Introduction in the technical design for anaerobic treatment systems

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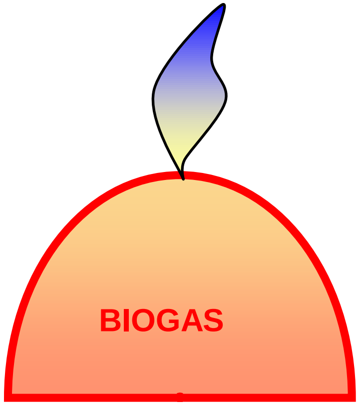
Sanitary biogas systems

- … are efficient, hygienic and ecologically sound wastewater treatment units with the additional benefits of energy production and an effluent of high nutrient content.
- … can be combined with any type of (low-)flush toilet (including pour flush) and their effluent can be used directly for fertiliser application and irrigation.
- … can be followed by constructed wetlands or other aerobic tertiary treatment to allow other forms of reuse of the effluent for car-washing, toilet flushing or outdoor cleaning purposes.
- The treatment of organic solid kitchen and garden wastes can also be integrated into the concept to increase biogas production and reduce household waste.
- Unlike septic tank systems, sanitary biogas units do not require frequent sludge removal.

Parameters which are influencing the digestion process are

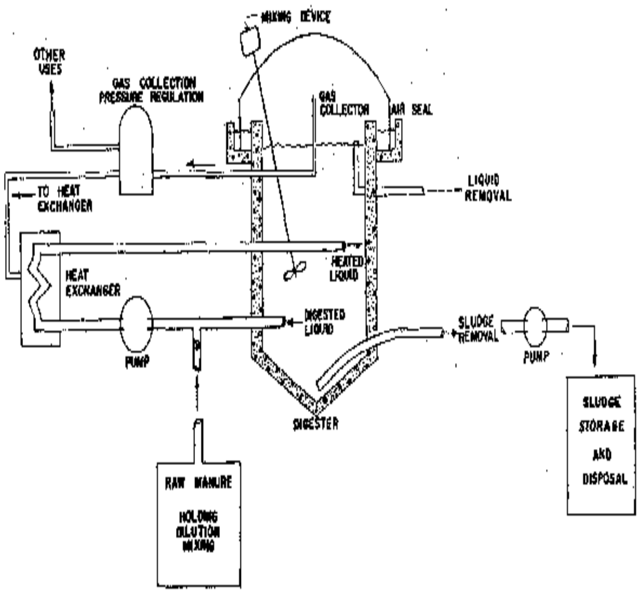
- Feeding — carbon
- Mix fresh and old material — inoculation
- Water — physical
- Temperature — conditions
- pH value — milieu
- Retention time — time to act



How does anaerobic treatment of solids differ from that of wastewaters ?

Anaerobic treatment of high solids such as animal manure, biological sludge, nightsoil, etc. is commonly known as “anaerobic digestion” and is carried out in airtight container known as anaerobic digester (AD).

- AD is usually continuous flow stirred tank reactor (CFSTR) for which HRT and SRT is nearly the same i.e the ratio of SRT/HRT = 1.



- Design is based on volatile solids (VS) loading rate

Anaerobic treatment of wastewaters requires long SRT to achieve better treatment efficiency

- The ratio of SRT/HRT ~ 10-100
- The high ratio allows the slow growing methanogens to remain in the reactor for longer time .

How do we achieve high SRT in anaerobic treatment system ?

Advantage of anaerobic process

1. Less energy requirement as no aeration is needed

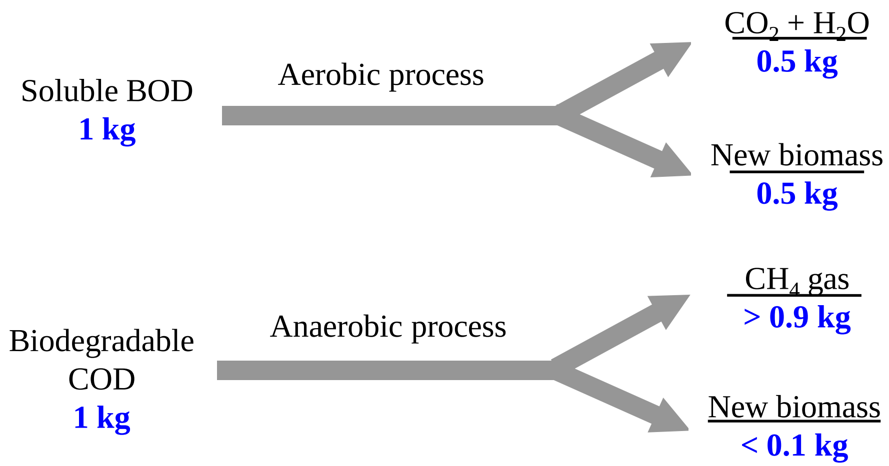
0.5-0.75 kWh energy is needed for every 1 kg of COD removal by aerobic process

2. Energy generation in the form of methane gas

1.16 kWh energy is produced for every 1 kg of COD removal by anaerobic process

3. Less biomass (sludge) generation

Anaerobic process produces only 20% of sludge that of aerobic process



4. Less nutrients (N & P) requirement

Lower biomass synthesis rate also implies less nutrients requirement : 20% of aerobic

5. Application of higher organic loading rate

Organic loading rates of 5-10 times higher than that of aerobic processes are possible

6. Space saving

Application of higher loading rate requires smaller reactor volume thereby saving the land requirement

7. Ability to transform several hazardous solvents including chloroform, trichloroethylene and trichloroethane to an easily degradable form

Limitations of anaerobic processes

1. Long start-up time

Because of lower biomass synthesis rate, it requires longer start-up time to attain a biomass concentration.

2. Long recovery time

If an anaerobic system subjected to disturbances either due to biomass wash-out, toxic substances or shock loading, it may take longer time for the system to return to normal operating condition.

3. Specific nutrients/trace metal requirements

Anaerobic microorganisms especially methanogens have specific nutrients e.g. Fe, Ni, and Co requirement for optimum growth.

4. More susceptible to changes in environmental conditions

Anaerobic microorganisms especially methanogens are prone to changes in conditions such as temperature, pH, redox potential, etc.

5. Treatment of sulfate rich wastewater

The presence of sulfate not only reduces the methane yield due to substrate competition but also inhibits the methanogens due to sulfide production.

6. Effluent quality of treated wastewater

The minimum substrate concentration (S_{min}) from which microorganisms are able to generate energy for their growth and maintenance is much higher for anaerobic treatment system. Owing to this fact, anaerobic processes may not able to degrade the organic matter to the level meeting the discharge limits for ultimate disposal.

7. Treatment of high protein & nitrogen containing wastewater

The anaerobic degradation of proteins produces amines which are no longer be degraded anaerobically. Similarly nitrogen remains unchanged during anaerobic treatment. Recently, a process called ANAMMOX (ANaerobic AMMonium OXididation) has been developed to anaerobically oxidize NH_4^+ to N_2 in presence of nitrite.

$$1NH_4^+ + 1.32NO_2^- + 0.066CO_2 + 0.13H^+ \rightarrow 1.02N_2 + 0.26NO_3^- + 2.03H_2O + 0.066CH_2O_{0.5}N_{0.15}$$

Comparison between anaerobic and aerobic processes

Anaerobic	Aerobic
Organic loading rate:	
High loading rates:10-40 kg COD/m^3-day (for high rate reactors, e.g. AF,UASB, E/FBR)	Low loading rates:0.5-1.5 kg COD/m^3-day (for activated sludge process)
Biomass yield:	
Low biomass yield:0.05-0.15 kg VSS/kg COD	High biomass yield:0.35-0.45 kg VSS/kg COD
(biomass yield is not constant but depends on types of substrates metabolized)	(biomass yield is fairly constant irrespective of types of substrates metabolized)
Specific substrate utilization rate:	
High rate: 0.75-1.5 kg COD/kg VSS-day	Low rate: 0.15-0.75 kg COD/kg VSS-day
Start-up time:	
Long start-up: 1-2 months for mesophilic : 2-3 months for thermophilic	Short start-up: 1-2 weeks

Anaerobic	Aerobic
SRT: Longer SRT is essential to retain the slow growing methanogens within the reactor.	SRT of 4-10 days is enough in case of activated sludge process.
Microbiology: Anaerobic process is multi-step process and diverse group of microorganisms degrade the organic matter in a sequential order.	Aerobic process is mainly a one-species phenomenon.
Environmental factors: The process is highly susceptible to changes in environmental conditions.	The process is less susceptible to changes in environmental conditions.

How much methane gas can be generated through complete anaerobic degradation of 1 kg COD at STP ?

Step 1: Calculation of COD equivalent of CH_4

CH_4 + $2O_2$ -------------------> CO_2 + $2H_2O$

16 g 64g

=> 16 g CH_4 ~ 64 g O_2 (COD)

=> 1 g CH_4 ~ 64/16 = 4 g COD ------------ (1)

Step 2: Conversion of CH_4 mass to equivalent volume

Based on gas law, 1 mole of any gas at STP (Standard Temperature and Pressure) occupies volume of 22.4 L.

=> 1 Mole CH_4 ~ 22.4 L CH_4

=> 16 g CH_4 ~ 22.4 L CH_4

=> 1 g CH_4 ~ 22.4/16 = 1.4 L CH_4 ---------- (2)

Step 3: CH_4 generation rate per unit of COD removed

From eq. (1) and eq. (2), we have,

=> 1 g CH_4 ~ 4 g COD ~ 1.4 L CH_4

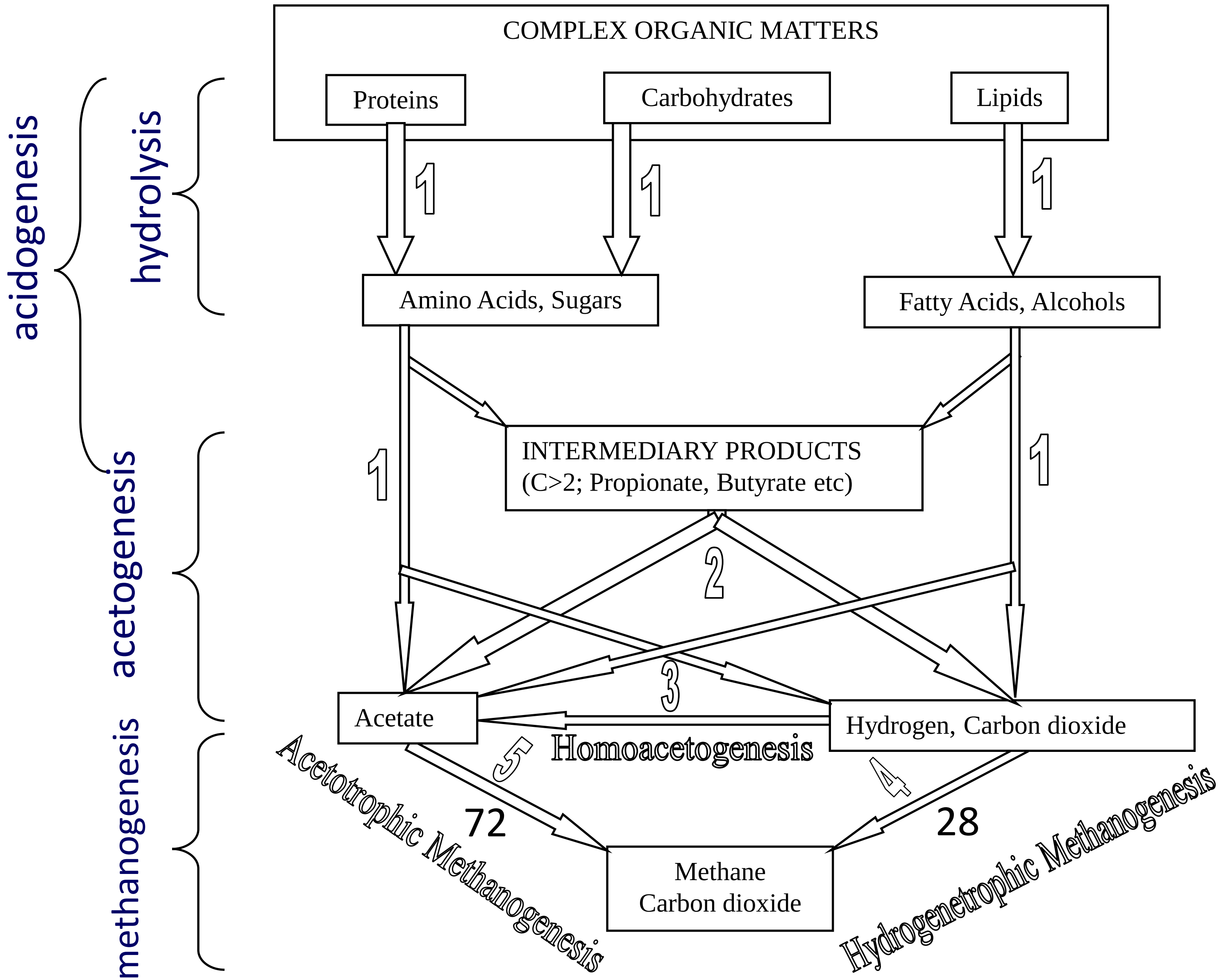
=> 4 g COD ~ 1.4 L CH4

=> 1 g COD ~ 1.4/4 = 0.35 LCH_4

or 1 Kg COD ~ 0.35 m^3 CH_4 ----------- (3)

complete anaerobic degradation of 1 Kg COD produces 0.35 m^3 CH_4 at STP

Organics Conversion in Anaerobic System



Essential conditions for efficient anaerobic treatment

- Avoid excessive air/O_2 exposure
- No toxic/inhibitory compounds present in the influent
- Maintain pH between 6.8 –7.2
- Sufficient alkalinity present
- Low volatile fatty acids (VFAs)
- Temperature around mesophilic range (30-38 ^{o}C)
- Enough nutrients (N & P) and trace metals especially, Fe, Co, Ni, etc. COD:N:P = 350:7:1 (for highly loaded system) 1000:7:1 (lightly loaded system)
- SRT/HRT >>1 (use high rate anaerobic reactors)

Environmental factors

The successful operation of anaerobic reactor depends on maintaining the environmental factors close to the comfort of the microorganisms involved in the process.

