

# ENVE 424

## Anaerobic Treatment

### Lecture 8

## Low Rate and High Rate Anaerobic Digestion Technologies

2012 – 2013 Fall

06 Dec 2012

Assist. Prof. A. Evren Tugtas



Marmara  
Üniversitesi

# Lecture notes of Prof. Dr. Barış Çallı



# Reactor Configurations

- ❖ Slowly growing anaerobic bacteria require longer sludge retention times (SRT) in anaerobic reactors.
- ❖ Loading rates are therefore, primarily dictated by the concentration of active biomass in anaerobic reactors.
- ❖ Consequently, maintenance of a high SRT is the major point of interest in practical application of AD process.
- ❖ High rate anaerobic treatment could be achieved by employing efficient biomass retention methods.

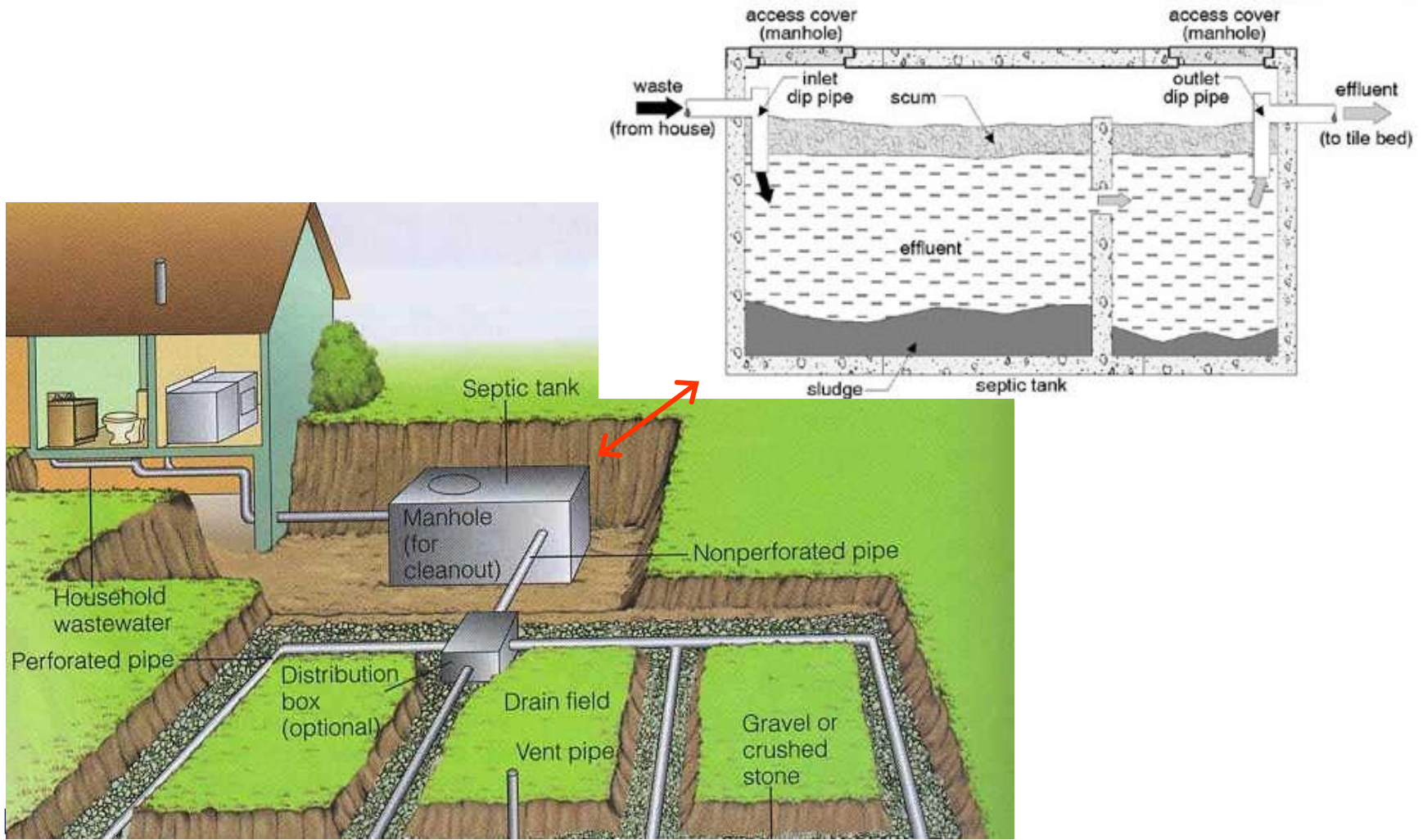
# Reactor Configurations

- ❖ In anaerobic reactors to maintain higher biomass densities, SRT has to be in excess of HRT (hydraulic retention time). →  
 $SRT \gg HRT$
- ❖ High biomass densities also provide greater resistance to any inhibitory substances in the influent.
- ❖ To accomplish the higher treatment efficiency and reliability associated with a long SRT, a number of novel anaerobic reactor configurations have been developed.

