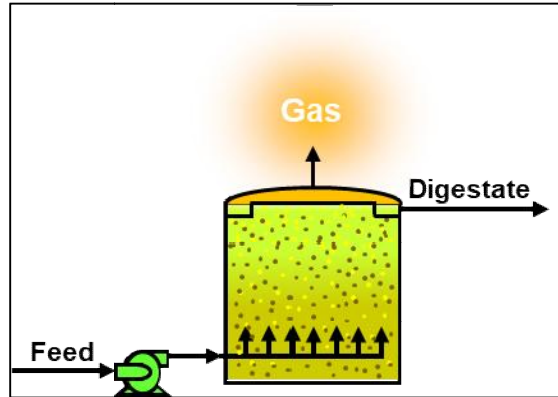


Fig. 14. Low rate anaerobic reactor [97]

4.10 Anaerobic Contact Process (ACP)

Anaerobic contact processes (ACPs) are a type of treatment system that consists of an agitated reactor, external settling tank(s) and sludge and microorganism return [40,96,57]. The mixing shears biological solids to keep them small while the external clarifier continuously returns “seed” organisms to the reactor [80]. A diagram of an ACP is displayed in Fig. 15 showing external recirculation for the APC reactor in Fig. 15a and a Clarifier for biomass recovery and recirculation in Fig. 15b. Biogas generated in the reactor is collected and can be forwarded to energy conversion technologies. ACPs are designed to keep the ratio of active microorganisms to

organic matter high and the system’s performance primarily depends on the amount of contact between the microorganisms and substrate and the substrate retention time [57, 80]. Mixing plays a key role in the ACP’s efficiency because it promotes heat transfer, prevents stratification and surface crust formation, and assists in preventing the build-up of inhibitory intermediates [57,80]. Furthermore, mixing allows ACPs to reach steady-state rapidly and transfer mass more quickly than UASBs and other conventional anaerobic systems [47,57]. The homogeneity and contact produced from mixing allows a high-quality effluent to be obtained at short hydraulic retention times [57].

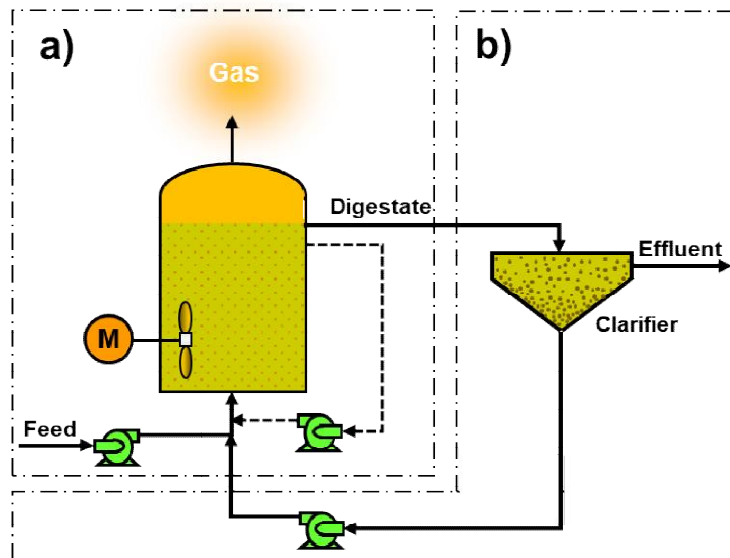


Fig 15. Diagram of an anaerobic contact process (ACP) with a) reactor, b) clarifier [99]

Current ACPs apply gentle and/or intermittent mixing in their separation units, which engenders sludge with favorable sedimentation properties [40]. In fact, intermittent mixing is favored over rapid mixing because rapid mixing diminishes the efficiency of methanogens [47]. The gentle and/or intermittent mixing also helps the separation units yield effluent containing predominantly suspended solids and semi liquid waste [40].

In addition to mixing, the sludge return also promotes extra contact between the biomass and organic matter from the wastewater, making the biomass highly concentrated [96]. Furthermore, shock loading may have less of an impact on ACPs than other anaerobic systems due to the settling tank [57]. The lack of internal fittings in ACPs makes them well suited for treating wastewaters with high solids content [40]. The system design also ensures that the biomass remains suspended and biogas evacuates the reactor for AD to proceed [57]. As a result of these qualities, ACPs are relatively compact, efficient, and treat wastewater at high rates [57,96].