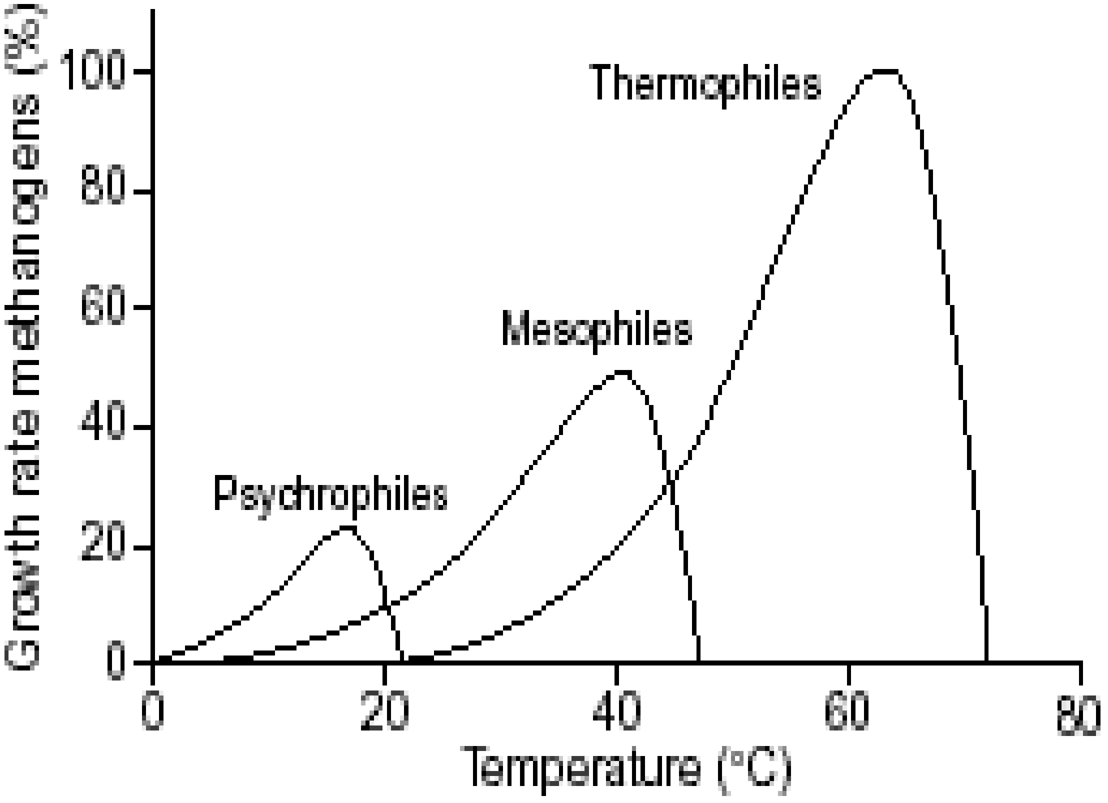
Temperature

- Anaerobic processes like other biological processes strongly depend on temperature.

- In anaerobic system: three optimal temperature ranges;

  - Psychrophilic (5 - 15^{o}C)
  - Mesophilic (35 – 40 °C)
  - Thermophilic (50-55 ^{o}C)

Effect of temperature on anaerobic activity



Rule of thumb: Rate of a reaction doubles for every 10 degree rise in temperature upto optimal temp.

pH

There exist two groups of bacteria in terms of pH optima namely acidogens and methanogens.The best pH range for acidogens is 5.5 – 6.5 and for methanogens is 7.8 – 8.2. The operating pH for combined cultures is 6.8-7.4 with neutral pH being the optimum. Since methanogenesis is considered as a rate limiting step, It is necessary to maintain the reactor pH close to neutral.

Low pH reduces the activity of methanogens causing accumulation of VFA and H_2. At higher partial pressure of H_2, propionic acid degrading bacteria will be severely inhibited thereby causing excessive accumulation of higher molecular weight VFAs such as propionic and butyric acids and the pH drops further. If the situation is left uncorrected, the process may eventually fail. This condition is known as a “SOUR” or STUCK”

The remedial measures: Reduce the loading rates and supplement chemicals to adjust the pH. chemicals such as $NaHCO_3$, NaOH, Na_2CO_3, Quick lime (CaO), Slaked lime [$Ca(OH)_2$], NH_3 etc. can be used.

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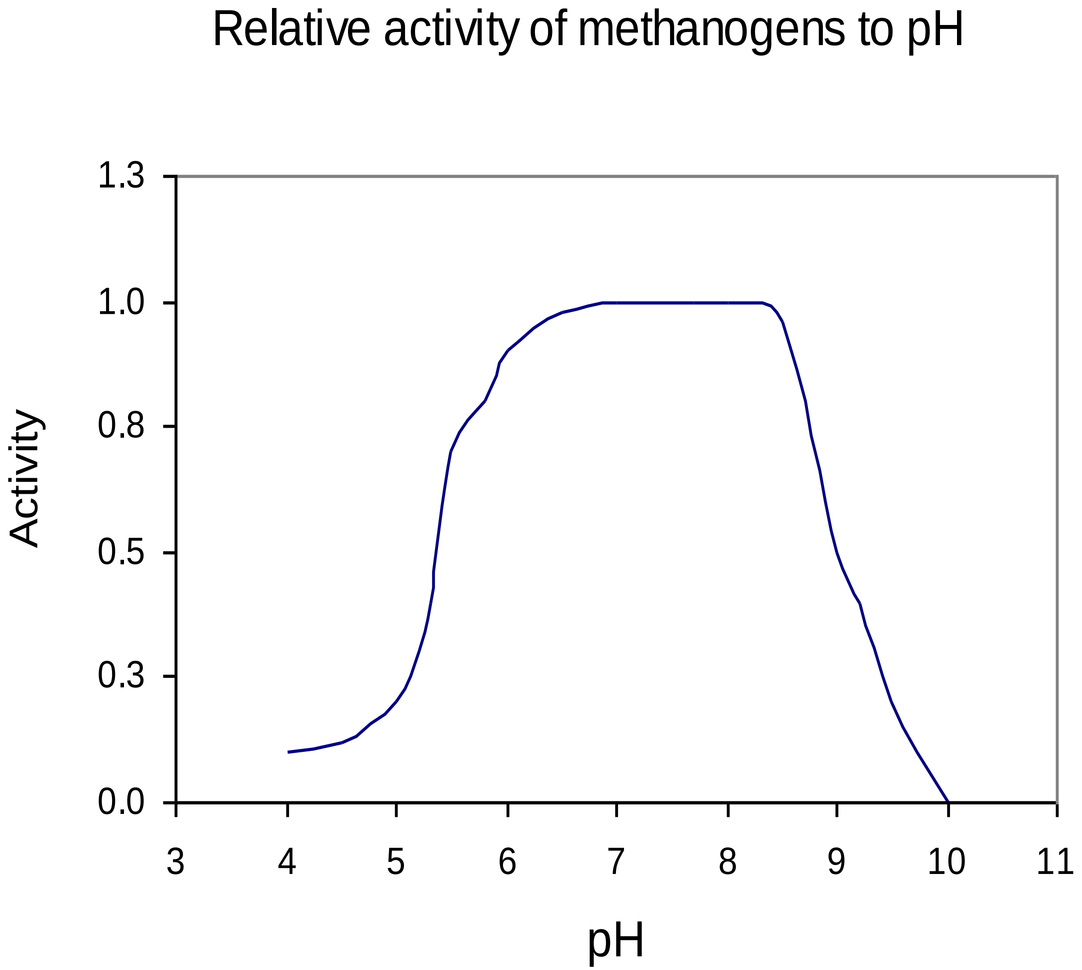


Relative activity of methanogens to pH
Activity
1.3
1.0
0.8
0.5
0.3
0.0
3
4
5
6
7
8
9
10
11
pH

An anaerobic treatment system has its own buffering capacity against pH drop because of alkalinity produced during waste treatment: e.g. the degradation of protein present in the waste releases NH_3 which reacts with CO_2 forming ammonium carbonate as alkalinity.

$$NH_3 + H_2O + CO_2 \rightarrow NH_4HCO_3$$

The degradation of salt of fatty acids may produce some alkalinity.

$$CH_3COONa + H_2O \rightarrow CH_4 + NaHCO_3$$

Sulfate and sulfite reduction also generate alkalinity.

$$CH_3COO^- + SO_4^{2-} \rightarrow HS^- + HCO_3^- + 3H_2O$$

When pH starts to drop due to VFA accumulation, the alkalinity present within the system neutralizes the acid and prevents further drop in pH. If the alkalinity is not enough to buffer the system pH, we need to add from external as reported earlier.

Nutrients and trace metals

All microbial processes including anaerobic process requires macro (N, P and S) and micro (trace metals) nutrients in sufficient concentration to support biomass synthesis. In addition to N and P, anaerobic microorganisms especially methanogens have specific requirements of trace metals such as Ni, Co, Fe, Mo, Se etc. The nutrients and trace metals requirements for anaerobic process are much lower as only 4 - 10% of the COD removed is converted biomass.

COD:N:P = 350:7:1 (for highly loaded system) 1000:7:1 (lightly loaded system)

Inhibition/Toxicity

The toxicity is caused by the substance present in the influent waste or byproducts of the metabolic activities. Ammonia, heavy metals, halogenated compounds, cyanide etc. are the examples of the former type whereas ammonia, sulfide, VFAs belong to latter group.

Types of anaerobic reactors

Low rate anaerobic reactors

- **Anaerobic pond**
- **Biogas Septic tank**
- **Imhoff tank**
- **Standard rate anaerobic digester**

Slurry type bioreactor, temperature, mixing, SRT or other environmental conditions are not regulated. Loading of 1-2 kg COD/m^3-day.

