Anaerobic Digestion (AD) for Organic Waste/Sludge Treatment/ Energy Recovery

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History

- Ancient technology
- First Anaerobic Digestion plant in Bombay in 1859
- In 1895 Methane produced by AD was used to light street lamps in Exeter, England

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Introduction

- Anaerobic digestion (AD) is the method of organic wastes treatment aimed at decomposition of complex organic substances into simple, chemically stabilized compounds, mainly methane and CO_2 and digestate (biofertilizer a.k.a Compost).
- This conversion of complex organic compounds to methane and CO_2 is possible due to the cooperation of four different groups of microorganisms: fermentative, syntrophic, acetogenic, and methanogenic bacteria.
- The main process steps of anaerobic digestion of organic wastes are: hydrolysis, acid formation, acetogenesis, and methanogenesis.
- Microbes adopt various pathways to evade the unfavourable conditions in the anaerobic digester like competition between sulphate reducing bacteria (SRB) and methane forming bacteria for the same substrate.
- Sewage Treatment Sludge, Organic Food Waste, Animal Manure can all be used as feed stocks.

Classification based on Temperature Range

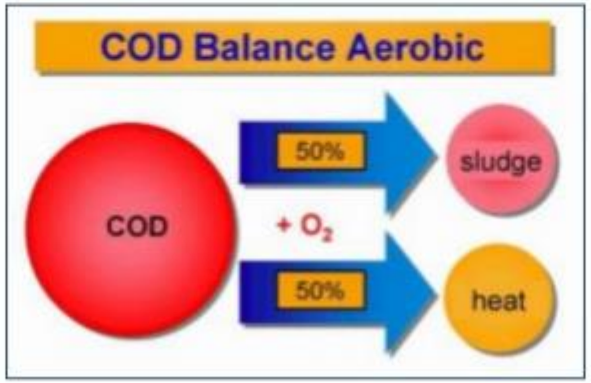
- Anaerobic digestion of sewage sludge is an energy/nutrient recovery technology (Metcalf & Eddy, 2014). Anaerobic digestion is usually performed under mesophilic (around 30–37 °C) or thermophilic (around 50–55 °C) Thermophilic conditions show a higher volume and rate of biogas production at the same C/N ratios. Approximately 30% higher volume of biogas production is achieved compared with mesophilic conditions. Better pathogen destruction is also achieved.
- Mesophilic digestion systems are generally more stable than thermophilic systems due to the fact that a wider diversity of bacteria grow.
- conditions (Fair and Moore, 1934).

Residence Time

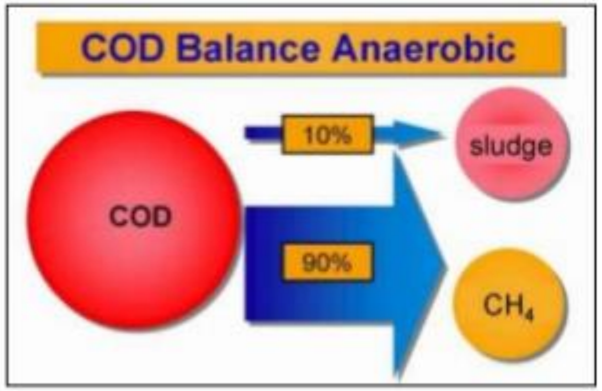
- In a typical two stage mesophilic digester, residence time varies between 15 and 40 days
- A single stage thermophilic digester, residence time is normally around 14 days
- Ephyra ™ asserts that it cuts digester residence time to 8 days.