One common problem associated with ACPs is the gas generated by the anaerobic bacteria in the ACP yields poor sludge settlement in the settling tank [96]. However, this problem can be minimized if vacuum degasification, thermal shock, and/or flocculating agents are used [96]. Thus, the reactor may be heated, and a plain sedimentation clarifier is often preceded by a degasification [80]. If a different clarifier is used, it may be preceded by a vacuum flotation solids separation device [80].

ACPs are used to treat low to high-strength wastewaters and remove COD from high-strength wastewaters effectively and economically [80,87]. ACPs are often used if the wastewaters being treated have difficulty forming granules or the concentrations of certain troublesome constituents are too high [96]. ACPs can operate with high concentrations of total suspended solids and lipids and can treat organic loading rates as high as 10 kg COD/m³/day, which is relatively low [40,57,96]. As a result, large tanks are frequently used in ACPs [57]. ACPs can achieve COD removal efficiencies approaching 90% with a hydraulic retention time of less than a day [60]. They rapidly hydrolyze complex organic compounds using little energy, produce little excess biosolids, and use heat accompanying the wastewater to promote the AD process [60].

4.11 Batch Reactor

In a batch process a feed is first charged into a vessel and after some amount of time, the contents of the vessel are removed [100]. A diagram of a batch reactor is displayed in **Fig. 16**. During this time, no mass enters or leaves the vessel system [100]. Biogas generated can be recovered during the AD batch operation and forwarded to the energy conversion technologies. The previously mentioned reactors are continuous and known for operating at steady state, whereas batch operations are intrinsically transient [100,102]. In other words, conditions within the batch reactor change with time [84]. If the contents of the batch reactor are adequately mixed during operation, then the changes in the conditions will be approximately homogeneous throughout the reactor [102].

Batch reactors are commonly used in laboratories to investigate the feasibility of a chemical process [102]. Batch reactors have flexibility to accommodate multi-product processes, as well as relatively low equipment and maintenance costs [102]. They are employed when scaling up a process from the laboratory to industrial setting [102].

There are many disadvantages to utilizing batch reactors on the industrial scale. The auxiliary steps required in batch processes make them less efficient than continuous processes [102]. Furthermore, batch processes used in industry have higher manpower costs and their process instrumentation and control is more complicated than continuous processes [102]. Lastly, the product quality of batch processes are more inconsistent than continuous processes [102].

Semi-continuous (also called semi-batch) processes involve adding at least one reactant or removing at least one product from the system continuously [100, 102]. Thus, semi-batch processes aim to control the product distribution of equilibrium-limited reactions, the kinetics effects of complex reactions, and prevent runaway, highly-exothermic reactions [100,102].

4.12 Uncovered Lagoon

Uncovered lagoons or vessels are used as the primary storage and treatment vessel of agricultural residues from dairy, beef, swine and poultry operations where many livestock is managed in a limited space since the 1960 [103]. Fig. 17 shows a Process sketch of such a lagoon

system. The feed (livestock residue) enters the lagoon through an influent structure at a solids content of 1 to 6% [105, 106] if organic bedding material is used and up to 12% if sand is used as bedding material for the livestock operation. certain times of the year the residue content (manure) in the lagoon is pumped out and land applied onto agricultural fields with spreading vessels and/or sprayer systems. During the manures storage time anaerobic fermentation occurs and methane gas (CH₄), carbon dioxide (CO₂), nitrous oxide (N₂O) and ammonia (NH₃) is released into the atmosphere [105,106,107]. All these gases contribute to global warming. According to the United States Environmental al Protection Agency (EPA) N₂O stay approximately for 114 years in the atmosphere before destroyed by a sink or chemical reaction and has a 100-year Global Warming Potential (GWP) of 298 compared to CO₂ [108]. In comparison has a GPW of 28-36 [108].

Beside Green House Gas (GHG) emissions lagoon systems account for odor emissions through releasing NH₃ which is converted into N₂O and contribute to Particulate Matter with a size 25 µm (PM_{2.5}) [109] This requires to locate the lagoon in remote areas. Lagoon systems require relatively long retention times and large area of land to build. In addition, they can provide seepage into the groundwater if not professionally lined [110].