High rate anaerobic reactors

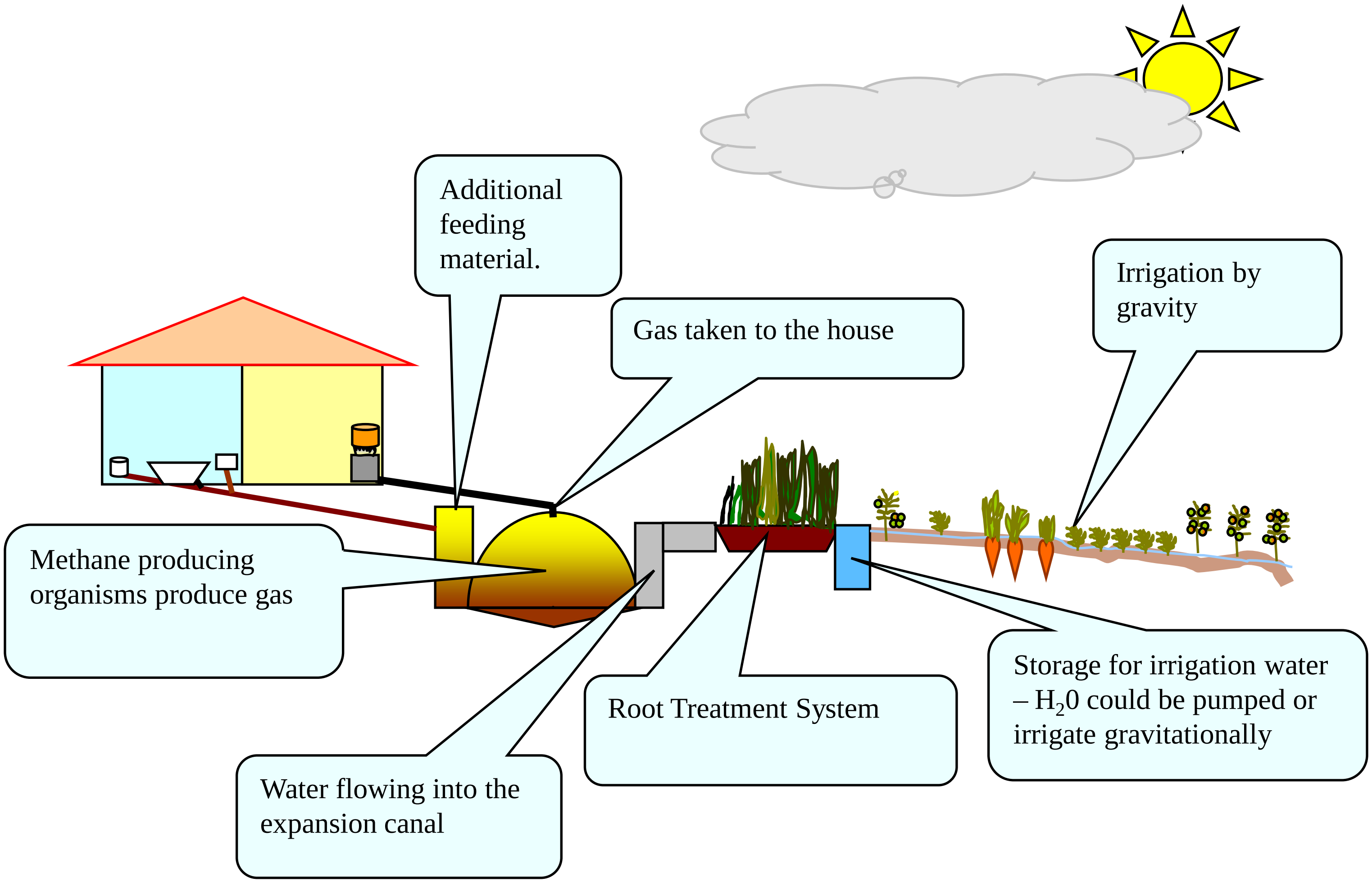
- **Anaerobic contact process**
- **Anaerobic filter (AF)**
- **Upflow anaerobic slugde Blanket (UASB)**
- **Fluidized bed Reactor**
- **Hybrid reactor: UASB/AF**
- **Anaerobic Sequencing Batch Reactor (ASBR)**

Able to retain very high concentration of active biomass in the reactor. Thus extremely high SRT could be maintained irrespective of HRT. Load 5-20 kg COD/m^3-d

COD removal efficiency : 80-90%

Up-Scaling

- The design of biogas digesters demands engineering expertise. The factors decisive for design are too complex to be expressed in simple up-scaling tables.
- Construction must be carried out by qualified masons.
- Capacity building, i.e. training for design and construction of biogas digesters is outlined in



Sketch of biodigester replacing a septic tank. Wastewater as well as kitchen and garden waste enter the digester and are broken down to biogas and fertile water.

The advantages: No more emptying of septic tank. Reuse of all water in the garden. Less cost on cooking energy.

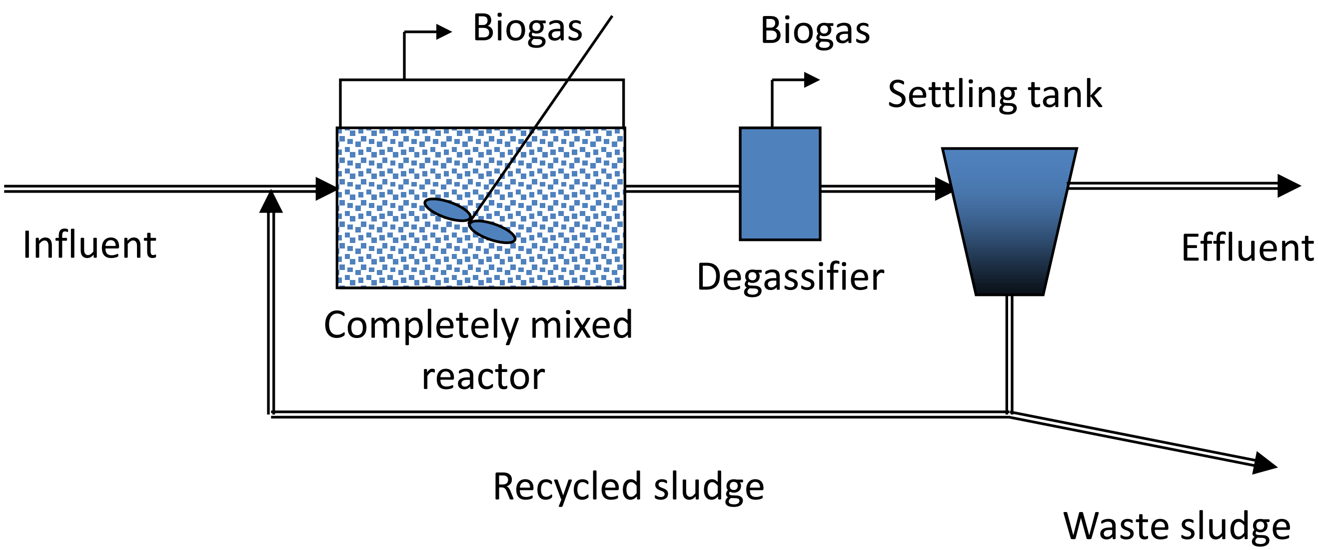
General Spread Sheet for "Fixed Dome" Biogas Plants, Input and Treatment Data

daily flow	hours of ww flow	flow per hour	COD in g/m³	COD / BOD_5 ratio	liquid HRT	settleable SS / COD ratio	lowest digester temper.	ideal BOD rem rate sludge	ideal BOD rem rate liquid	total BOD rem.rate acc.to ° C	BOD out	COD out	de-sludging interval
given	given	calcul.	given	given	**chosen**	given	given	calcul.	calcul.	calcul.	calcul.	calcul.	**chosen**
m³/d	h	m³/h	mg/l	mg/l / mg/l	h	mg/l / mg/l	° C	%	%	%	mg/l	mg/l	months
3	**14**	0,18	**4.000**	**2,00**	**240**	**1,00**	**20**	102%	42%	80%	394	1.089	**36**
guiding figures=>					*for domestic wastewater :*	*0,5*							

Data common for both					Ball Shaped Digester				Biogas Plant Half Round Shape				
Sludge volume	water volume	total volume	gas holder volume = VG	free distance above slurry zero line	volume of empty space above zero line	radius ball shape	actual digester radius (ball)	actual net volume of digester	volume of empty space above zero line	radius half round shape	actual digester radius (half round)	actual net volume of digester	potential biogas product.
calcul.	calcul.	calcul.	calcul.	**chosen**	calcul.	**required**	**chosen**	**check**	calcul.	**required**	**chosen**	**check**	calcul.
m³	m³	m³	m³	m	m³	m	m	m³	m³	m	m	m³	m³/d
3,58	42,9	46,4	0,75	**0,25**	0,43	2,26	**2,25**	45,66	0,54	2,85	**2,85**	46,45	1,00
0,0017	*l/g BODrem*		*not less than*	*0,25*									

Anaerobic contact process (ACP)

Anaerobic contact process is essentially an anaerobic activated sludge process. It consists of a completely mixed reactor followed by a settling tank. The settled biomass is recycled back to the reactor. Hence ACP is able to maintain high concentration of biomass in the reactor and thus high SRT irrespective of HRT. Degassifier allows the removal of biogas bubbles (CO_2, CH_4) attached to sludge which may otherwise float to the surface.



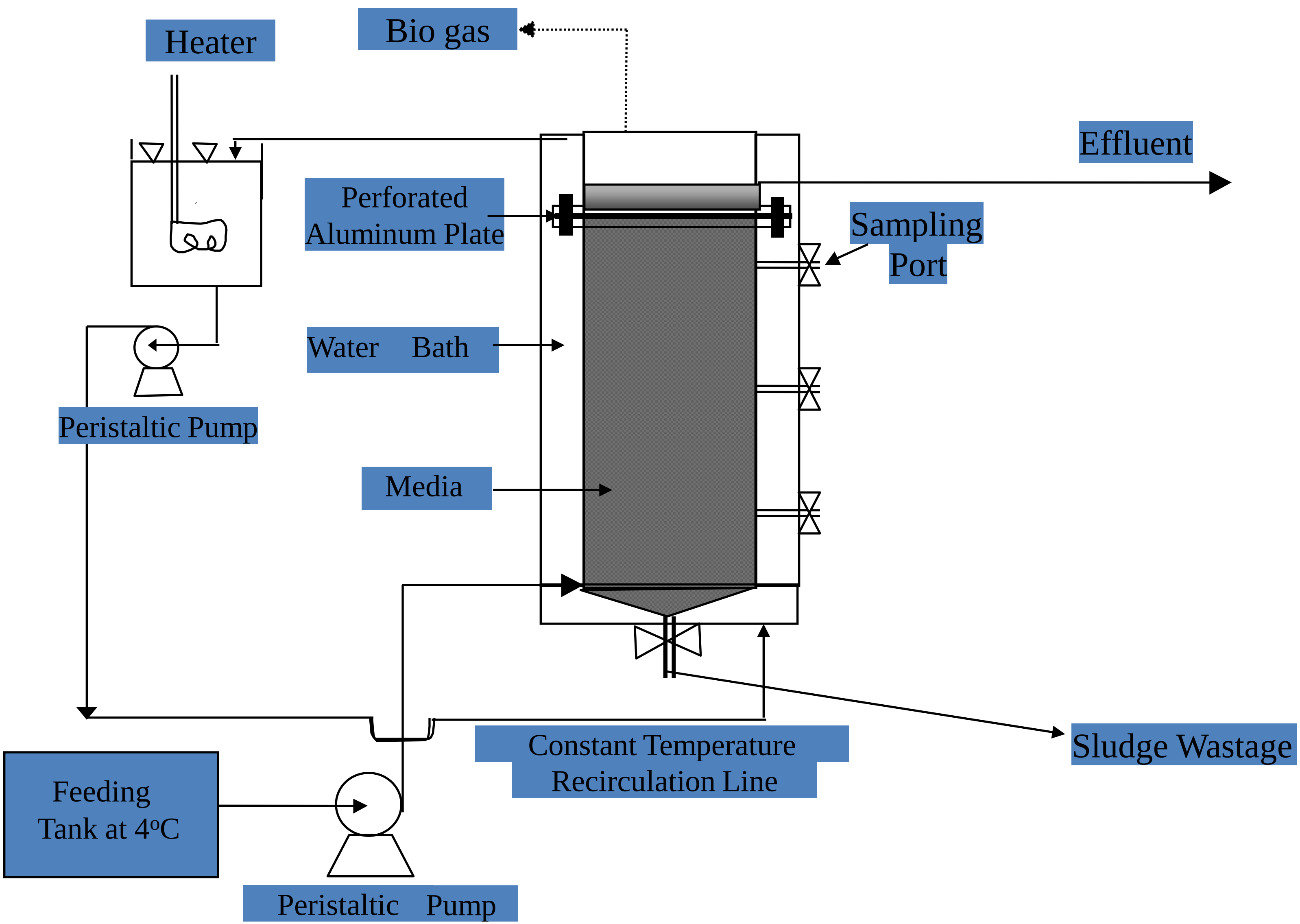
ACP was initially developed for the treatment of dilute wastewater such as meat packing plant which had tendency to form a settleable flocs. ACP is suitable for the treatment of wastewater containing suspended solids which render the microorganisms to attach and form settleable flocs.