AD Compared to Aerobic WW Treatment

COD Balance Aerobic Biodegradation

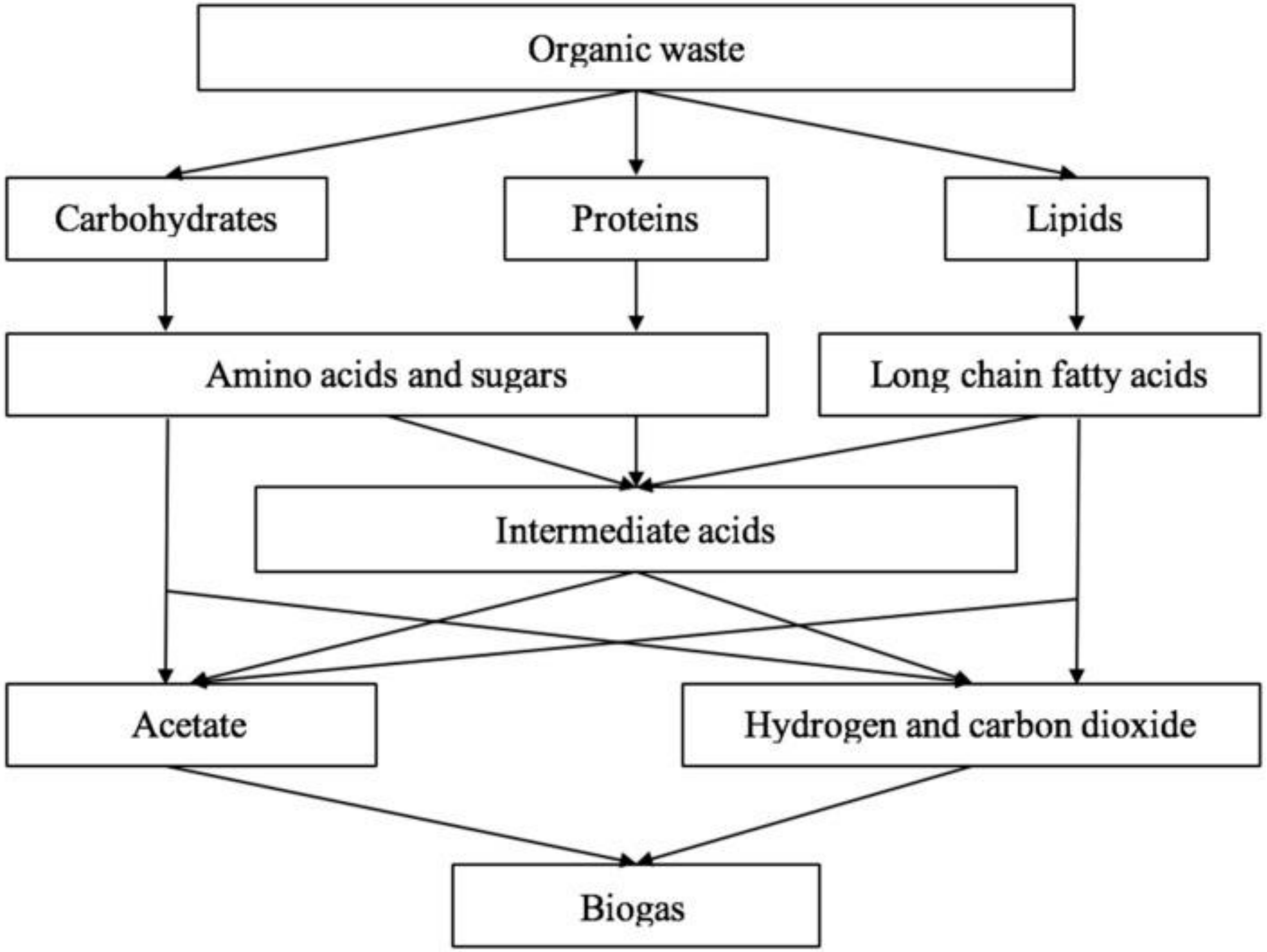


COD Balance Anaerobic Biodegradation



Disadvantage of AD compared to Aerobic Biodegradation is that the start up time of an AD reactor can be up to 3 months compared to 2 weeks for aerobic reactor. In case of availability of Seed culture, it’s much shorter.

Groups of Organic Waste



Hydrolysis

- During hydrolysis of the polymerized, mostly insoluble large organic compounds, like cellulose/carbohydrates, proteins and fats, are broken down into soluble monomers and dimers, that is, monosaccharides, amino acids, fatty acids and alcohols. Hydrolysis of fats is temperature sensitive. It does not work too well at low T.
- This is accomplished through enzymes from the group of hydrolases (amylases, proteases, and lipases) produced by appropriate strains of hydrolytic bacteria.
- Hydrolysis is carried out by bacteria from the group of relative anaerobes of genera like Streptococcus and Entero bacterium
- This step is very slow and **rate limiting**.

Hydrolysis of Cellulose – Chemical Reaction

$$(C6H10O5)n + n\ H2O \rightarrow n\ C6H12O6 + n\ H2$$

What can be noted from the chemical reaction in is the hydrolysis of cellulose ($C_6H_{10}O_5$) via reaction with water (H_2O) to form glucose ($C_6H_{12}O_6$) as the primary product and giving off H_2.

Acidogenesis a.k.a Fermentation

- During this stage, acidifying bacteria convert water-soluble chemical substances, including hydrolysis products, to short-chain organic acids (formic, acetic, propionic, butyric, and pentanoic), amino acids and peptides, alcohols (methanol, ethanol), aldehydes, carbon dioxide, and hydrogen.
- Among the by-products of acidogenesis are ammonia and hydrogen sulphide which give an intense unpleasant smell to this phase of the process.
- The acid phase bacteria belonging to facultative anaerobes use oxygen accidentally introduced into the process, creating favourable conditions for the development of obligatory anaerobes of the following genera: Pseudomonas, Bacillus, Clostridium, Micrococcus, or Flavobacterium.
- This step lowers the pH in the reactor and if not buffered becomes toxic to the biomass. It also consumes H2.

Acetogenesis

- In this process, the acetogenic bacteria including those of the genera of Syntrophomonas and Syntrophobacter convert the acid phase products into acetates and hydrogen which is used by methanogenic bacteria.
- As a result of acetogenesis, hydrogen is released, which exhibits toxic effects on the microorganisms which carry out this process. Therefore, a symbiosis is necessary for acetogenic bacteria with autotrophic methane bacteria that use hydrogen, a process referred to as syntrophy.
- Acetogenesis is a phase which determines the efficiency of biogas production, because approximately 70% of methane arises from the process of acetate reduction.
- The partial pressure of Hydrogen should be kept neither too low (rate limiting) nor too high (toxic).