4.13 Covered Anaerobic Lagoon

To reduce air emission of lagoon systems mostly applied in agricultural applications, a covered with a flexible liner can be added to the lagoon. This allows to operate the lagoon as an AD system under semi plug flow operational conditions as shown in Fig. 18. In general, the waste stream from cow, pig and poultry operations is transferred using an influent

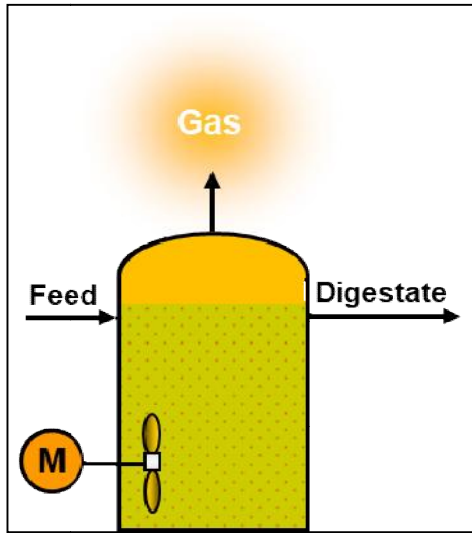


Fig. 16. Process diagram of a batch reactor [101]

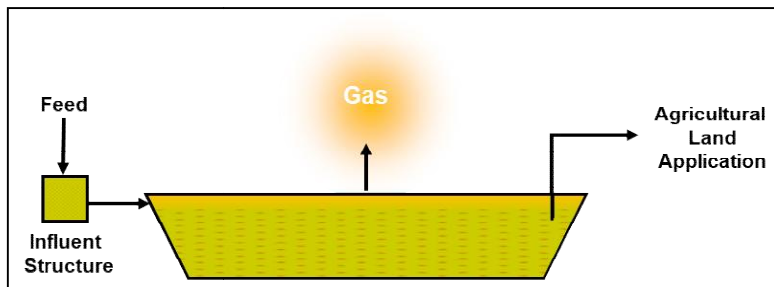


Fig. 17. Process sketch of an agricultural lagoon system [104]

influent structure into the lagoon either in ground or above ground. In many cases a solid removal system such as a settling tank, bow or gravity screen, screw or belt press are required to remove large solids such as bedding material, sand and large undigested food particles that can settle, short circuit and or plug the tub digester. The biogas produced is removed on top of the liner for further processing.

The pretreated manure enters the Lagoon with 0.5 to 2% solids content [112,113] and operation temperatures is between preferably 30° to 35° [112]. Lower temperatures require higher retention time, whereas at temperatures below 15°C anaerobic bacteria become ineffective [112]. Anaerobic lagoon systems have most times built with a depth of 2.4 to 6.0 m (8 to 20 ft) and contain a earth or Polyethylene (PE) liner.

allow no short circuiting and should have a freeboard of 0.9 m (3ft) [112, 113]. A larger lagoon depth is recommended to minimize surface area and provide better heat retention in the reactor [112]. the size of the lagoon depends on the agricultural operation storage requirements and retention time of the lagoons

AD system. Sizes of 0.5 to over 2 acers can be found [113]. Agricultural lagoon systems are generally not heated and operate at ambient temperatures [112] with retention times of 1 to 50 days depending on lagoon size [114,112], but can also be up to 360 days depending of the facility management [115]. Covered agricultural lagoons are able to utilize high manure solids concentrations of up to 12% solids content that might plug other AD systems because they include large dilution volumes that result in very low Organic Loading Rate (OLR) that range from 0.05 to 0.2 kilograms COD per cubic meter per day (3.1 and 12.5 lbs. COD/1,000ft³/d). The HRT for covered anaerobic lagoons can vary from 60 to 360 days, depending on the management of the facility. Typically, heated lagoons will have a much shorter HRT than ambient temperature lagoons [115]. In addition, prior to entering the lagoon settling basins remove grit such as sand used for animal bedding. Due to their operation under ambient temperatures. Anaerobic Lagoons are mostly found in areas that have elevated temperatures year-round such as the southern and western U.S. [112]. The lagoons cover is a gas tight flexible and floating are covered [112].