The biomass concentration in the reactor ranges from 4-6 g/L with maximum concentration as high as 25-30 g/L depending on settleability of sludge. The loading rate ranges from 0.5 – 10 kg COD/m^3-day. The required SRT could be maintained by controlling the recycle rate similar to activated sludge process.

Anaerobic filter

- Anaerobic filter: Young and McCarty in the late 1960s to treat dilute soluble organic wastes.
- The filter was filled with rocks similar to the trickling filter.
- Wastewater distributed across the bottom and the flow was in the upward direction through the bed of rocks
- Whole filter submerged completely
- Anaerobic microorganisms accumulate within voids of media (rocks or other plastic media)
- The media retain or hold the active biomass within the filter
- The non-attached biomass within the interstices forms a bigger flocs of granular shape due to rising gas bubble/liquid
- Non-attached biomass contributes significantly to waste treatment
- Attached biomass not be a major portion of total biomass.
- 64% attached and 36% non-attached

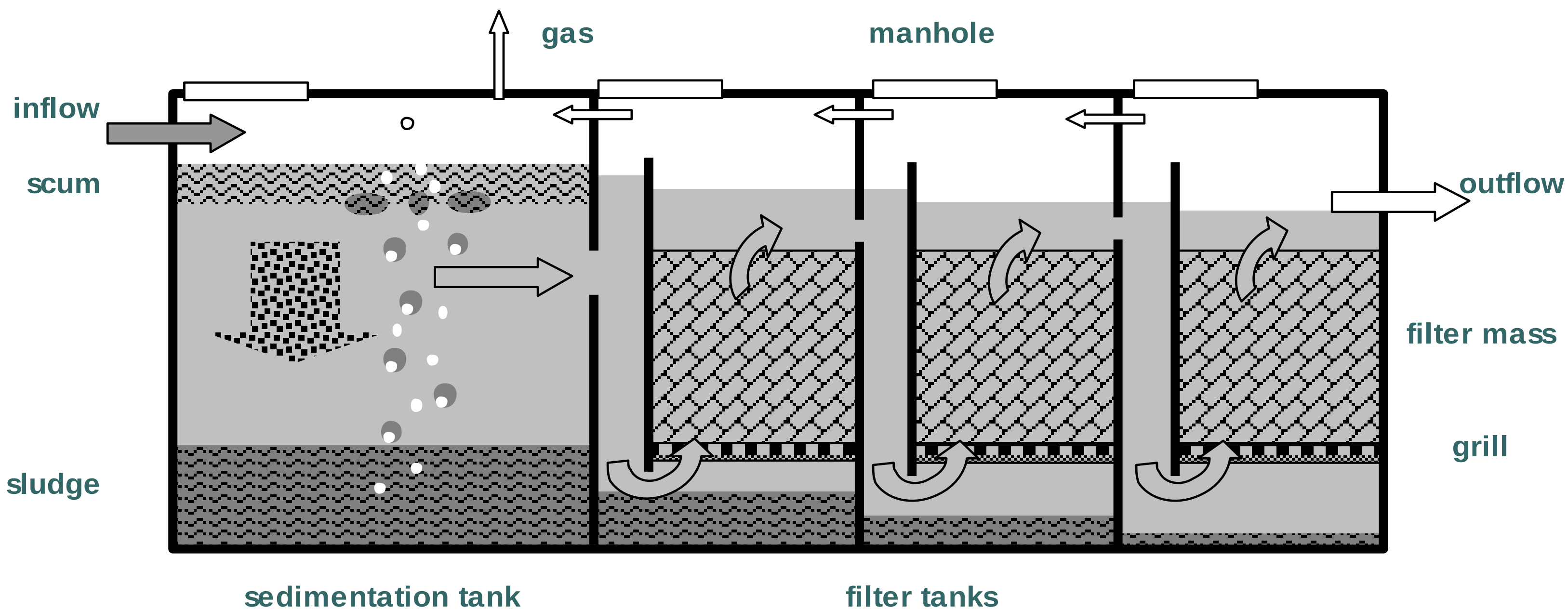
Upflow Anaerobic Filter



Anaerobic filter

Principle of Anaerobic Filter

1. Sedimentation / floatation
2. Anaerobic digestion of suspended and dissolved matter inside the filter
3. Anaerobic digestion (fermentation) of bottom sludge



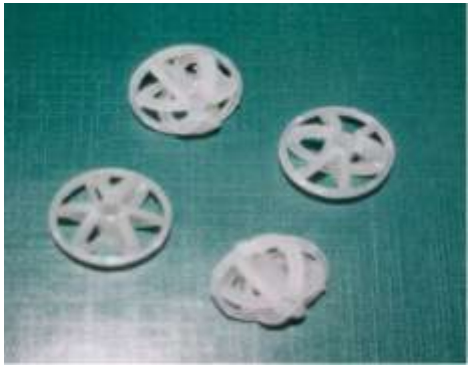



General spread scheet for anaerobic filter (AF)											
general data						**dimensions**					
daily waste water flow	time of most waste water flow	COD inflow	BOD_5 inflow	$SS_{settl.}$ / COD ratio	lowest digester temper.	specific surface of filter medium	voids in filter mass	depth of filter tanks	length of each tank	number of filter tanks	width of filter tanks
given	**given**	**given**	**given**	**given**	**given**	**given**	**given**	**chosen**	**chosen**	**chosen**	**chosen**
m^3/day	h	mg/l	mg/l	mg/l / mg/l	° C	m^2/m^3	%	m	m	No.	m
60,00	**12**	**1.038**	**465**	**0,46**	**25**	**100**	**35%**	**2,00**	**2,00**	**4**	**6,25**
		COD/BOD_5		*normal*		*range*	*range*		**cal.max**		
		2,23		*0,35-0,45 (domestic)*		*80 -120*	*30-45*		2,00		
treatment data											
HRT inside AF reactor	max. velocity in filter voids	factors to calculate COD removal rate of anaerobic filter						COD removal rate	BOD_5 removal rate	COD outflow of AF	BOD_5 outflow of AF
check!	**check !**	calculated according to graphs						calcul.	calcul.	calcul.	calcul.
h	m/h	f-temp	f-load	f-strenght	f-surface	f-HRT	f-chamb.	%	%	mg/l	mg/l
27,7	1,14	1,00	1,00	0,96	1,00	0,68	1,16	76%	85%	251	71
normal	*max.*										
24 - 48 h	*2,00*										

intermediate calculations					
max. peak flow per hour	BOD/COD rem. Factor AF	org.load on AF COD	filter height	net volume of filter tanks	**biogas pro-duction**
calcul.	calc.	calcul.	calcul.	calcul.	calcul.
m^3/h	ratio	kg/m^3*d	m	m^3	m^3/d
5,00	1,12	0,90	0,95	69,13	11,81

yellow cells are input data for following treatment system

Originally, rocks were employed as packing medium in anaerobic filter. But due to very low void volume (40-50%), serious clogging problem was witnessed. Now, many synthetic packing media made up of plastics, ceramic tiles of different configuration have been used in anaerobic filters. The void volume in these media ranges from 85-95 %. Moreover, these media provide high specific surface area typically 100 m^2/m^3 or above which enhance biofilm growth.



Since anaerobic filter is able to retain high biomass, long SRT could be maintained. Typically HRT varies from 0.5 – 4 days and the loading rates varies from 5 - 15 kg COD/m^3-day. Biomass wastage is generally not needed and hydrodynamic conditions play important role in biomass retention within the void space

.

Down flow anaerobic filter (DAF)

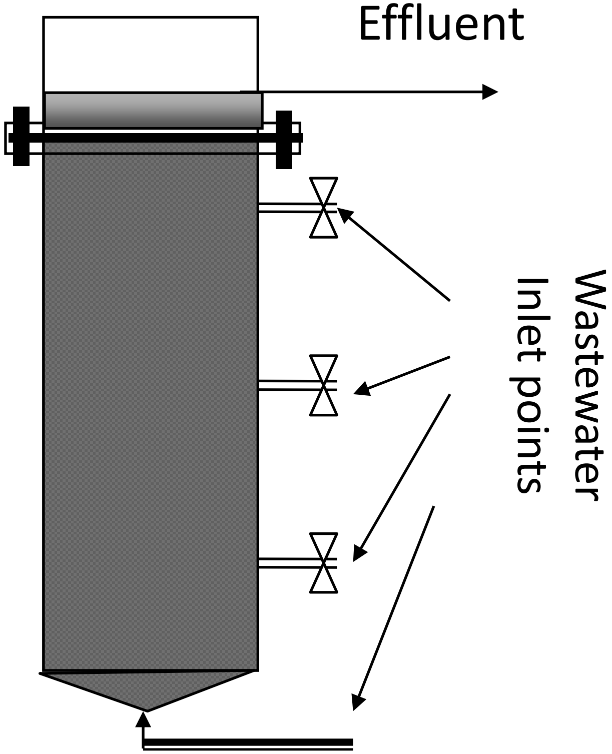
Down flow anaerobic filter is similar to trickling filter in operation. DAF is closer to fixed film reactor as loosely held biomass/sludge within the void spaces is potentially washed out of reactor. The specific surface area of media is quite important in DAF than UAF. There is less clogging problem and wastewater with some SS concentration can be treated using DAF.

Multi-fed Upflow Anaerobic Filter (MUAF)

Waste is fed through several points along the depth of filter.
Such feeding strategy has unique benefits:

:

1. Homogeneity in biomass distribution
2. Maintenance of completely mixed regime thus preventing short - circuiting and accumulation of VFA.
3. Uniform substrate concentration within the reactor and prevent heavy biomass growth at bottom thus avoids clogging
4. Effective utilization of whole filter bed