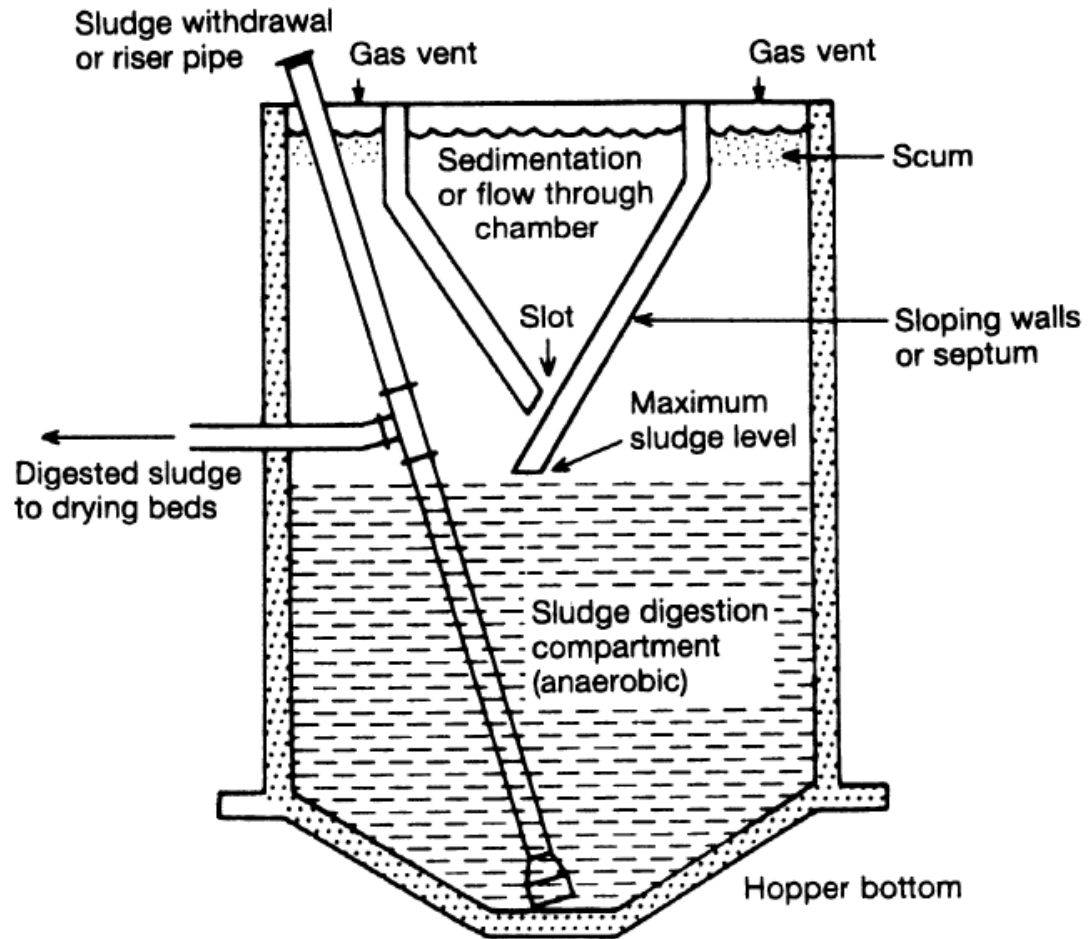
# History of anaerobic reactors

- 1881 First conventional anaerobic digester was used to liquidify the solid components of sewage
- 1891 First septic tank to retain solids in sewage
- 1905 Development of the 'Imhoff' tank in Germany
- 1930s Digesters were started to be mixed and heated to improve the digestion of solids in the sewage
- 1955 Anaerobic contact process was developed to treat soluble organics and dilute wastewaters