Reaction Sequence of Acetogenesis

$$C6H12O6 \leftrightarrow 2\ CH3CH2OH \text{ (ethanol)} + 2\ CO2$$

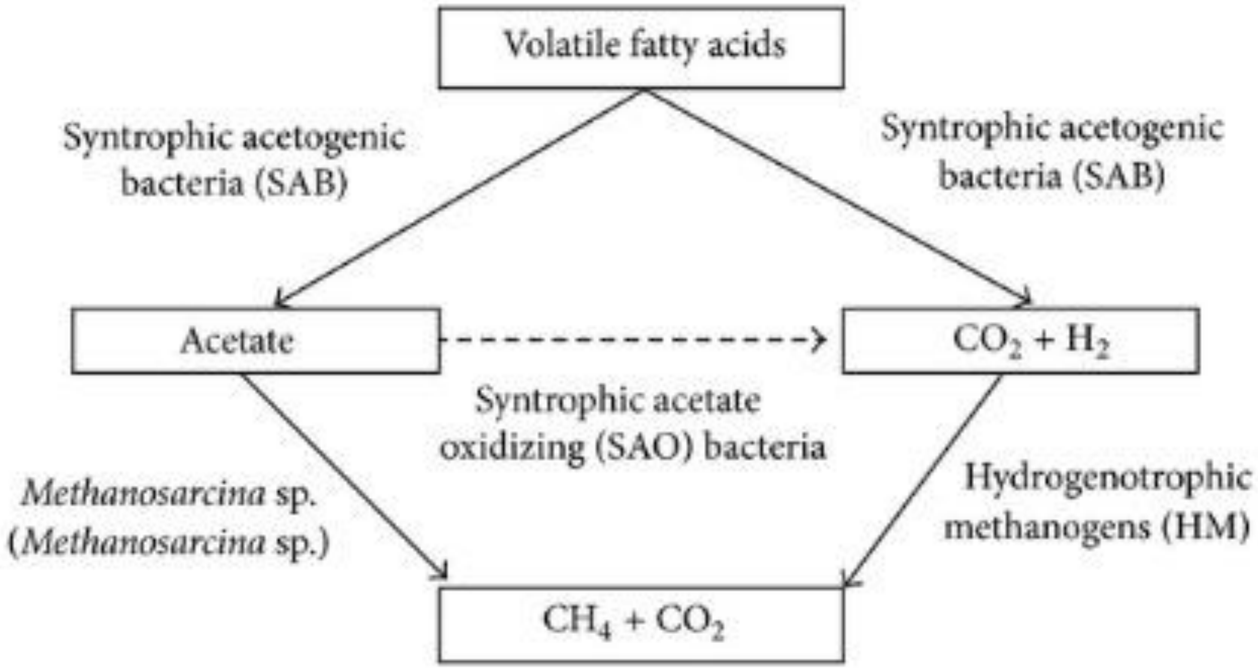
$$C6H12O6 + 2\ H2 \leftrightarrow 2\ CH3CH2COOH \text{ (propionic acid)} + 2\ H2O$$

$$C6H12O6 \rightarrow 3\ CH3COOH \text{ (acetic acid)}$$

Methanogenesis

- In this phase the production of methane by methanogenic bacteria occurs.
- Methanogens as absolutely anaerobic microorganisms inhabit anaerobic environment ecosystems, such as tundras, marshlands, rice fields, bottom deposit, swamps, sandy lagoons, tanks where wastewater is decomposed, sewage sludge, solid wastes landfills, and ruminants' stomachs (in the rumen).
- These microorganisms are particularly sensitive to changes in temperature and pH, and their development is inhibited by high levels of volatile fatty acids and other compounds, such as hydrogen, ammonia, and H_2S in the environment
- Among methanogenic microorganisms, we can distinguish psychro- (20 °C), meso- (35 °C) and thermophilic microorganisms (55 °C).
- The methanogenic Archaea are responsible for the final and critical step of anaerobic digestion, as they produce valuable methane.

Methanogenic Pathways



The SAB consist mostly of Clostridium sp. at both mesophilic and thermophilic conditions. The hydrogenotrophic methanogens in both mesophilic and thermophilic anaerobic digesters belong to the two orders of Methanobacteriales and Methanomicrobiales

Methanogenesis Reactions

$CH3COOH \rightarrow CH4 + CO2$

$CO2 + 4\ H2 \rightarrow CH4 + 2\ H2O$

$2\ CH3CH2OH$ (ethanol) $+ CO2 \rightarrow CH4 + 2\ CH3COOH$ (acetic acid)

Process Factors Influencing AD

- Retention Time
- pH: ideally between 6.8 and 7.2
- C:N Ratio
- Mixing
- Temperature
- F/M Ratio or Organic Loading Rate (OLR)
- Alkalinity
- Trace Metals (Micronutrients ex. Mg, Ni and Co)
- Concentration of Sulphate (SRB's favouring)
- Pollutants
- Presence of O2
- Microbiology of the Biomass
- Total Ammonia Nitrogen (TAN)
- Hydrogen Partial Pressure (HPP)

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Volatile Fatty Acids to Alkalinity Ratio

- The FOS/TAC (VFA/ALK) ratio is a process monitoring ratio:

- A VFA/TA ratio of **0.23-0.3** constitutes a stable range for AD, and a quotient <0.23 is an indication of an under-fed AD...

Adding Olivine and Trace Metals

- Addition of finely powdered Olivine, a magnesium silicate, and trace metals such as Nickel and Cobalt helps with achieving higher rates of Methanisation according to Scholarly articles
- An additional benefit is that some of the CO_2 is sequestered In-Situ by the Magnesium Oxides.

Adding ZVI to Enhance AD

- The rate limiting steps in AD are hydrolysis and acidification.
- Zero Valent Iron (ZVI) as a reducing material is expected to enhance AD by speeding up the hydrolysis and acidification steps.

Adding PAC/GAC

- Adding activated carbon can stabilize the process by binding up toxic ammonia.