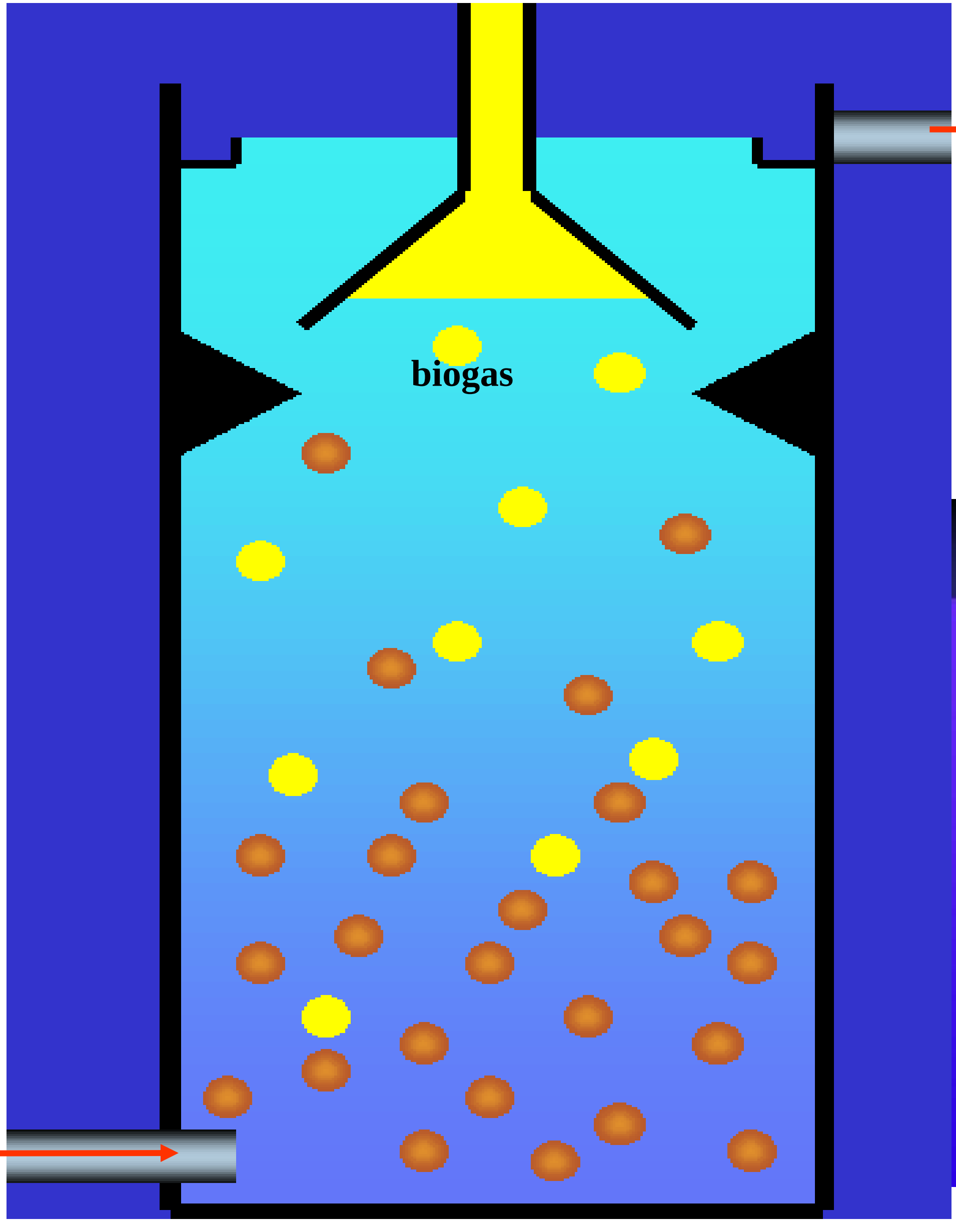


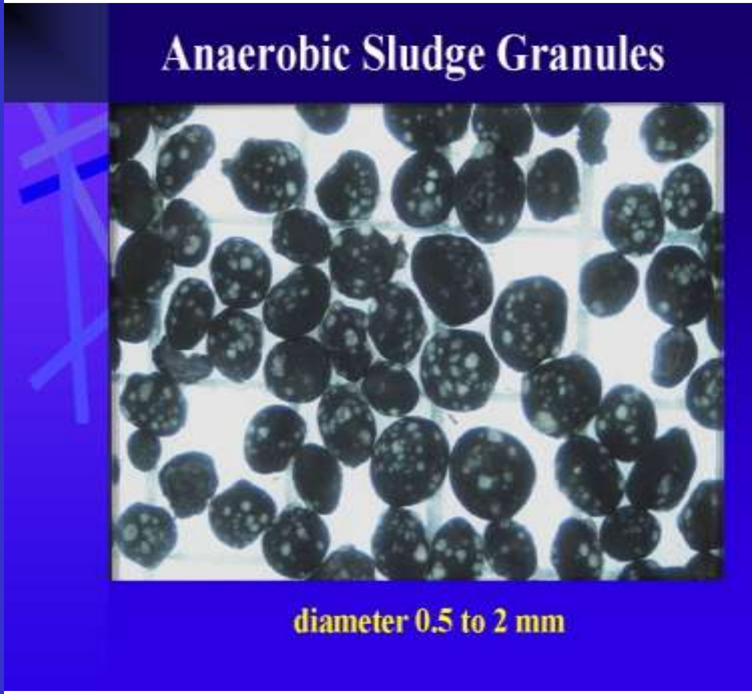
Upflow Anaerobic Sludge Blanket (UASB)

UASB was developed in 1970s by Lettinga in the Netherlands.
UASB is essentially a suspended growth system in which proper hydraulic and organic loading rate is maintained in order to facilitate the dense biomass aggregation known as granulation. The size of granules is about 1-3 mm diameter. Since granules are bigger in size and heavier, they will settle down and retain within the reactor. The concentration of biomass in the reactor may become as high as 50 g/L. Thus a very high SRT can be achieved even at very low HRT of 4 hours.

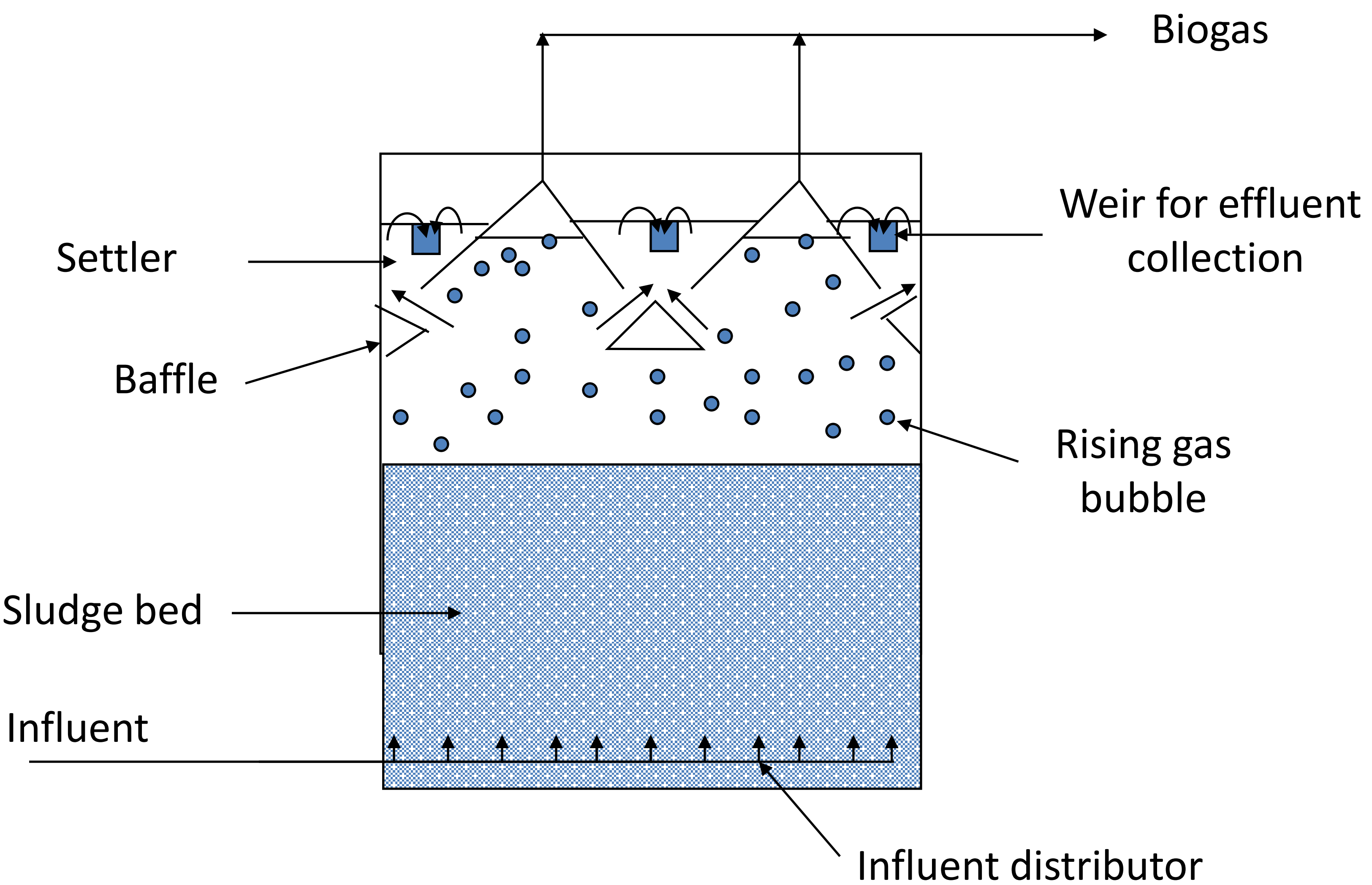
The granules consist of hydrolytic bacteria, acidogen/acetogens and methanogens. Carbohydrate degrading granules show layered structure with a surface layer of hydrolytic/fermentative Acidogens. A mid-layer comprising of syntrophic colonies and an interior with acetogenic methanogens.

UASB Reactor





UASB Reactor



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Loading rate:

15-30 kg COD/m^3-day

Important components of UASB:

1. Influent flow distributor
2. Sludge blanket
3. Solid-liquid-gas separator
4. Effluent collector

Type of waste treatable by UASB:

Alcohol, bakers yeast, bakery, brewery, candy, canneries, chocolate, citric acid, coffee, dairy & cheese, distillery, Domestic sewage, fermentation, fruit juice, fructose, landfill leachate, paper & pulp, pharmaceutical, potato processing, rubber,sewage sludge liquor, slaughter house, soft drinks, starch (barley, corn, wheat), sugar processing, vegetable & fruit, yeast etc.

Important considerations in UASB operation

- Initial seeding of some well digested anaerobic sludge could be used. The seed occupies 30-50% of total reactor volume. Minimum seeding is 10% of the reactor volume.

- Provide optimum pH, and enough alkalinity.

- Supplement nutrients and trace metals if needed. Provide N & P at a rate of COD: N:P of 400:7:1 (conservative estimate).

- Addition of Ca^{2+} at 200 mg/L promotes granulation. Ca^{2+} conc. higher than 600 mg/L may form $CaCO_3$ crystals which may allow methanogens to adhere to and then become washed out of the system.

Static Granular Bed Reactor (SGBR)

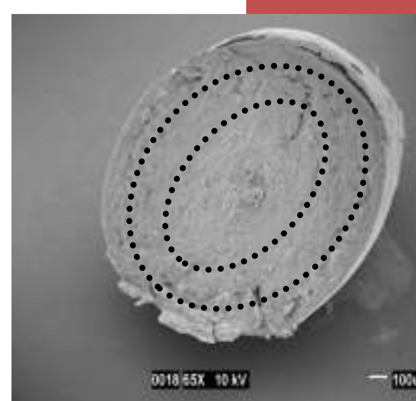
- Developed at Iowa State University by Dr. Ellis and Kris Mach

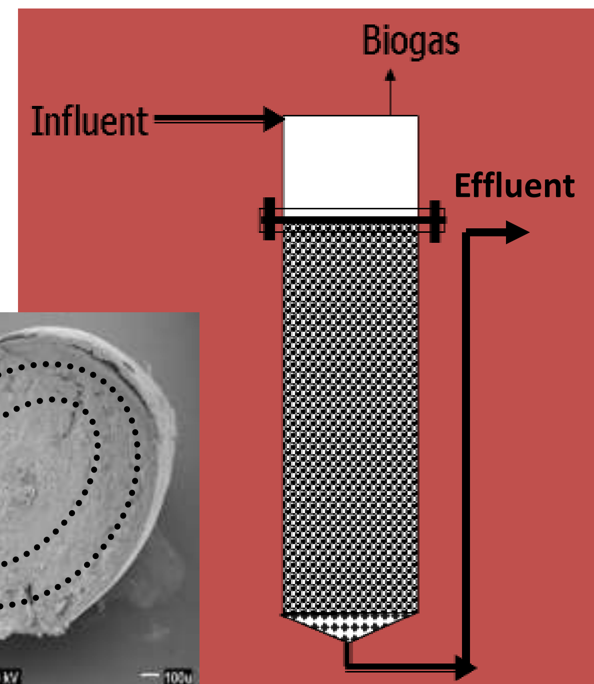
- Just opposite to UASB; flow is from top to bottom and the bed is static

- No need of three-phase separator or flow distributor

- Simple in operation with less moving parts

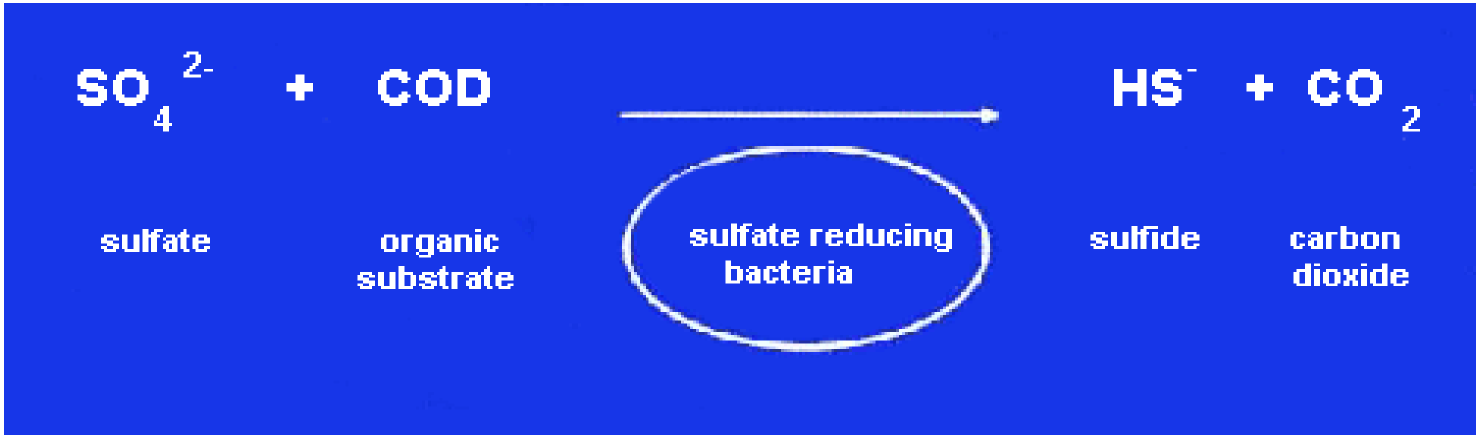
- Major issue: head loss due built-up of solids





Effect of sulfate on methane production

When the waste contains sulfate, part of COD is diverted to sulfate reduction and thus total COD available for methane production would be reduced greatly.