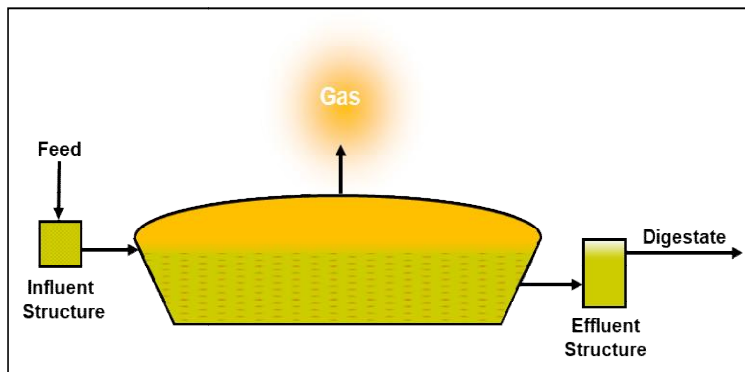


Fig. 18. Diagram of an anaerobic lagoon system [111]

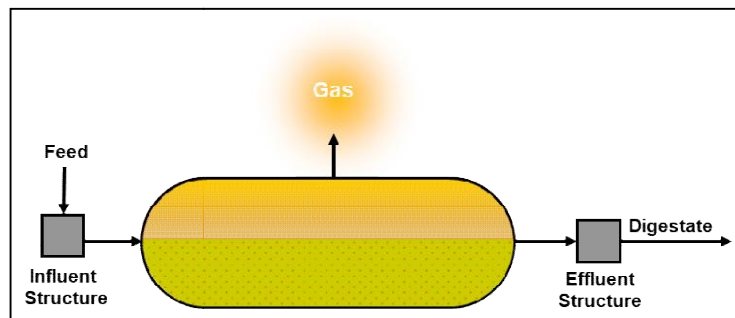


Fig. 19. Diagram of a tube digester system [116]

4.14. Anaerobic Tube Digester

Another form of the lagoon digester is the Tube Digester (TD) system shown in Fig. 19. The to digest material enters the TD at one end and exits the TD after a HRT of 20-50 days on the other end through an effluent structure. 50% to 60% of the TD volume is utilized for material to digest. The remaining volume is utilized as biogas storage. The produced biogas is removed on top of the tube and transferred to the energy converting unit.

Temperatures are in the 20°C to 35°C range [117]. TD can be built as a rectangular concrete tube [115] or Polyethylene (PE) long tube of up to 50 m in length and volumes of up to 1000 m³ [118]. TD build out of PE tube are mostly found in developing countries with diameters of up to 9 m [117, 118], were concrete TD versions can be found more in industrialized countries due to higher digester cost and regulatory requirements. Both systems are inexpensive to operate, because no mechanical and/or computerized systems are needed for operation. They can be built with diameters of up to 9 m in diameter and operating volumes of up to 1000 m³ [118]. TD They operate under the same conditions as lagoon digester and have a feed solids content of 2% [112]. In many cases a solid removal system such as a settling tank, bow or gravity screen, screw or belt press are required to remove large solids such as bedding material, sand and large

undigested food particles that can settle, short circuit and or plug the tub digester.

4.15 Plug Flow Anaerobic Digester

Plug Flow Anaerobic Digester (PFAD) systems are designed to move the to digest material in a “plug” through the digester. As the new material enters the digester on one side a certain volume of the digester is displaced and forced to exit the digester on the other side. PFDA can also be used feed co-digestion material. The operational consistency is up to 14% [115] solids content. If feedstock at lower solids content is used, settling occurs and feedstock separates into a floating layer and heavier feedstock on the bottom, resulting in short circuiting of the digested material between the layers as it makes its way through the digester. The produced biogas is removed on top of the plug flow digester and transferred to the energy converting unit.

The Organic Loading Rate (OLR) for a plug-flow system is typically between 1- and 6-kilograms COD per cubic meter per day (62.3–374 lbs./COD/1,000 ft³/d), with a HRT between 18 and 20 days [115]. Plug flow digester require operating temperature is in the range of 15°C to 30°C, same as for lagoon and tub digester if operated, and are generally not heated. Lower temperatures require higher retention time, whereas at temperatures below 15°C anaerobic