Technologically Five Process Stages

- Pre-treatment/Hydrolysis
- Anaerobic Digestion
- Gas Treatment (scrubbing out H_2S and CO_2)
- Digestate treatment (sterilization) - Dewatering
- Supernatant Aerobic/ANNAMOX Treatment (digester supernatant is high in P and Ammonia-N as AD does not reduce these nutrients they might actually increase)

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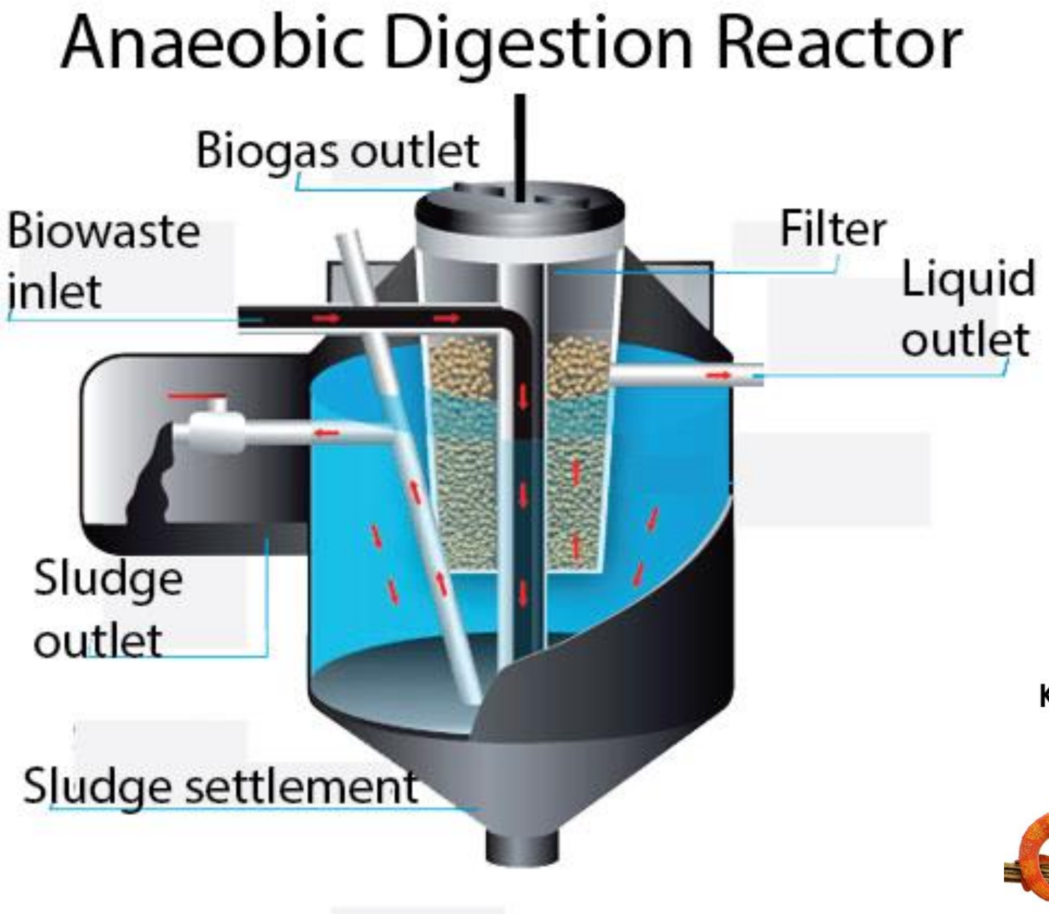
Chemistry of AD

- Several factors affect the performance and stability of AD systems; among them are process chemistry linked to interspecies hydrogen transfer (IHT), hydrogen partial pressure (HPP), the use of microbial electrochemical systems (MES) and non-biological conducting materials (like GAC) to improve microbial interaction.
- Carbon, nitrogen and oxygen (C, N, and O) are the main components of the organic matter that are used up by the consortium of microorganisms in the digestion process.

Types of Digesters

- 6 main types of Anaerobic Digesters: Complete Stir Tank Batch Reactor (CSTR), Plug-Flow, Packed Bed Biofilm AD, Covered AD Lagoon, UASB (upflow anaerobic granules sludge bed reactor) and **BIOPAQ®IC** (internal circulation).
- Excellent e-Learning Video on Types of Anaerobic Digesters: https://www.youtube.com/watch?v=u_ArD9jemaE

Large AD Vertical Reactor Schematic (Municipal AD)



Large Egg Shaped Digesters (Municipal)