Sulfide will also impose toxicity to methanogens at Concentration of 50 to 250 mg/L as free sulfide.

Stoichiometry of Sulfate Reduction

$$8e + 8H^{+} + SO_4^{2-} \longrightarrow S^{2-} + 4H_2O$$

$$8e + 8H^{+} + 2O_2 \longrightarrow 4H_2O$$

$$2O_2 / SO_4^{2-} = 64/96 \sim 0.67$$

- COD/SO_4^{2-} ratio ≤ 0.67
- $COD/SO_4^{2-} > 0.67$

Theoretically, 1 g of COD is needed to reduce 1.5 g of sulfate.

Example 2:

A UASB reactor has been employed to treat food processing wastewater at 20^{o}C. The flow rate is 2 m^3/day with mean soluble COD of 7,000 mg/L. Calculate the maximum CH_4 generation rate in m^3/day. What would be the biogas generation rate at 85% COD removal efficiency and 10% of the removed COD is utilized for biomass synthesis. The mean CH_4 content of biogas is 80%. If the wastewater contains 2.0 g/L sulfate, theoretically how much CH_4 could be generated?

Solution:

Maximum CH_4 generation rate:

The complete degradation of organic matter in the waste could only lead to maximum methane generation and is also regarded as theoretical methane generation rate.

$$\therefore \text{ Total COD removed} = \frac{(7000 \times 10^{-6})}{(10^{-3})} \times (2) \text{ Kg/d}$$

$$= 14 \text{ Kg/d}$$

From eq. (3) in example 1, we have :

1 Kg COD produces 0.35 m^3 CH_4 at STP

14 Kg COD produces ~ 0.35 x 14 = 4.9 m^3 CH_4/d at STP

At 20°C, the CH_4 gas generation = 4.9 x(293/273)

= 5.3 m^3/d

The maximum CH_4 generation rate = 5.3 m^3/d

Biogas generation rate:

Not all COD (organic matter) is completely degraded. The fate of COD during anaerobic treatment process can be viewed as :

- Residual COD (in effluent)
- COD converted to CH_4 gas
- COD diverted to biomass synthesis
- COD utilized for sulfate reduction (if sulfate is present)

$$\text{Total COD removed} = \frac{(7000 \times 10^{-6})}{(10^{-3})} \times (2) \times 0.85 \text{ Kg/d}$$

$$= 11.9 \text{ Kg/d}$$

As 10% of the removed COD has been utilized for biomass synthesis remaining 90% of the removed COD has thus been converted to CH_4 gas.

COD utilized for CH_4 generation = 11.9 x 0.9 Kg/d

= 10.71 Kg/d

From eq. (3) in example 1, we have:

1 Kg COD produces 0.35 m^3 CH_4 at STP

10.71 Kg COD produces ~ 0.35 x 10.71 = 3.75 m^3 CH_4/d at STP

At 20°C, the CH_4 gas generation = 3.75 x (293/273)

= 4.02 m^3/d

The bio-gas generation rate = 4.02/0.80 = 5.03 m^3/d

Methane generation rate when sulfate is present:

When the waste contains sulfate, part of COD is diverted to sulfate reduction and thus total COD available for methane production would be reduced greatly.

$$\text{Organic matter} + \text{Nutrients} + SO_4^{2-} \xrightarrow{\text{Sulfate-reducing bacteria}} H_2S + H_2O + HCO_3^- + \text{New biomass}$$

Theoretically, 1 g COD is required for reduction of 1.5 g sulfate.

Total COD consumed in sulfate reduction = 1.33g = 1333.33 mg

COD available for methane production = (7000 –1333.33) mg/L
= 5666.67 mg/L

$$\therefore \text{ Total COD available for CH4 generation} = \frac{(5666.67 \times 10^{-6})}{(10^{-3})} \times (2) \text{ Kg/d}$$

$$= 11.33 \text{ Kg/d}$$

From eq. (3) in example 1, we have:

1 Kg COD produces 0.35 m^3 CH_4 at STP

11.33 Kg COD produces ~ $0.35 \times 11.33 = 3.97 m^3$ CH_4/d at STP

At 20°C, the CH_4 gas generation $= 3.97 \times (293/273)$

$= 4.3 \ m^3/d$

The CH_4 generation rate when sulfate is present = 4.3 m^3/d

Presence of sulfate reduces methane yield by about 19%

Expanded bed reactor (EBR)

- Expanded bed reactor is an attached growth system with some suspended biomass.

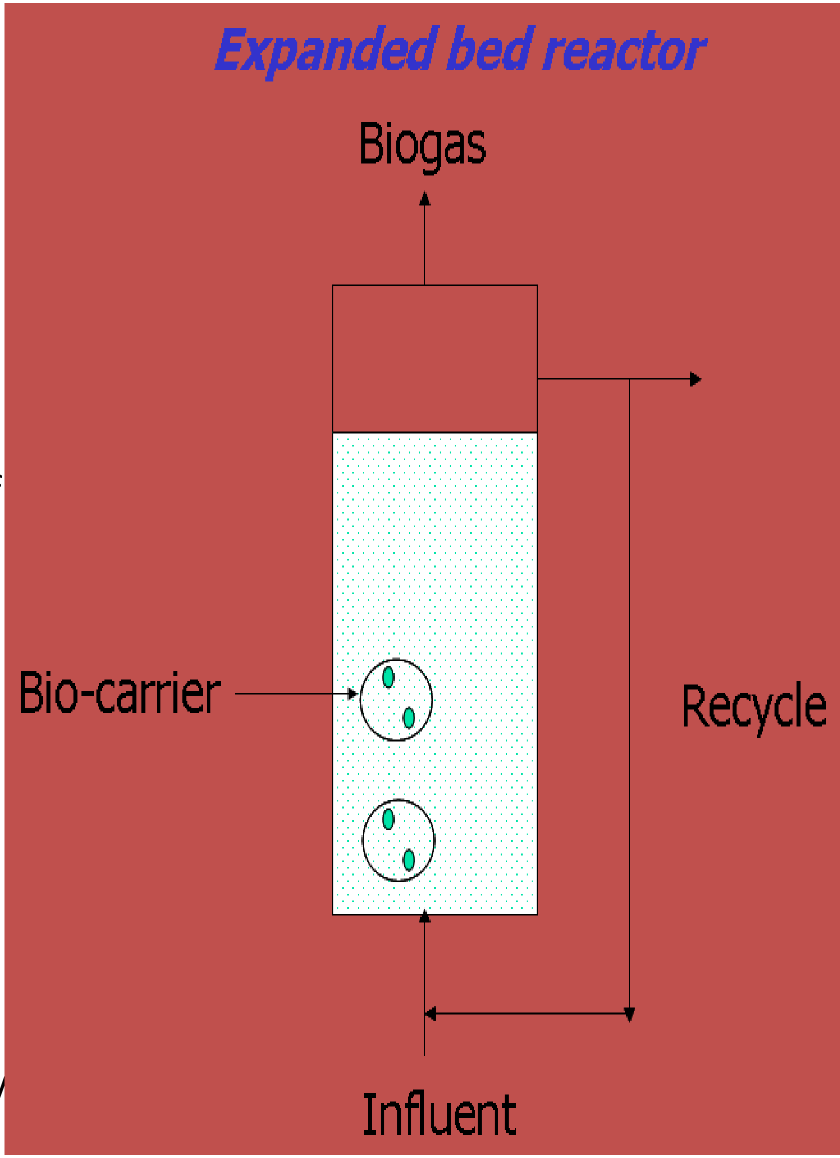
- The biomass gets attached on bio-carriers such as sand, GAC, pulverized polyvinyl chloride, shredded tyre beads etc.

- The bio-carriers are expanded by the upflow velocity of influent wastewater and recirculated effluent.

- In expanded bed reactor, sufficient upflow velocity is maintained to expand the bed by 15-30%.

- The expanded bed reactor has less clogging problem and better substrate diffusion within the biofilm.

- The biocarriers are partly supported by fluid flow and partly by contact with adjacent biocarriers and they tend to remain same relative position within the bed.



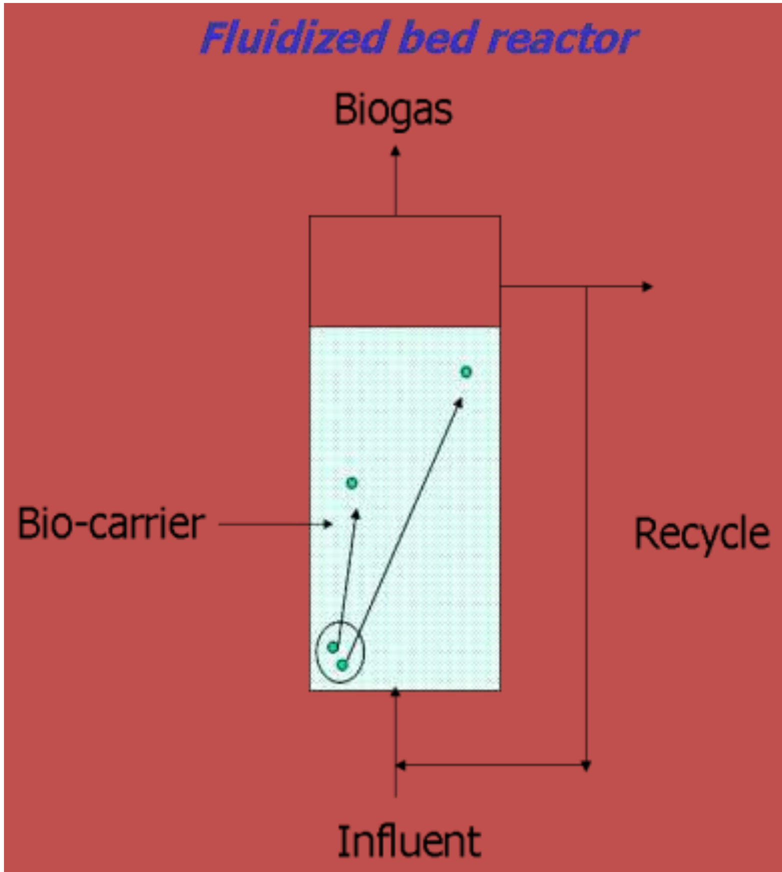
Fluidized bed reactor (FBR)

- FBR is similar to EBR in terms of configuration. But FBR is truly fixed film reactor as suspended biomass is washed–out due to high upflow velocity.

- The bed expansion is 25-300% of the settled bed volume which requires much higher upflow velocity (10-25 m/hr).

- The bio-carriers are supported entirely by the upflow liquid velocity and therefore able to move freely in the bed.