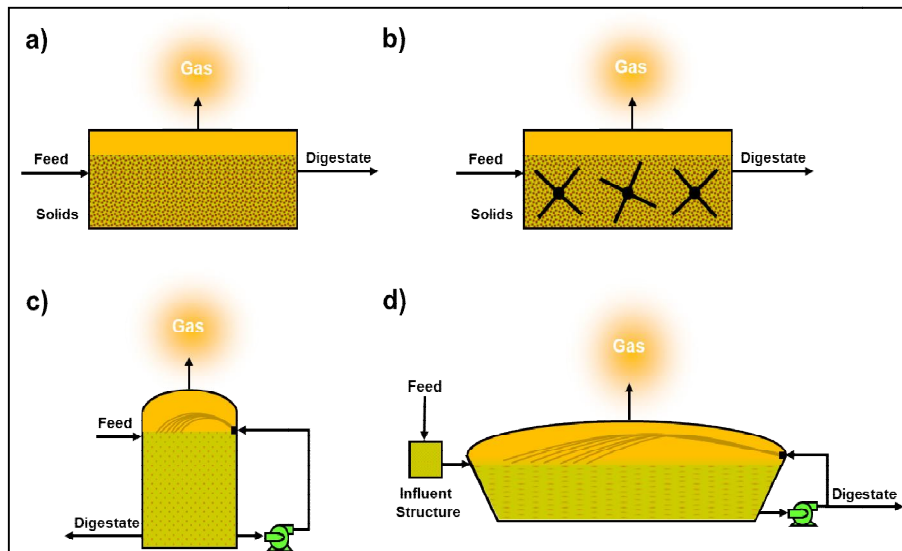


Fig. 20. Diagram of an plug flow digester system, a) vessel unstirred (lagoon type), b) vessel stirred (pipe type), c) digester with external recirculation (tank style), d) large lagoon vessel with external recirculation [119]

bacteria become ineffective [112]. HRT of PFAD systems are 20 to 60 days depending on PFAD size, feedstock and facility management.

Fig. 16 shows four versions of plug flow digesters. Fig. 20 a & d represents a conventional plug flow digester vessel either in rectangular tube style version [115], or pipe style design [120] with and without mixing. Solids content can be up to 50% in force stirred pipe style digester types [25]. Fig. 20 c & d represent large vessel plug flow digesters incorporating external recirculation by pumping the digester suspension externally out of the digester on the bottom and spraying the material continuously on top of the liquid layer. This creates a downward flowing plug layer and a homogenized anaerobic digestion [121]. As the substrate is pumped out of the vessel, a heat exchanger can allow heating of the substrate before it is sprayed as a layer in the digester vessel [121]. In addition, heating of the substrate allows the PFAD to operate at a constant temperature avoiding seasonal low operation temperatures. This creates better anaerobic decomposition of the material which results in a higher throughput, biogas production and better operational performance.

4.16 Dry Anaerobic Fermentation Process

The Dry Anaerobic Fermentation Process (DAFP) system, shown in Fig. 21, allows the anaerobic digestion of dry substrate without mixing or pre reparation above 15% to up to 50% solids content [25,123]. The organic substrate for

AD is moved into an air and gas tight compartment, called dry fermenter (DF), and an AD process is initiated by controlled sprinkling digester liquid, called pergulate, with a consistency of approximately 1 to 2% solids content onto the organic substrate. The pergulate trickles down the organic substrate and initiates the AD process. As the pergulate trickles down the biomass it retains small fractions of the biomass. The pergulate is collected on the bottom of the RC and moved back into the AD tank where it continues to digest. Biogas is produced and collected from the gas tight DF and the AD vessel. During the AD process in the DF the biomass is reduced by approximately 30% [123]. The produced biogas is transferred to the gas conversion unit such as an engine and generator to produce electricity and heat, or boiler for heat or steam production, or forwarded to an gas cleaning upgrade unit for the production of renewable compressed biogas (RCB) [124]. Digestate can be removed periodically or continuously for land application as fertilizer.

A staggered operation of multiple DF with volumes of 100 m³ and a loading capacity of up to 100 t fresh biomass [125] is necessary to ensure a continuous biogas production during an approximately up to 21-day HRT operation at a temperature of 42°C to 44°C [123, 125]. Monitoring of the biogas production ensures optimum time between loading and emptying the RC. After emptying the RC the digested biomass is converted into compost for agricultural applications [123].