A Plug Flow AD Horizontal Reactor for Farms

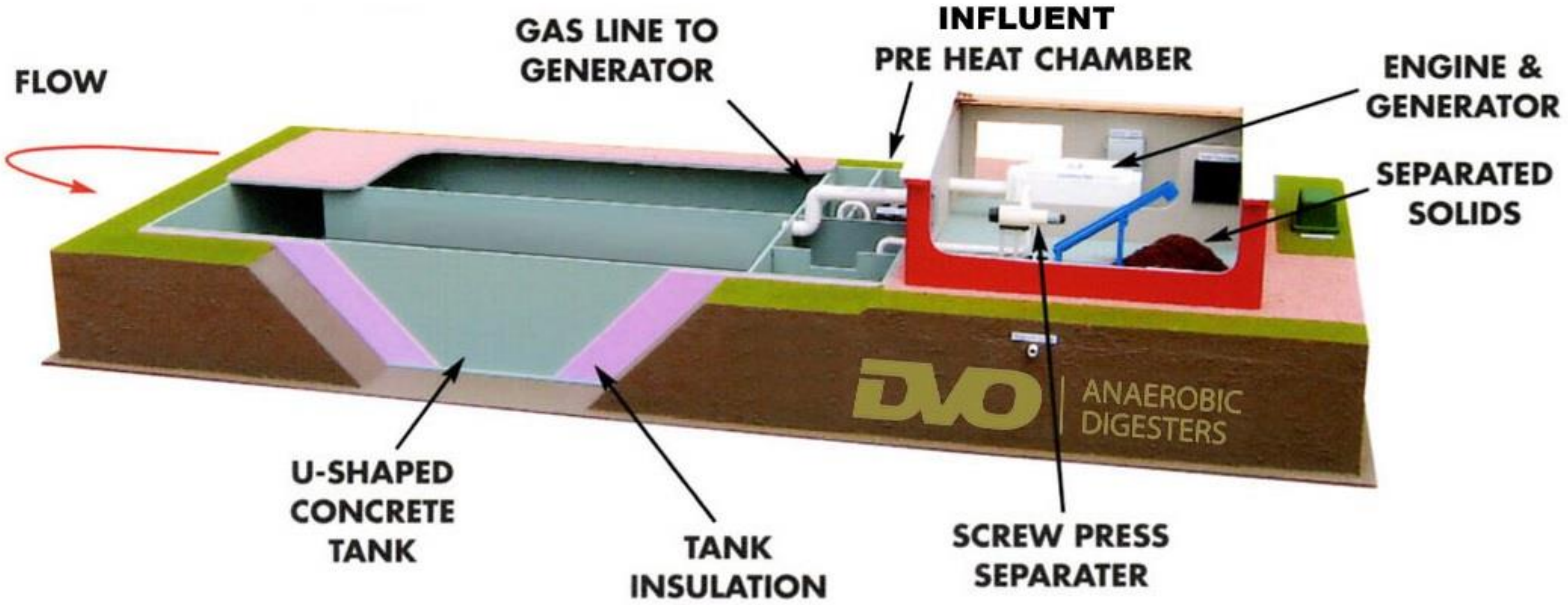
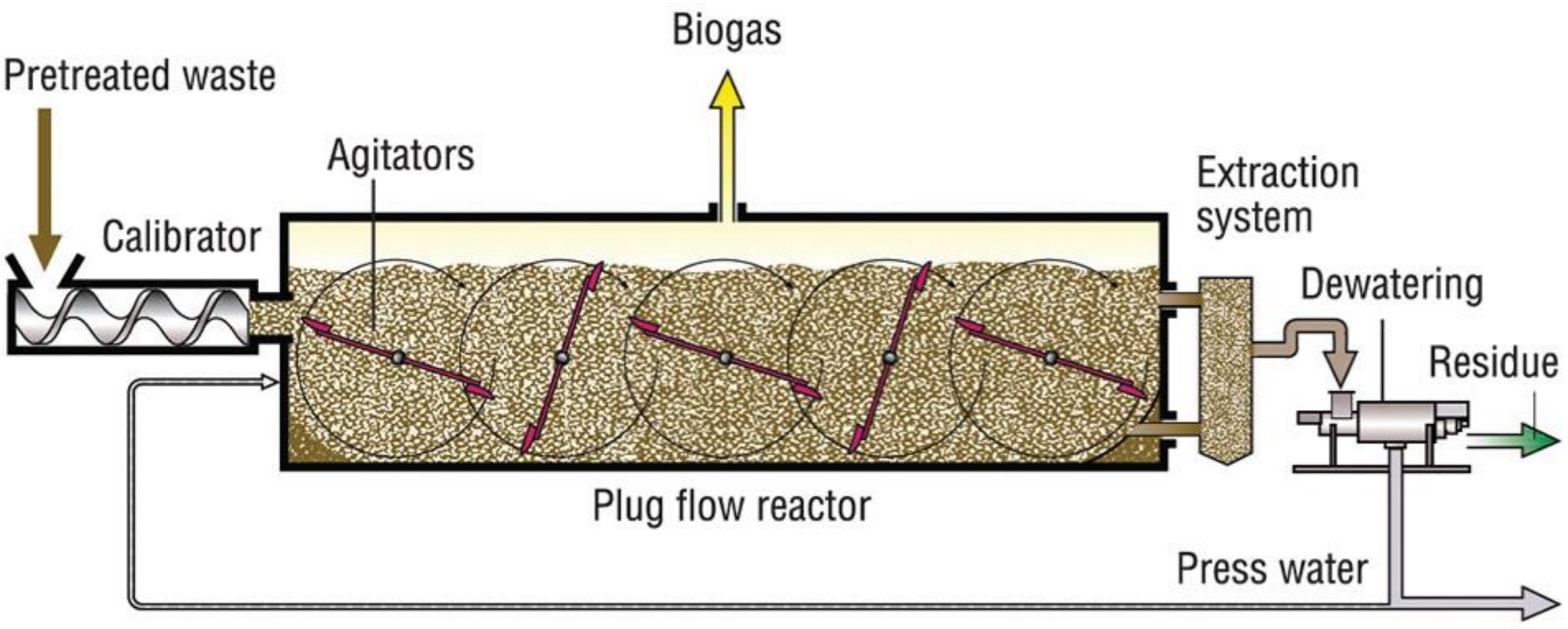


Photo of Farm Horizontal AD – 750 kW

Plug Flow Reactor Schematic

Figure 2. Schematic of the Strabag LARAN® dry plug flow reactor



Source: Strabag Umweltanlagen GmbH

Upflow (Granular) Anaerobic Sludge Blanket Process - UASB

- Developed in Holland by Dr. Gatze Lettinga in the 1970s
- High Rate
- Positive Energy Footprint
- Low sludge production
- Popular - 72% of all AD plants are based on UASB
- Up to 90% Removal efficiency of Biodegradable COD
- Up flow encourages formation of heavier granules and washes out suspended bacteria
- The four top applications of high rate anaerobic reactor systems are for:
    - Breweries and beverage industry
    - Distilleries and fermentation industry
    - Food Industry
    - Pulp and paper.