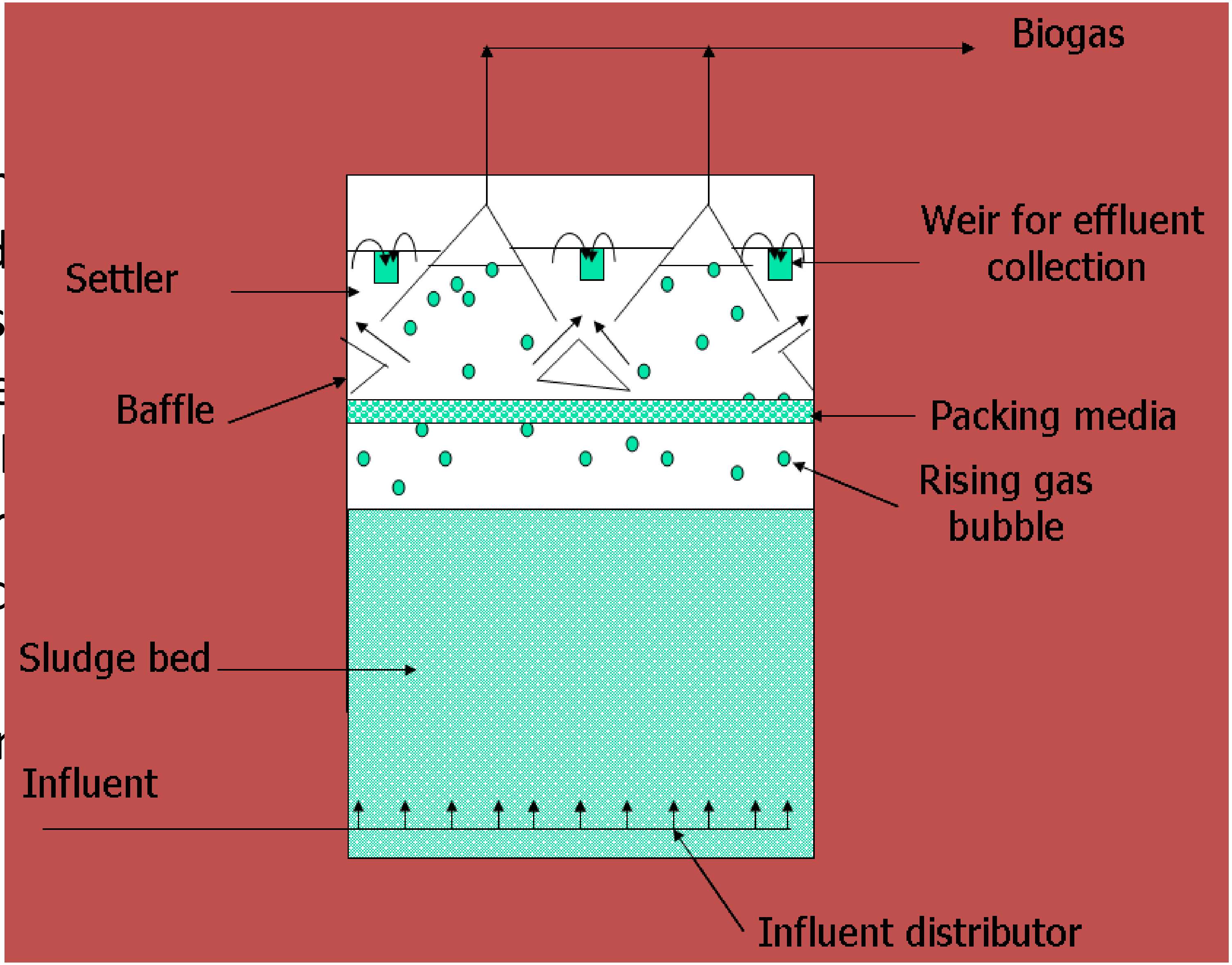
- The fluidized bed reactor is free from clogging problem short-circuiting and better substrate diffusion within the biofilm.



Hybrid system: UASB/AF

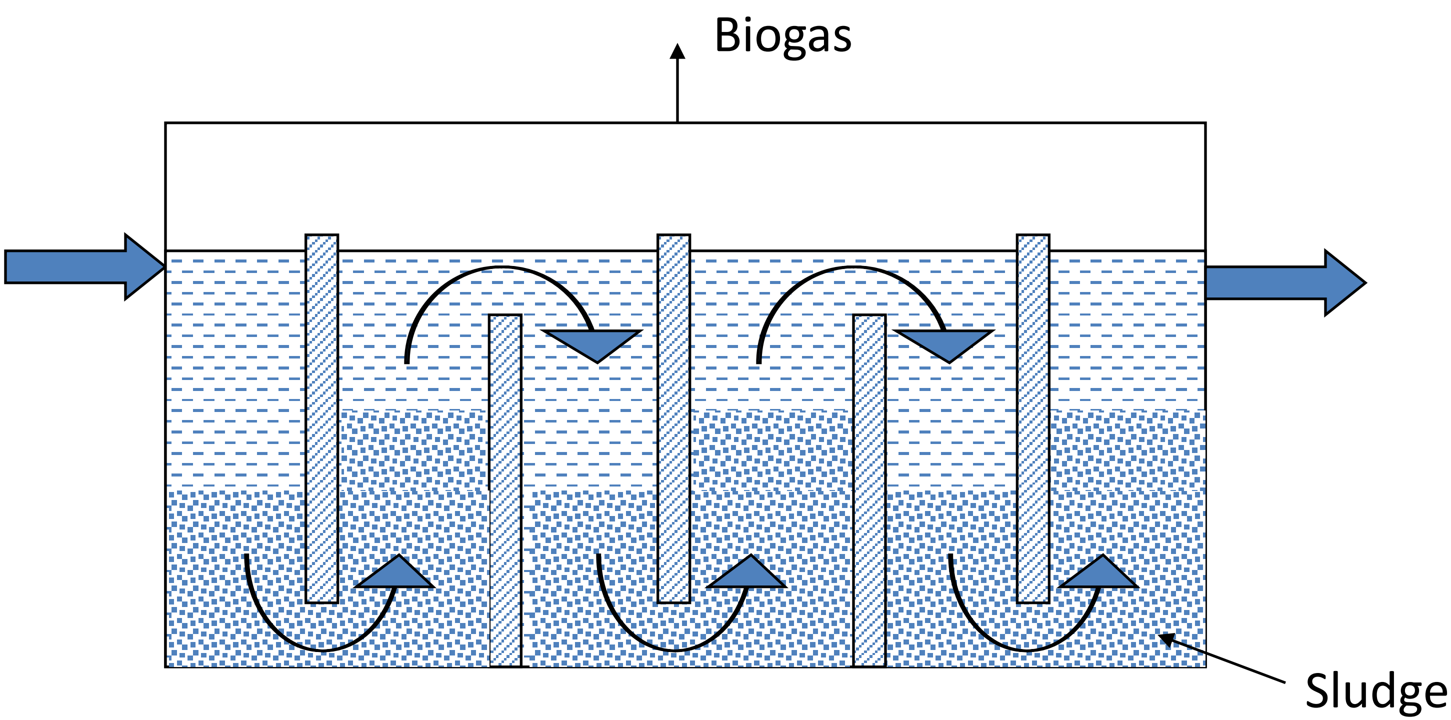
Hybrid syster
(bottom) and
prevents was
additional tre
sludge granul
UASB reactor
be retrofitted

Hybrid syster
reactor



Anaerobic baffled reactor

In anaerobic baffled reactor, the wastewater passes over and under the baffles. The biomass accumulates in Between the baffles which may in fact form granules with time. The baffles present the horizontal movement of of biomass in the reactor. Hence high concentration of biomass could be maintained within the reactor.



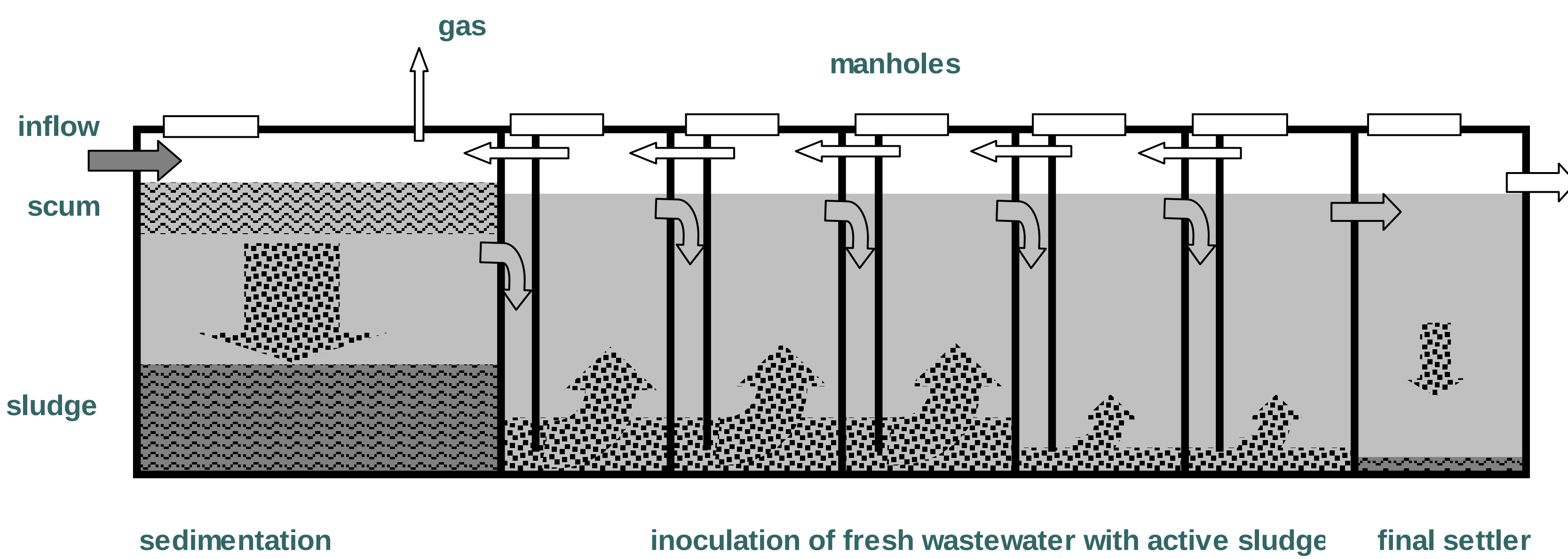
Baffled reactors

- … also sometimes called baffled septic tanks, are efficient, hygienic and ecologically sound anaerobic treatment units for collected organic wastewater.
- … can be combined with any type of (low-)flush toilet (including pour flush).
- Constructed out of local materials, the system provides easy maintenance, easily available spare parts and low operational costs; it does not have treatment process relevant movable parts and is not dependant on external energy inputs, like electricity.
- If the landscape is slightly sloped, water flow is caused by natural gravity, therefore no pumps are required.
- Effluent can be used for fertiliser irrigation or other forms of reuse for car-washing, toilet flushing or outdoor cleaning purposes, if followed by constructed wetlands or other aerobic tertiary treatment.
- If baffled reactors are constructed gas-tight, biogas can be collected and used

Baffled Reactor

Principle of Anaerobic Baffled Reactor

1. Sedimentation / floatation of solids
2. Anaerobic digestion of suspended and dissolved solids through sludge contact
3. Anaerobic digestion (fermentation) of bottom sludge
4. Sedimentation of mineralised (stabilised) suspended particles



General spread sheet for baffled reactor

general data						dimensions						
avg. daily waste water flow	time of most waste water flow	COD inflow	BOD_5 inflow	settleable SS / COD ratio	lowest digester temp.	depth at outlet	length of chambers		length of downflow shaft	width of chambers		number of upflow chambers
given	**given**	**given**	**given**	**given**	**given**	**chosen**	required	**chosen**	**chosen**	required	**chosen**	**chosen**
m³/day	h	mg/l	mg/l	mg/l / mg/l	° C	m	**max.!**	m	m	**min.!**	m	No.
60,00	**12**	**1.038**	**474**	**0,43**	**25**	**2,00**	0,80	**0,80**	**0,00**	6,25	**6,25**	**8**
		COD/BOD ratio	2,19	*0,35 -0,45 for domestic ww*					*min 12 cm, or 0 in case of down pipes*			

intermediate and secondary results

upflow velocity *best below 1 m/h*	factors to calculate BOD removal rate of baffled reactor					BOD rem rate calcul. by factors	max peak flow per hour	actual upflow velocity	actual volume of baffled reactor	HRT in baffled tank	org. load (BOD_5)	biogas (ass: CH_4 70%; 50% dissolved)
chosen	calculated according to graphs					86%	**max.!**	calcul.	calcul.	calcul.	calcul.	calcul.
m/h	f-overload	f-strength	f-temp	f-chamb.	f-HRT	applied	m³/h	m/h	m³	h	kg/m³*d	m³/d
1	1,00	0,87	1,00	1,08	0,92	84%	5,00	1,00	80,00	30	0,71	14,42