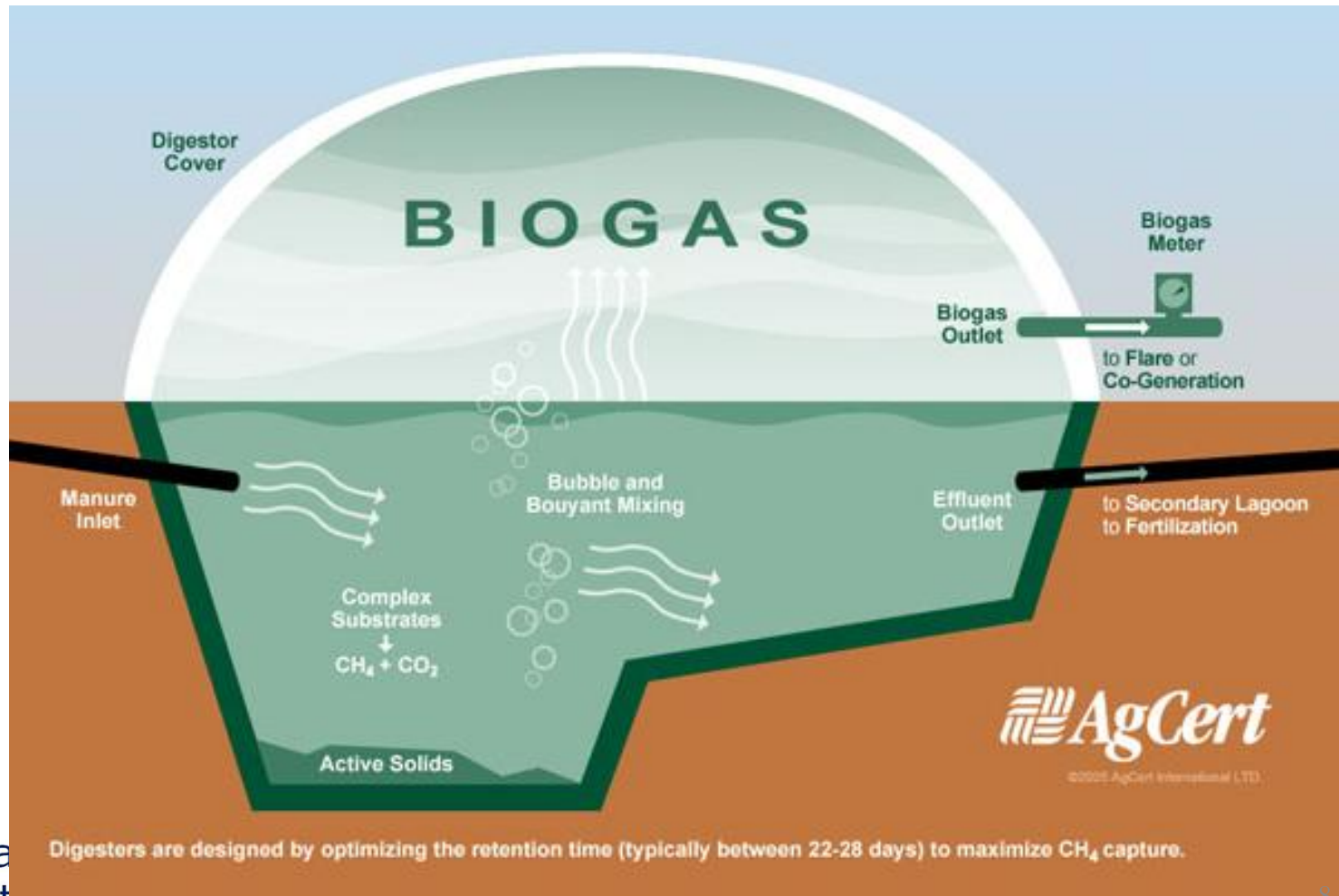
# Septic Tank System



# Imhoff Tank



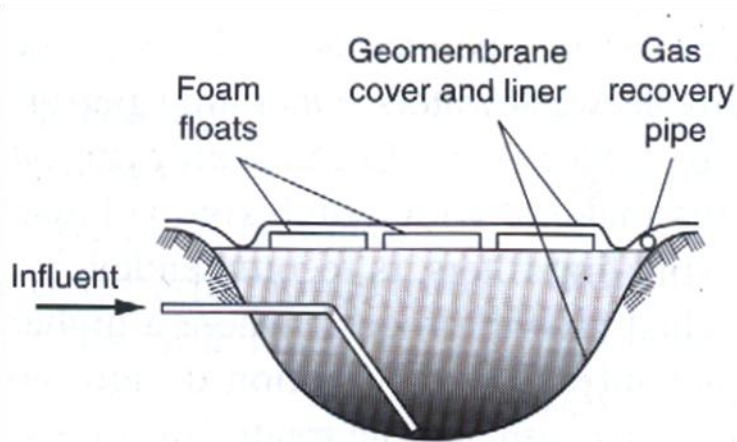
# Anaerobic lagoons



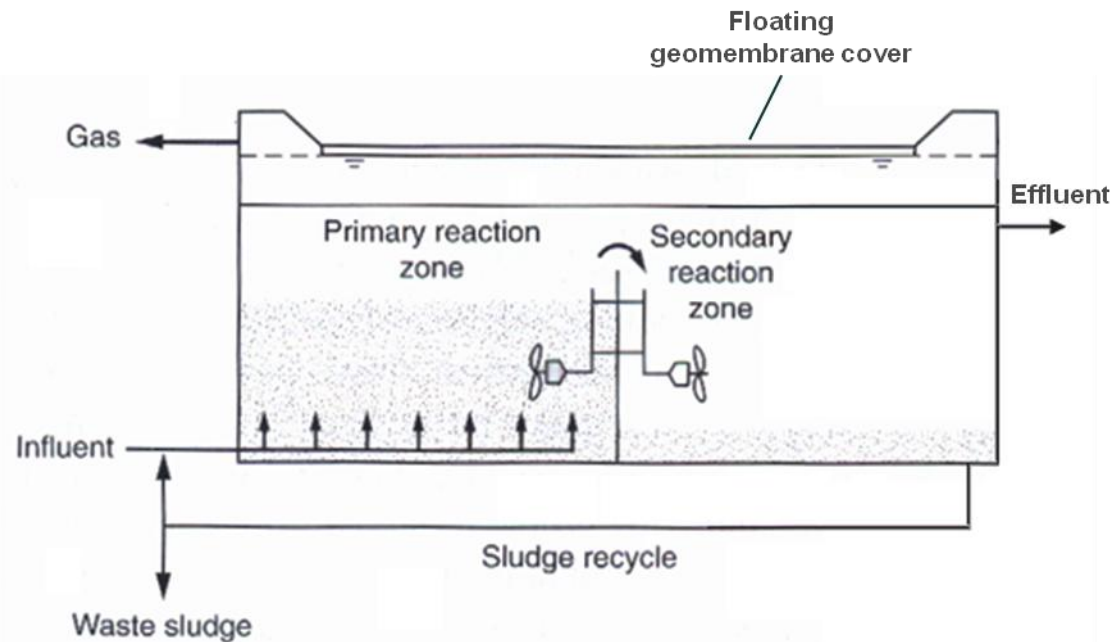
Digesters are designed by optimizing the retention time (typically between 22-28 days) to maximize CH<sub>4</sub> capture.



# Anaerobic lagoons



Simple covered  
anaerobic lagoon



ADI-BVF<sup>®</sup> lagoon  
process

# Composition of sewage sludge

Typical composition of sewage sludges before and after digestion  
(g per 100g total solids)

Constituent	Raw sludge	Digested sludge
Suspended solids	95	97
COD	140	100
Organic carbon	40	31
Organic matter	60–80	45–60
Greases and fats	7–35	3.5–17
Cellulose	4	0.6
Hemicelluloses	3	1.6
Lignin	6	8
Protein	22–28	16–21
Anionic detergents	0.5–1.5	0.7–2.2



# Low-rate Digestion

- ❖ Low-rate digestion is the oldest and simplest type of the anaerobic sludge digestion process.
- ❖ Essentially, it is a large cylindrically shaped tank with a sloping bottom and a flat or domed roof.
- ❖ An external heat source may or may not be provided.
- ❖ No mixing is provided.
- ❖ Although the gas generated and its rise to the surface provide some degree of mixing, the stabilization results in a stratified condition within the digester