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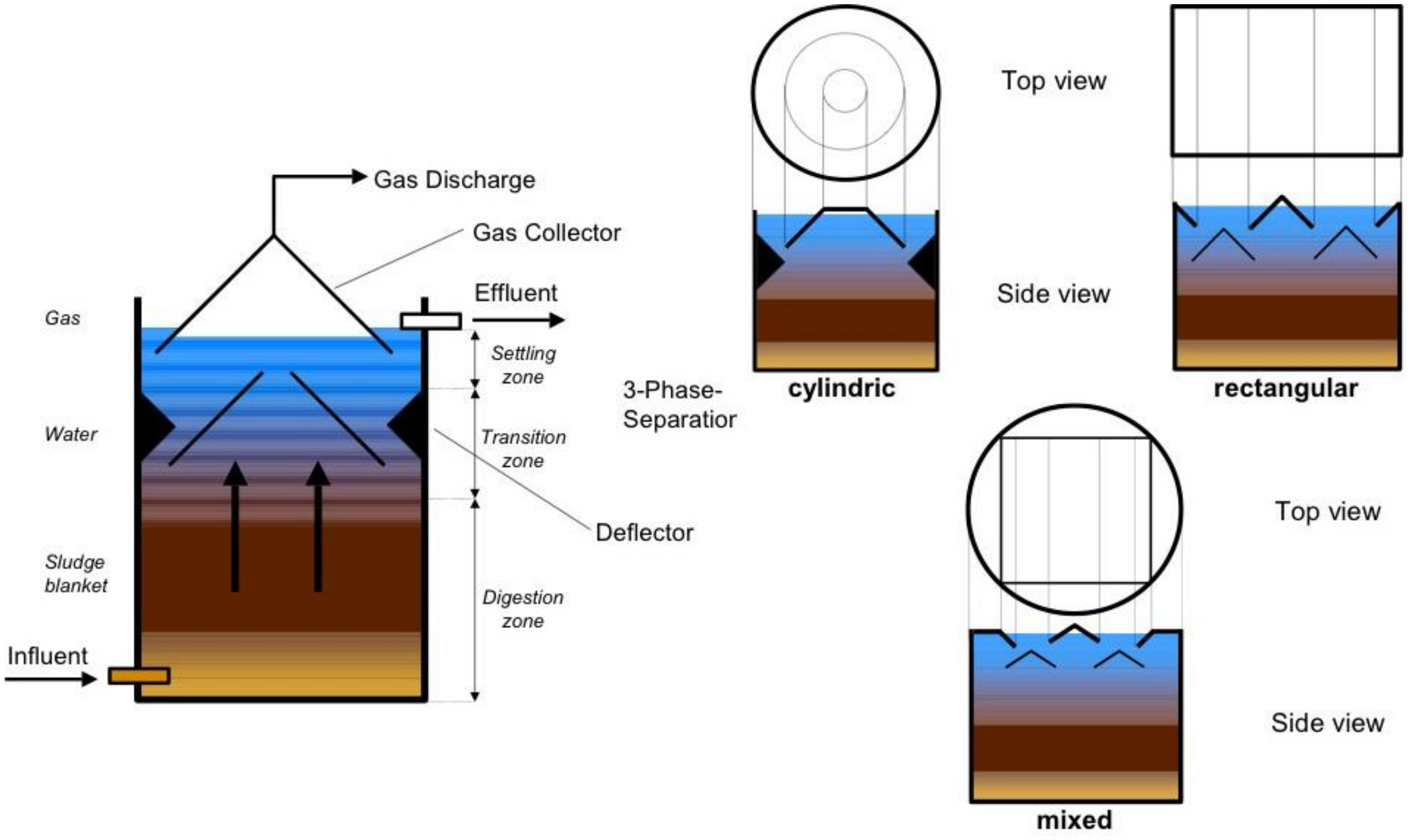
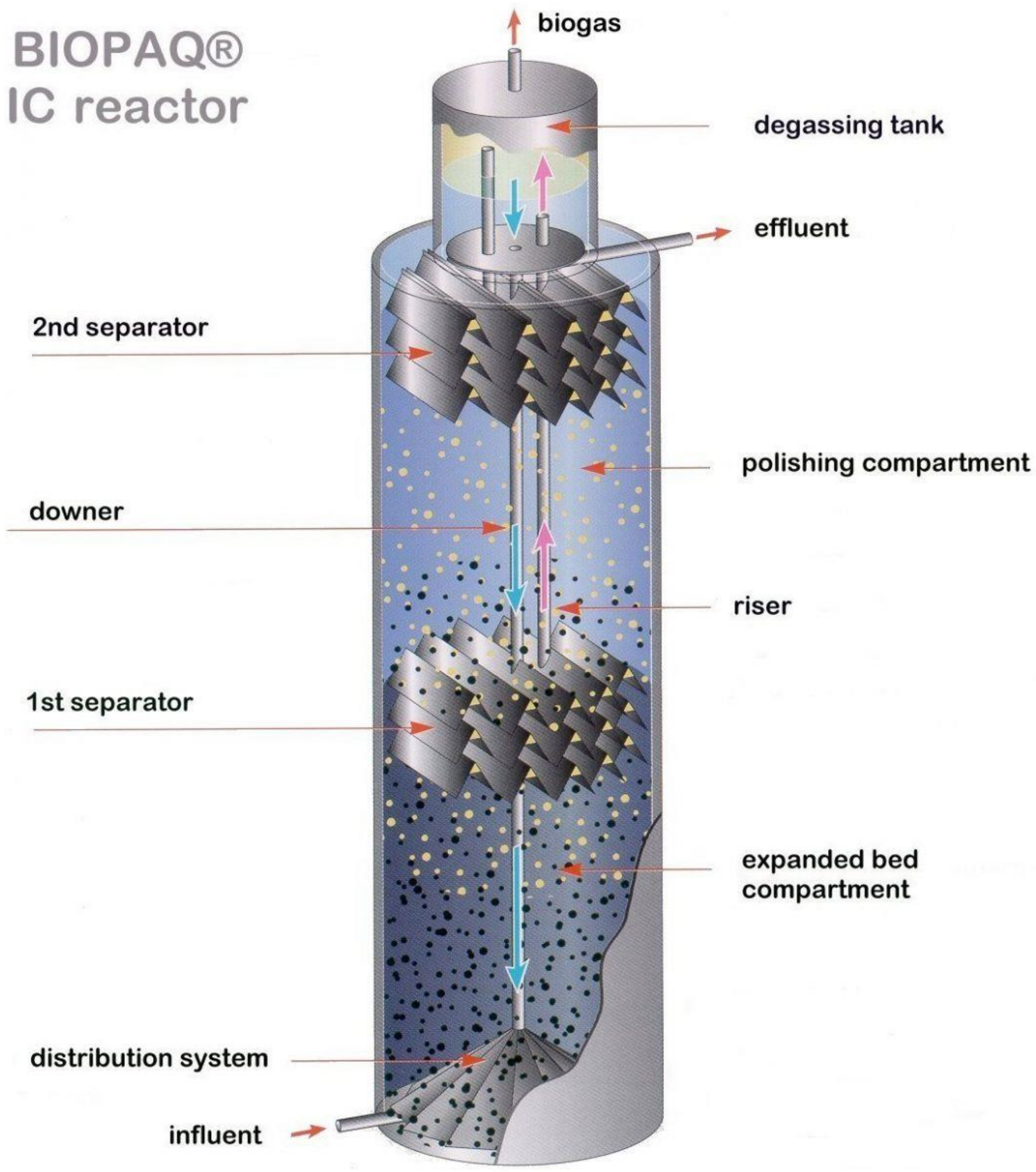
UASB Reactor