procedure of calculation

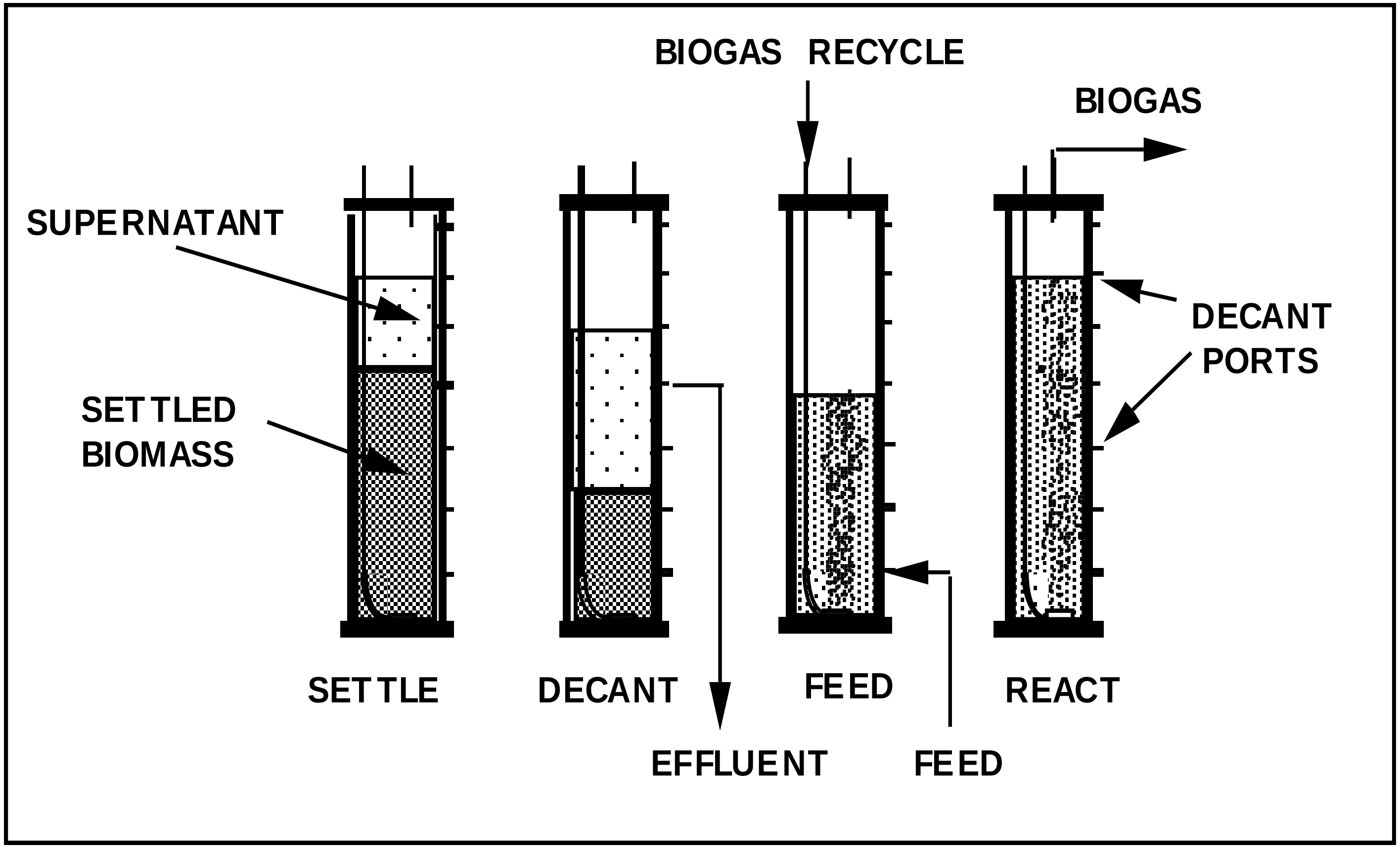
1. Fill in all figures in bold (until A12) 2. Check your effluent quality whether CODout or BODout is sufficient. 3. Check whether the total length of the tank suits your site. 4. If the result is not satisfying increase or reduce the number of chambers (M6) first. 5. If the result is still not satisfying increase or reduce the depth (G6).

treatment efficiency

total BOD_5 rem.rate	COD / BOD removal factor	total COD rem.rate	COD out	BOD out
calcul.	calcul.	calcul.	calcul.	calcul.
%		%	mg/l	mg/l
84%	1,04	81%	198,12	76,51

yellow cells are input data for following treatment system

Anaerobic Sequential Bed Reactor



Anaerobic Process Design

Design based on volumetric organic loading rate (VOLR):

$$VOLR = \frac{S_o \cdot Q}{V}$$

VOLR : Volumetric organic loading rate (kg COD/m^3-day)

S_o : Wastewater biodegradable COD (mg/L)

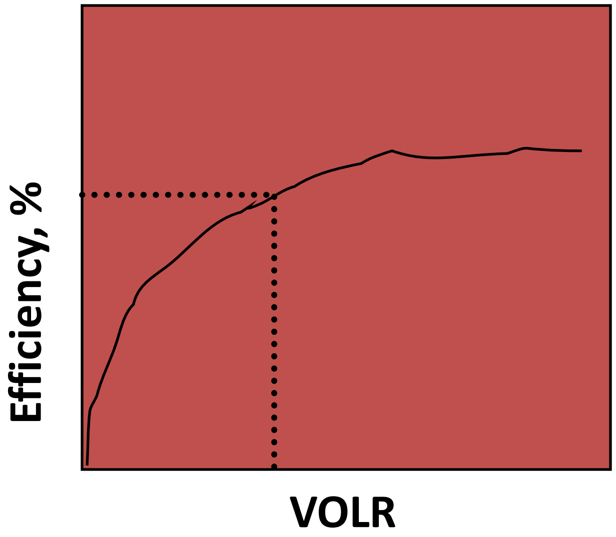
Q : Wastewater flow rate (m^3/day)

V : Bioreactor volume (m^3)

S_o and Q can be measured easily and are known upfront

VOLR can be selected!

How do we select VOLR?



- Conducting a pilot scale studies
- Find out removal efficiency at different VOLRs
- Select VOLR based on desired efficiency

Design based on hydraulic loading rate:

$$V = \theta_a \cdot Q$$

$$A = \frac{\theta_a \cdot Q}{H}$$

H : Reactor height (m)

θ_a : Allowable hydraulic retention time (hr)

Q : Wastewater flow rate (m^3/hr)

A : Surface area of the reactor (m^2)

Permissible superficial velocity (V_a)

$$V_a = \frac{H}{\theta}$$

For dilute wastewater with COD < 1,000 mg/L

Design Factors

Anaerobic digester is designed in terms of size by using various approaches. Some approaches are outlined below:

1. *Solids retention time (SRT)* : denoted by θ_c (days)
2. *Volatile solids loading rate* : kg VS/m^3-day
3. *Volume reduction*
4. *Loading factors based on population*

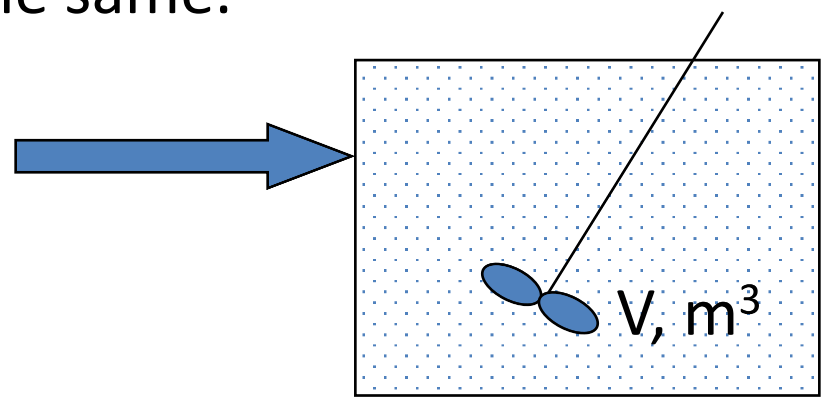
Important design parameters for anaerobic digesters

Parameters	Standard rate	High rate
Solid retention time, SRT in days	30 – 60	15-30
Volatile solids loadings, kg VS/m^3-day	0.5- 1.6	1.6 – 6.4
Digested solids concentrations, %	4 – 6	4 –6
Volatile solids reductions, %	35 – 50	45 – 55
Gas production, L/kg VS destroyed	500 - 650	700-1000
Methane content, %	65	65

Solids (SLUDGE) retention time (SRT) in a CSTR

Completely stirred anaerobic reactor (CSTR) is a completely mixed reactor for which solid retention time (SRT) and hydraulic retention time (HRT) is the same.

Influent flow rate (Q), m^3/day



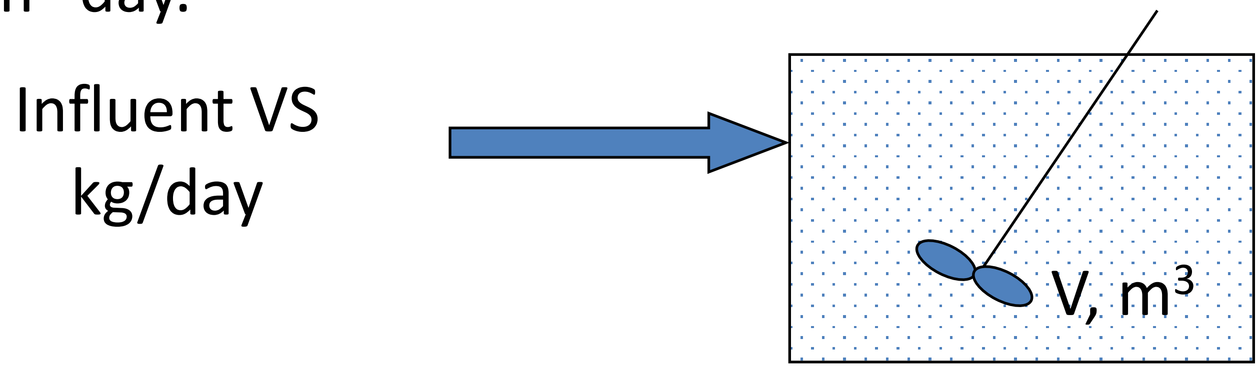
$$\text{HRT, days} = \frac{\text{Volume}}{\text{Flow rate}} = \frac{V\ (m^3)}{Q\ (m^3/\text{day})}\ \text{day}$$

For a given SRT (HRT), the size of reactor can be easily determined since flow rate (Q) is known to us.

Digester volume, $V\ (m^3)$ = Flow rate (Q) x SRT (θ_c)

Volatile solids loading rate

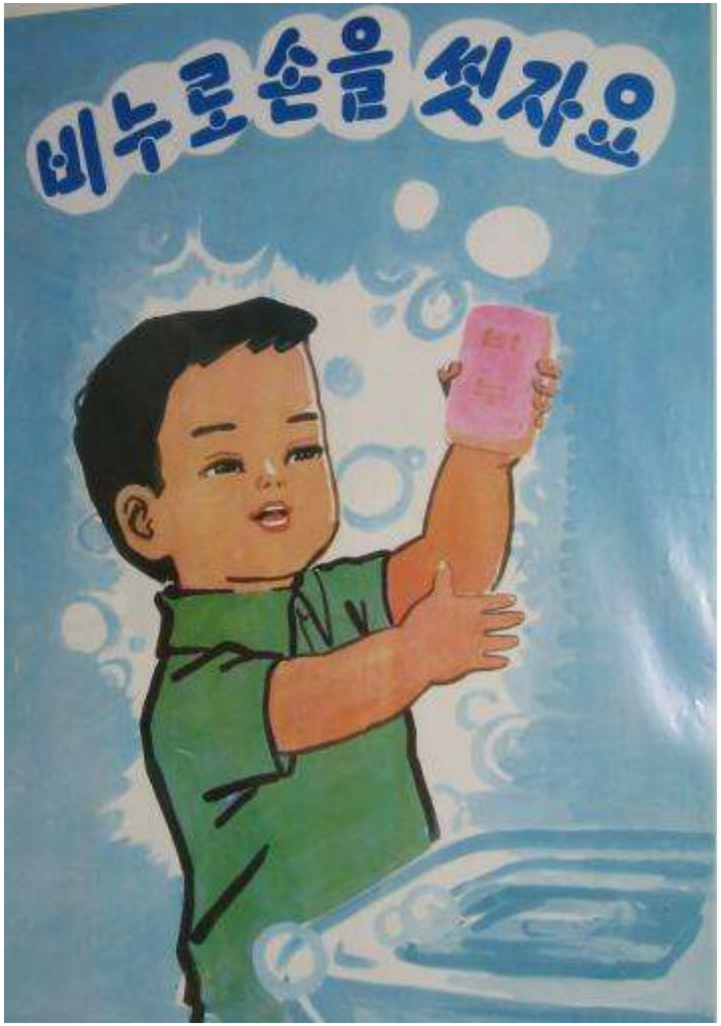
The size of an anaerobic digester can also be estimated based on volatile solids loading rate expressed as kg VS/m^3-day.



$$\text{Volatile solids loading rate, (kg VS/m}^3\text{- day)} = \frac{\text{Influent VS (kg/day)}}{\text{Reactor volume (m}^3\text{)}}$$

For a given volatile solids loading rate, the size of reactor can be easily determined since influent VS (kg/day) is known to us.

$$\text{Digester volume, V (m}^3\text{)} = \frac{\text{Influent VS (kg/day)}}{\text{Volatile solids loading rate,(kg VS/m}^3\text{- day)}}$$



Thank You

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