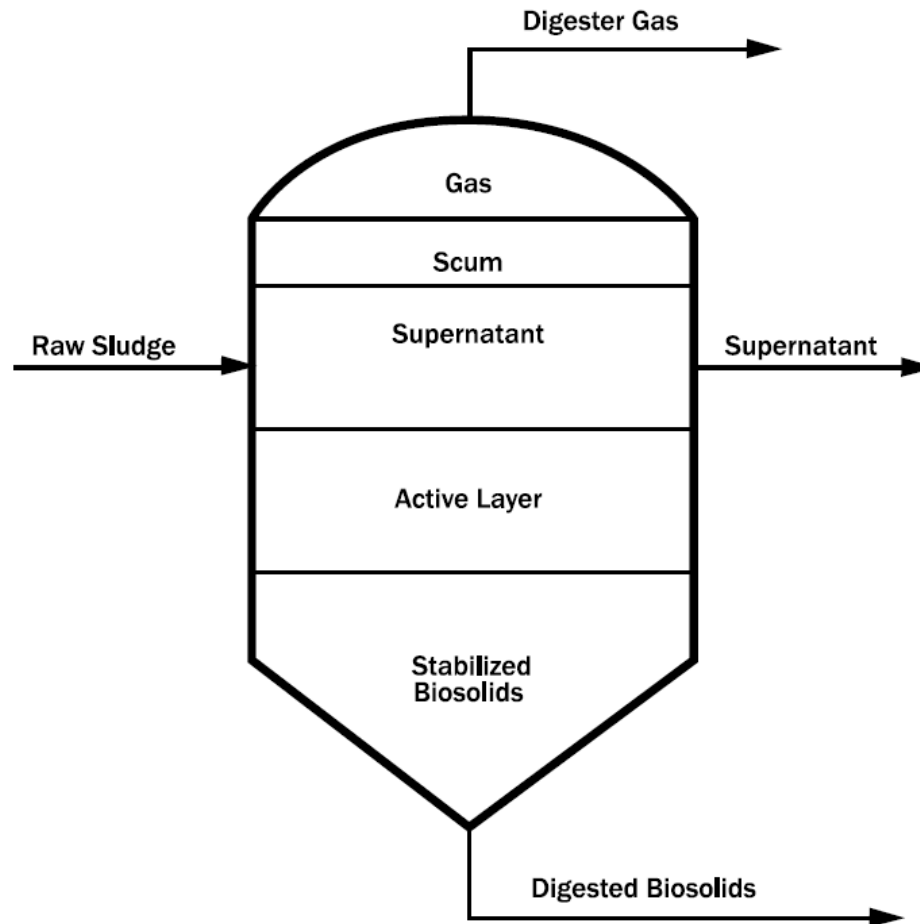


# Low-rate Digestion

- ❖ Supernatant is drawn off and recycled to influent of STP.
- ❖ Stabilized biosolids, which accumulate and thicken at the bottom of the tank, are periodically drawn off for removal.
- ❖  $\text{CH}_4$  gas collects above the liquid surface and is drawn off through the cover.
- ❖ Low-rate digestion is characterized by a long detention time, 30 to 60 days, and is sometimes considered for small plants of less than 4000  $\text{m}^3/\text{d}$ , however, they are seldom built today.



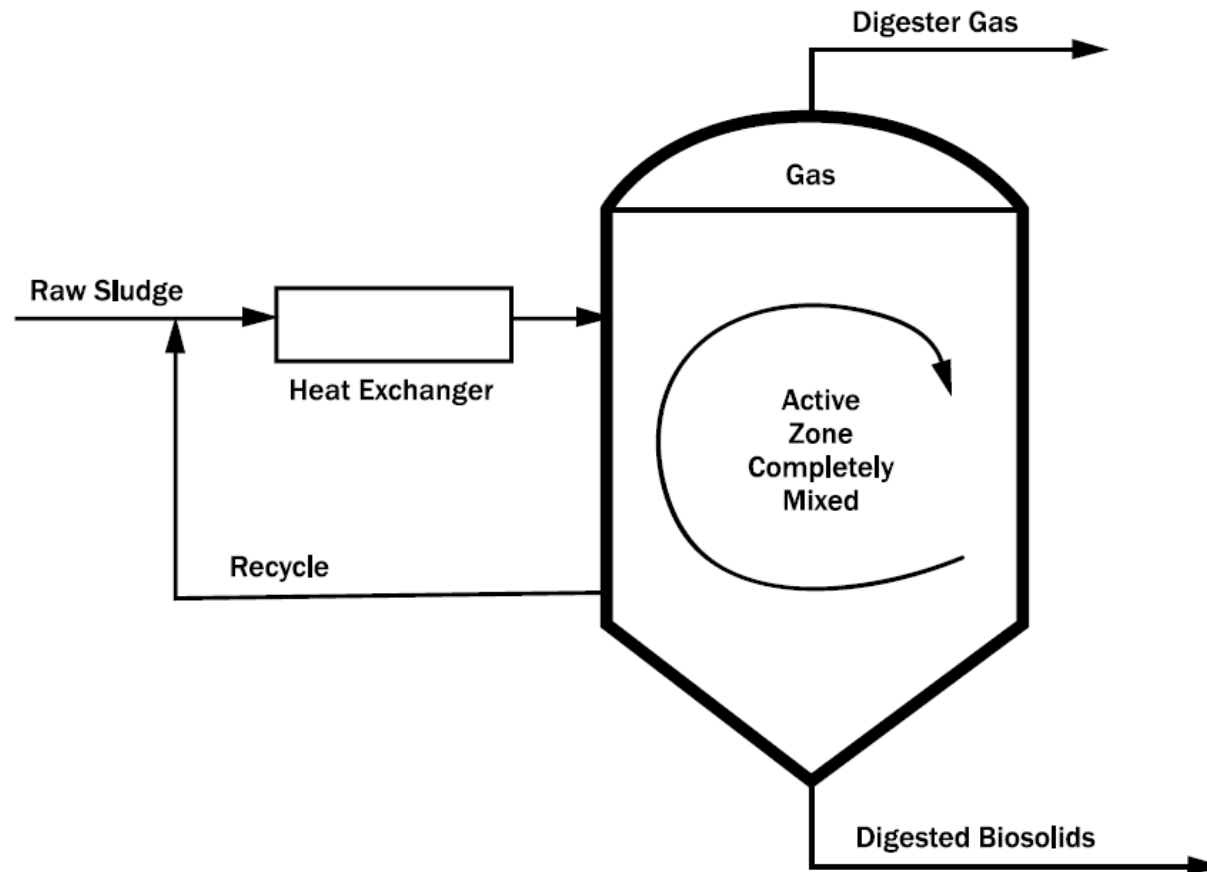
# Low-rate Digestion



# High-rate Digestion

- ❖ In the 1950s, several improvements to low-rate digestion were developed, resulting in a high-rate system.
- ❖ Heating, auxiliary mixing, thickening the raw sludge, and uniform feeding, the essential elements of a high-rate digestion system, act together to create a uniform environment.
- ❖ As a result, the tank volume is reduced and the stability and efficiency of the process are improved.