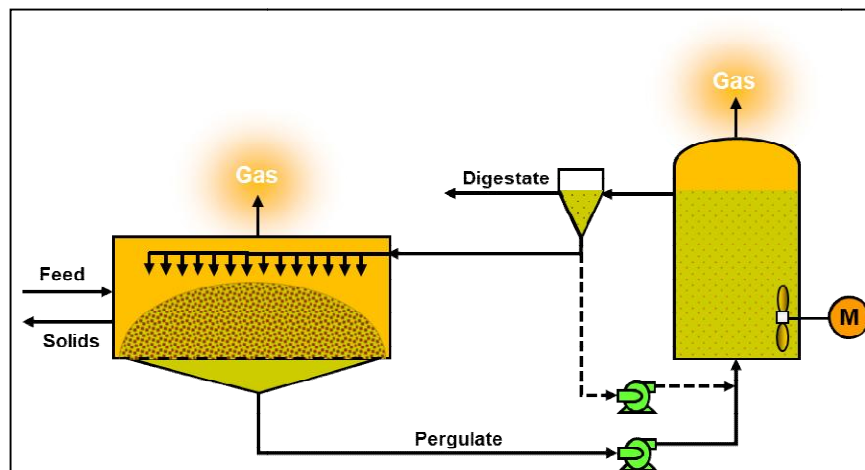


Fig. 21. Dry anaerobic fermentation system [122]

6. BIOGAS CONVERSION PROCESS

Fig. 22 represents a Biogas Production and Conversion (BPC) Process. Biogas is produced from a variety of feedstocks such as agricultural waste from livestock (milk cows, beef cattle, swine and poultry), crop residues, plant biomass. Industrial waste (food and beverage production residues, distiller grains) and municipal process waste (sewage sludge, municipal organic waste) [28,34,81,86] can be used as single or co-digest feedstock for AD processes. AD Feedstock can have solids content of up to 40% as shown in Table1 [25,58].

Therefore, it is important to select a suitable AD process for the feedstock that is processed in order for good operational stability and good biogas production. The sludge and effluent produced during digestion, especially from agricultural and food waste operations can be used as liquid fertilizer on farm fields. If solids are separated out compost and or animal bedding can be generated. The compost produced can be applied as fertilizer back onto farm fields or green house operations. The produced Biogas can be used in an cogeneration unit which consists of an internal combustion engine that drives an electrical generator [25]. The engine heat from the combustion process can be utilized as heat source for heating the anaerobic digester and

farm buildings or supplied as heat to industrial and residential buildings as well as process heat for industrial operations. The electricity generated can be used to offset energy needed on the farm e.g. to run ventilators and or milk cooling equipment. Excess energy may be sold and fed into the local energy companies' electric grid or sold to industrial or residential customers. Instead of running a co-generation process the biogas can be upgraded to natural gas quality by removing CO₂ from the produced biogas. Technologies employed are adsorption, absorption and membrane technologies [25,127, 128] using processes such as and sold to energy companies, industrial, municipal and residential users. After purification biogas can be compressed and fed into energy companies natural gas pipeline. Upgraded and Compressed Biogas (CBG) and Liquefied Biogas (LBG) can be used for farm vehicle, offsetting operation cost, or sold as commercial fuel for trucks and cars. LBG can be also transported larger distances using tanker trucks [25,127,128]. The generation of bioenergy for agricultural municipal and industrial application has led to over 163 bioenergy communities in Germany as of 2019. These communities produce a minimum of 50% of their electricity and heat from renewable resources incorporating biomass conversion technologies such as AD [129].