BIOPAQ IC (High rate, Expanded Sludge Bed Reactor)

https://en.paques.nl/products/featured/biopaq-anaerobic-wastewater-treatment/biopaqic

IC stands for Internal Circulation



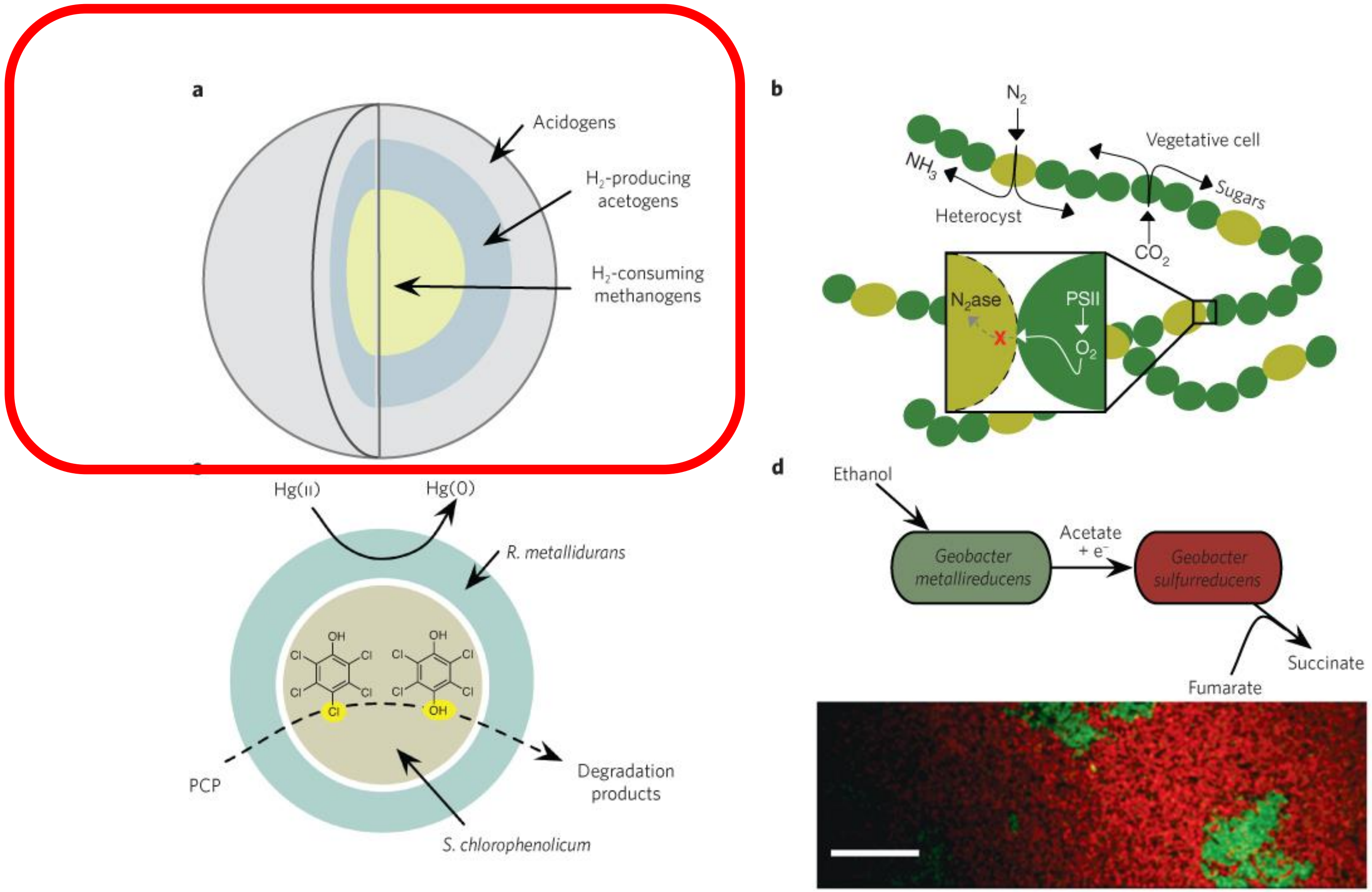
Ephyra ™ from Royal Haskoning

- Ephyra® A compact and sustainable technology for sludge digestion, Ephyra is based on plug flow digestion, where the hydraulic retention time (HRT) and solids retention time (SRT) are separated by using modular design. Reactor design, process control and operations have been optimised to improve performance and increase capacity.
- Ephyra operates three or four digesters in series to achieve high-rate plug-flow anaerobic digestion. Controlled recirculation optimizes the conditions in each digester. A unique feature of Ephyra is that it enables digestion at a very short sludge retention time of just six to eight days. These short retention times result in increased reactor capacity and a reduced footprint for new build digesters. The system is operated by an advanced software platform, the Aquasuite® Ephrya Controller, which ensures stable operation of the Ephyra digesters and includes adjustable recirculation for optimum process performance.

- https://www.royalhaskoningdhv.com/en/services/ephyra

Granular Anaerobic Sludge

AD Sludge Granule Structure



Biogas Scrubbing and Drying

- Water vapor in biogas needs to be removed usually by condensing on cold surface
- H_2S in biogas is corrosive to engines and needs to be removed in caustic scrubber
- CO_2 can also removed in the same process
- Product is nearly pure CH_4 (methane)

CO_2 and H_2S Scrubbing

- Several technologies are available to separate CH_4 from CO_2, H_2S and other molecules in the gas stream. Membranes are one of them but require protection from siloxanes and other components. Desotec's mobile activated carbon filtration is an effective pre-treatment.

Main biogas purification needs removal of :

- VOCs
- Siloxanes
- Terpenes
- H_2S
- Ammonia (NH_3)

Other Methods

- The biogas passes through a bed of **activated alumina** where the siloxanes are removed and from which a purified gas emerges. Subsequently passing regenerative gas through the bed enables the activated alumina to be re-used for siloxane extraction again.
- Another technique to remove trace substances in biogas is using microporous **zeolite** materials. Zeolites are crystalline, nano-porous aluminosilicates composed of a tetrahedral lattice of Si and Al.
- Addition of **iron chloride** into the digester tank can lock up Sulphide if the pH is right.
- Negative pH scrubbers
- Using Olivine to lock up CO_2 in situ

Biogas Storage

Video of Anaerobic Digester Operation On Dairy Farm

- **Anaerobic Digester - Bellingham Technical College**

https://www.youtube.com/watch?v=7LPfno2KPcg

Digestate

- The sludge that is left after anaerobic digestion completion is called "digestate." Digestate is a wet mixture that is usually separated into a solid and a liquid. Digestate is rich in nutrients and can be used as fertilizer for crops.
- Biofertilizer application is subject to a strict code of practice in the UK as per the EA.