# High-rate Digestion

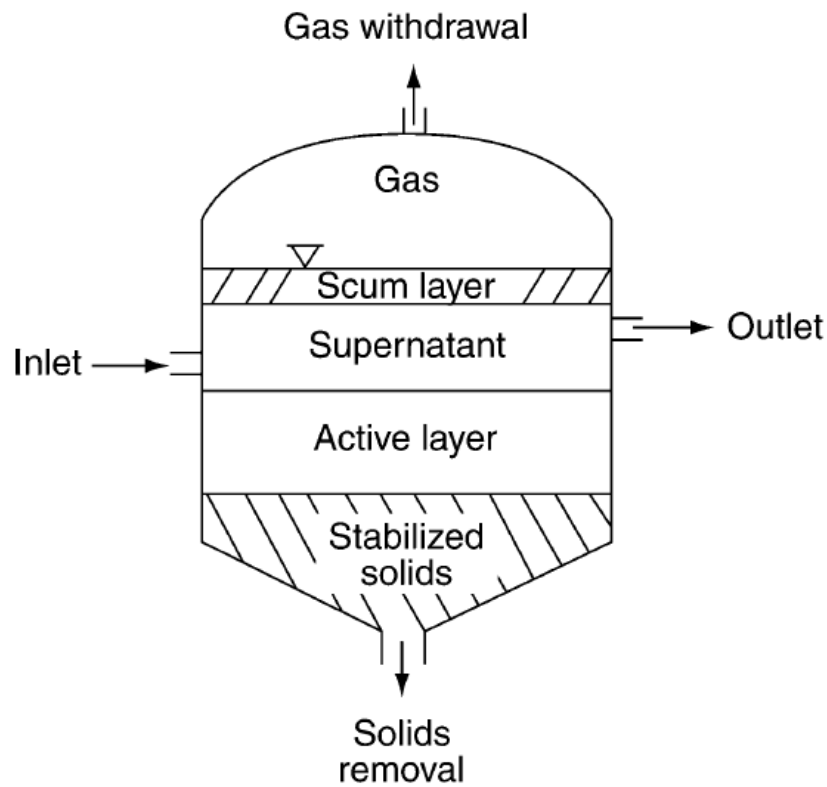


# High-rate anaerobic reactors

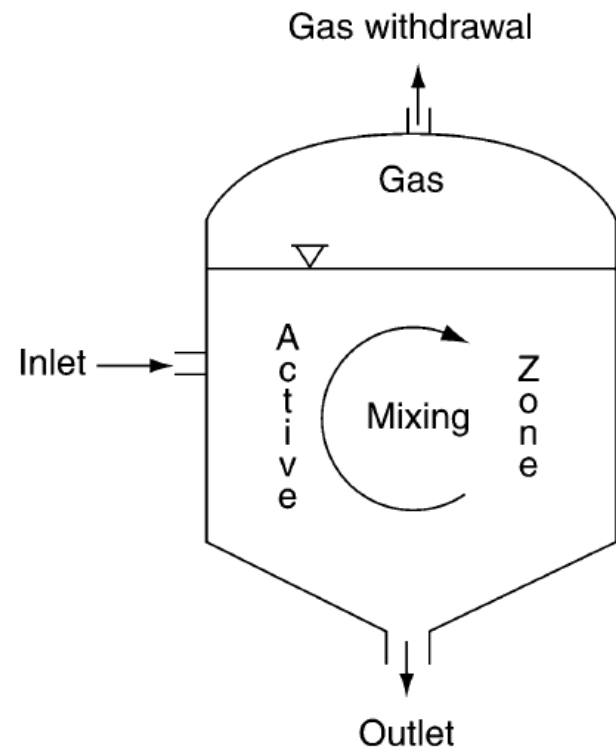
- ❖ Completely mixed anaerobic digester
- ❖ Anaerobic contact process
- ❖ Anaerobic sequencing batch reactor (ASBR)
- ❖ Anaerobic packed bed or anaerobic filter
- ❖ Anaerobic fluidized and expanded bed reactors
- ❖ Upflow anaerobic sludge blanket (UASB) reactor
- ❖ Anaerobic baffled reactor (ABR)



# Conventional & High-rate ADs



Conventional



High-rate

# Conventional & High-rate ADs

## Conventional AD

- Stratified
- Intermittant feeding and withdrawal
- Heated to 30-35°C
- HRT based on liquid input is 30-60 days
- VS loading: 500-1600 kg/m<sup>3</sup>.day

## High-rate AD

- Homogeneous due to mixing
- Continuous or intermittant feeding and withdrawal
- Heated to 30-35°C
- HRT based on liquid input is 15 days or less
- VS loading: 1600-800 kg/m<sup>3</sup>.day