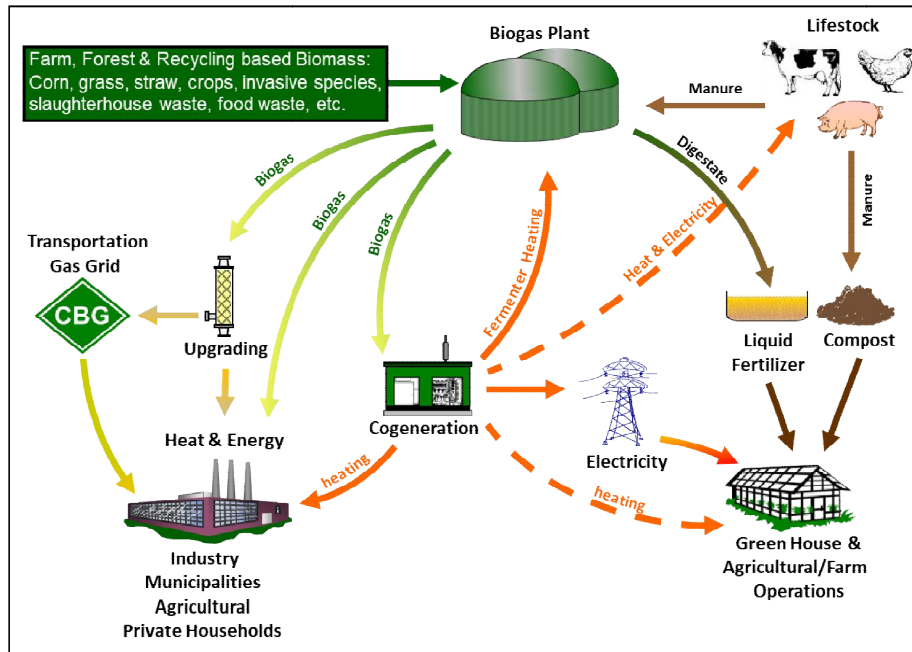


Fig. 22. Biogas production and conversion process [126]

6. CONCLUSION

Three-quarters of the global energy consumption is expected to come from fossil fuels by 2040 despite many drawbacks to the world's reliance on fossil fuels. The primary drawback of fossil fuels are in procuring, transporting, refining, and combusting them which generates pollution byproducts, global warming, which in turn generate a plethora of associated problems.

Biomass as a renewable resource and its conversion into renewable fuel products by AD can offset use and drawback of fossil fuels. AD is known since the 10th century BC has become today a versatile tool to produce renewable energy in form of biogas from many organic containing feedstock sources. These sources can be agriculturally based such as livestock waste, energy crops, plant (lignocellulosic) based, forest residues, or industrial and municipal waste such food waste, wastewater treatment sludge, distiller grains and food product residues.

Feedstocks can be used in anaerobic fermentation processes as single or co-digest feedstock. Feedstock can have solids content of up to 50% and different compositions which represents a challenge on its own for anaerobic digestion processes in order to achieve good operational stability and good biogas production.

Selecting a suitable AD process and temperature from today's available technical sound processes is essential to ensure stable process conditions. AD operation temperatures can be under 20°C (68°F) for psychrophilic, above 20°C to 45°C (68°F to 113°F) for mesophilic, and above 45°C to 55°C (113°F to 131°F) for thermophilic conditions. However, unheated AD lagoons and large type vessel systems may have operational drawbacks based on local weather conditions that may result in operating temperatures in the psychrophilic and or mesophilic range.

Feedstock solids content determines the implemented AD process. Most AD processes operate under mesophilic condition at HRT of approximately up to 30 days, whereas thermophilic condition require higher heating costs but yield faster biomass conversion below 15 days HRT. Psychrophilic condition result in a longer HRT above 60 days and less biogas production.

Low to medium solids content of below 1% to 3% solids content is suitable for activated sludge bed reactor, fixed bed reactors, low rate, hybrid type reactors, tube type reactors, and covered lagoon reactors are suited. However, lagoon type AD reactors require a large land area for implementation. In addition, AD Lagoon reactors are more suited for high volumetric volume processing and small particles which do not cause problems to the sludge bed formation and stability or cause plugging of the fixed bed material.

For medium solids contents between 3% and 8% mostly stirred type reactors are used with a HRT of approximately 20 days. Most of these reactors operate in the mesophilic range and can handle larger biomass particles such as cut straw and grass, animal bedding containing straw and sawdust.

High solids content above 8% to the upper limit of 15% due to associated pumping and mixing problems utilizes plug flow digester types with a HRT of approximately 20 days. Unstirred and stirred AD vessel applications are suited at the lower end of the solids content, whereas at the higher solids content pipe type stirred systems and vessel type AD systems with external recirculation are suited.

For extreme high solids contents over 15% dry anaerobic fermentation systems and forced plug flow systems are suitable for biogas generation with an HRT of 21 days at mesophilic conditions.

Selecting the right feed stock, anaerobic fermentation technology, and AD temperature is essential for future energy production of entities such as farms, industry and community to become independent from fossil fuels.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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