- It is banned in some countries such as Switzerland due to the risk of introduction of heavy metals, PFAS and other POP's.

Odor Control

1. Scrubber towers, packed with open plastic media, where the air is drawn upwards through the media against a counter flow of water containing a solution of chemicals to absorb and neutralize the ammonia, hydrogen sulphide, and other odorous compounds. The chemical solution will need treatment to remove the dissolved compounds, either by a treatment system installed onsite or taken away by a specialist waste management company for treatment offsite.
2. Activated carbon filters to absorb the ammonia, hydrogen sulphide, etc. The activated carbon filter media needs to be changed regularly to avoid it becoming saturated with absorbed gases and ceasing to work effectively. The media may be sent away for heat treatment so that it can be reused.
3. Air biofilters. These are towers or other containers packed with chipped wood or similar media, kept moist with water so that biofilm of aerobic bacteria and fungi develop, which biologically oxidize the ammonia, hydrogen sulphide, etc. to water and soluble, non-odorous compounds. The air being vented is drawn upwards through the media, which is kept moist by a downward trickle flow of water and dissolved nutrients (to maintain the biofilm). The main disadvantages of air biofilters is that they only become fully effective once the biofilm has become established on the media and they must be kept moist and aerobic at all times by maintaining a flow of air through them. In cold climates, the biofilters may need to be insulated/heated depending upon the temperature of the air being vented through them.

Disadvantages

- Poor operational stability still hinders the technology from being widely adopted
- CAPEX/OPEX required
- ROI may be too many years

Maintenance

- Maintenance of anaerobic digester tanks involves regular tank inspections, cleaning, and repairs of the system. The inspection process involves checking the structural integrity of the tank, including the roof, walls, and floors. Cleaning AD reactors is a very dirty job.
- Cleaning is also part of the maintenance routine
- It is important to follow ATEX rules as well as Confined Space safety procedures/protocols/standards

Suppliers of AD Technology

- Marches Biogas (http://marchesbiogas.com for farms - UK)
- DVO Inc USA (http://www.dvoinc.com for farms - USA)
- Bioconstruct Germany (http://www.bioconstruct.com/ for farms)
- OVIVO Water UK – AD for Municipals WWTWs (http://www.ovivowater.com/)
- Waterleau Belgium (http://www.waterleau.com) AD
- Degremont (http://www.degremont-industry.com/) for Municipal AD
- Paques from Holland (http://en.paques.nl/)
- Biothane of Veolia (http://technomaps.veoliawatertechnologies.com/biothane-uasb/en/)
- Royal Haskoning

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- Water Wiki
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- http://www.slideshare.net/zakiabedeen/anaerobic-aerobic-digestion
- http://www.sswm.info
- https://www.youtube.com/watch?v=yWckgtORS38
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