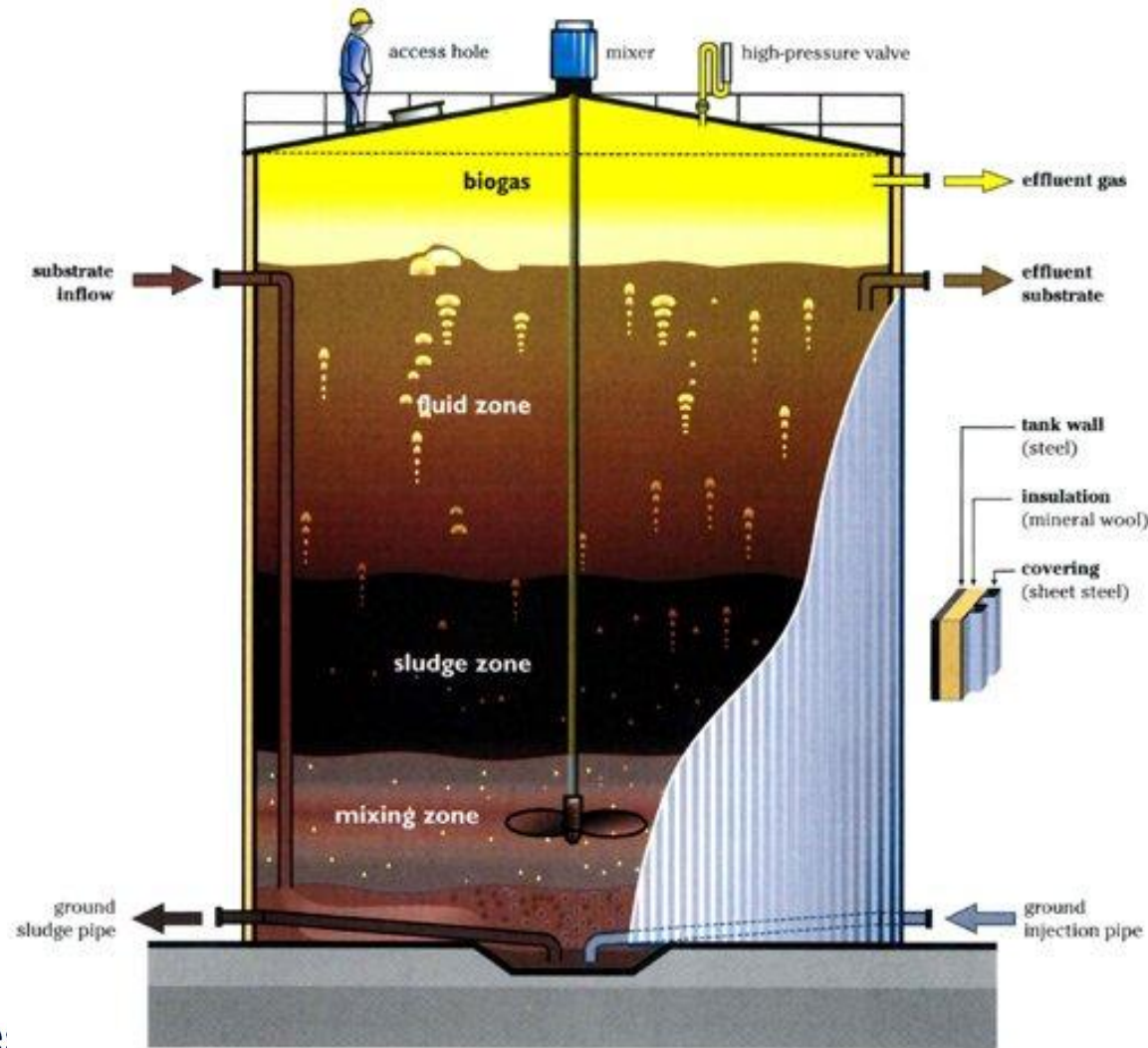
# Completely mixed AD

- ❖ Completely mixed reactor with no solids recycle in which the SRT equals the HRT.
- ❖ Wastewater and anaerobic bacteria are mixed together and allowed to react.
- ❖ When the organic pollutant is reduced to desired level, treated wastewater is then removed.
- ❖ Can be operated in either batch or continuous mode and depends on the continuous growth of new biomass to replace that lost in

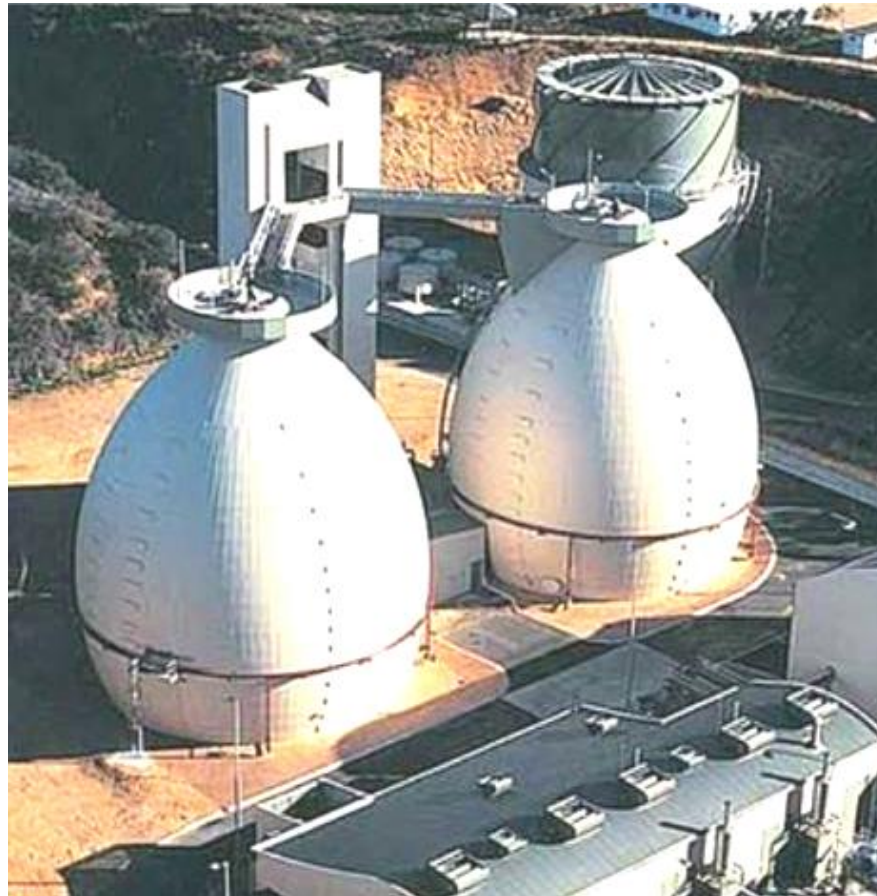
# Completely mixed AD

- ❖ At least 10 days of SRT and HRT are required because of slow growing methanogens.
- ❖ This necessitates a reactor with a very large volume.
- ❖ Large volume requirements and wash-out of micro-organisms in effluent pose serious problems and make ADs unsuitable for use with most industrial wastewaters.
- ❖ However, they can be used successfully for sludge treatment and for wastewaters that contain high solids and organic matter content.

# Completely mixed AD

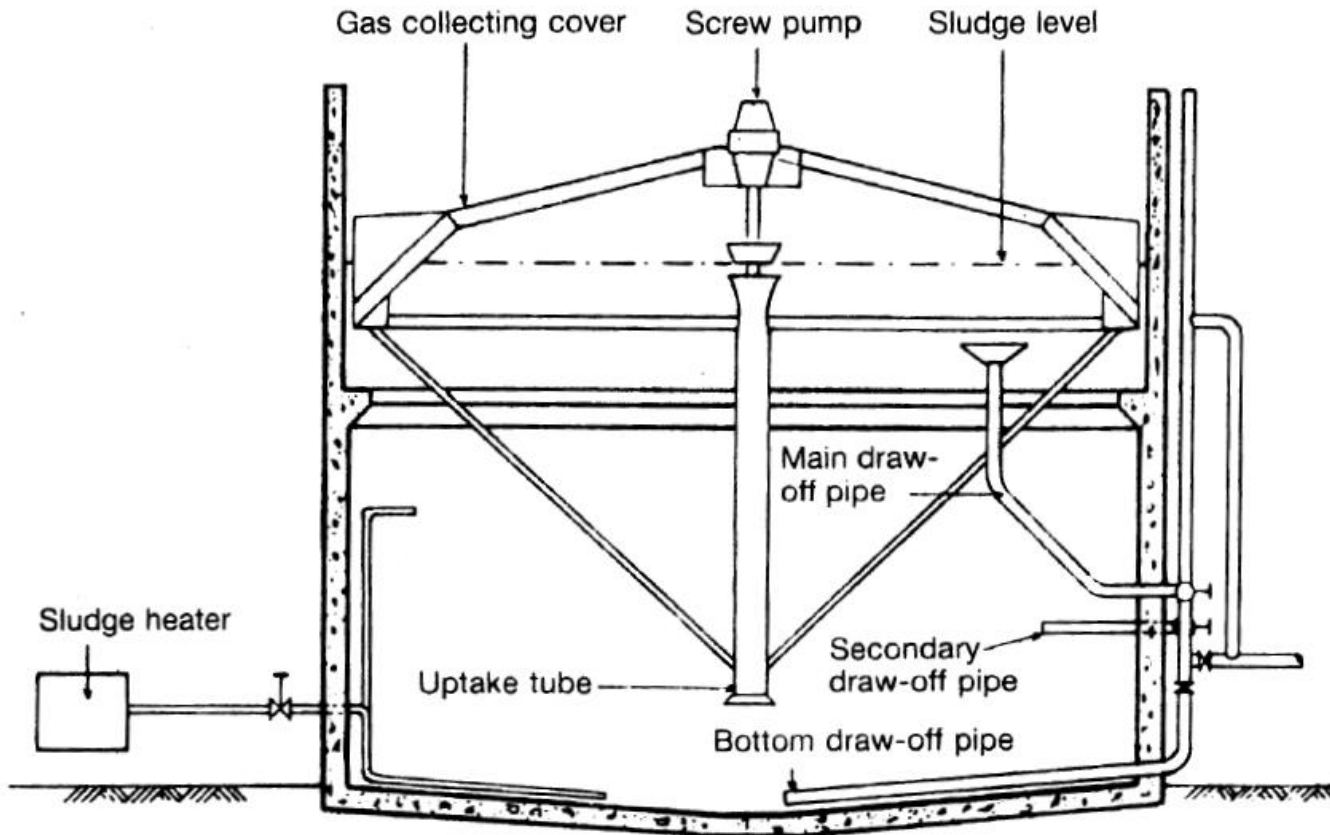


# Completely mixed AD



Egg-shaped Anaerobic Sludge Digester

# Completely mixed AD



# Anaerobic contact process (ACP)

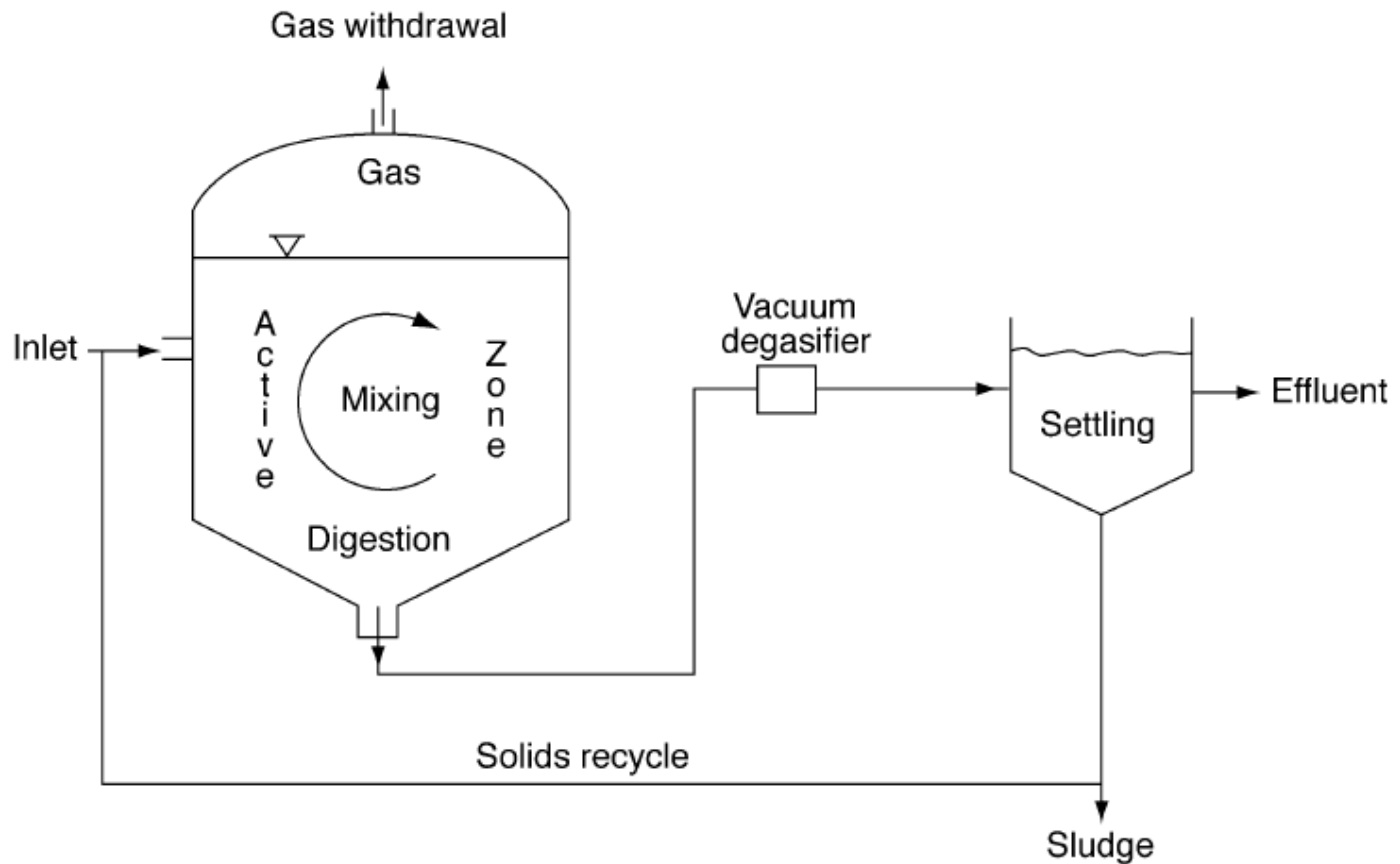
- ❖ Link between high biomass concentration, greater efficiency and smaller reactor size is the idea of ACP.
- ❖ Settling of anaerobic sludge in a settling tank and its return back to the reactor allows further contact between biomass and raw waste.
- ❖ In ACP, due to sludge recycling, the SRT is no longer coupled to the HRT.
- ❖ As a result, considerable improvements in treatment efficiency can be achieved.



# Anaerobic contact process (ACP)

- ❖ Major drawback is poor sludge settlement arose from gas formation by anaerobic bacteria in settling tank.
- ❖ Gas formation problem can be minimized by;
  - ❖ employing vacuum degasification
  - ❖ applying thermal shock prior to sedimentation
  - ❖ using flocculating agents in settling tank
  - ❖ incorporating inclined plates into the settler design
- ❖ Although simple in concept, individual units make ACP more complex than other high rate ADs.
- ❖ Absence of any internal fittings offers some advantages for the treatment of wastes having a high solids content.

# Anaerobic contact process

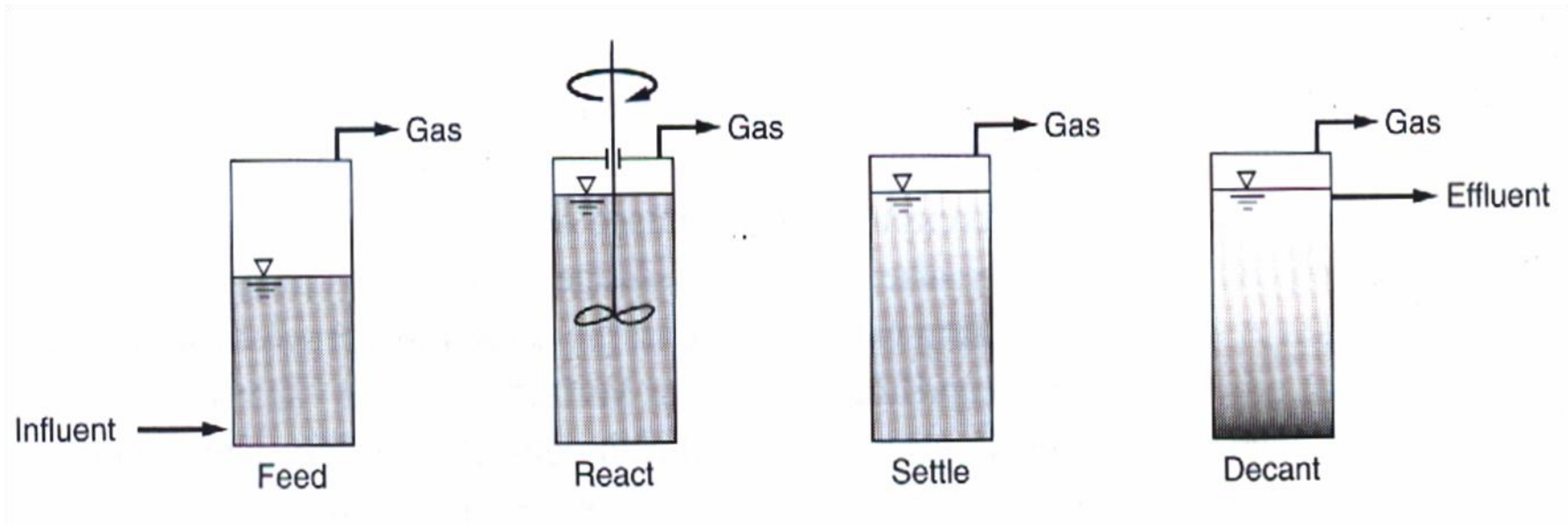


# Anaerobic Sequencing Batch Reactor

- ❖ Anaerobic sequencing batch reactor (ASBR) process is a batch-fed, batch-decanted, suspended growth system and is operated in a cyclic sequence of four stages: *feed*, *react*, *settle* and *decant*.
- ❖ Since a significant time is spent in settling the biomass from the treated wastewater, reactor volume requirement is higher than for continuous flow processes.
- ❖ However, it requires no additional biomass settling stage or solids recycle.
- ❖ No feed short-circuiting is another advantage of ASBRs over continuous flow systems.

# Anaerobic Sequencing Batch Reactor

- ❖ Operational cycle-times for the ASBR can be as short as 6 hours if biomass granulation is achieved.



# Anaerobic Filter (Packed Bed)

- ❖ Anaerobic filter is a fixed-film biological wastewater treatment process in which a fixed matrix (support medium) provides an attachment surface that supports the anaerobic microorganisms in the form of a biofilm.
- ❖ Treatment occurs as wastewater flows upwards through this bed and dissolved pollutants are absorbed by biofilm.
- ❖ Anaerobic filters were the first anaerobic systems that eliminated the need for solids separation and recycle while providing a high SRT/HRT ratio.

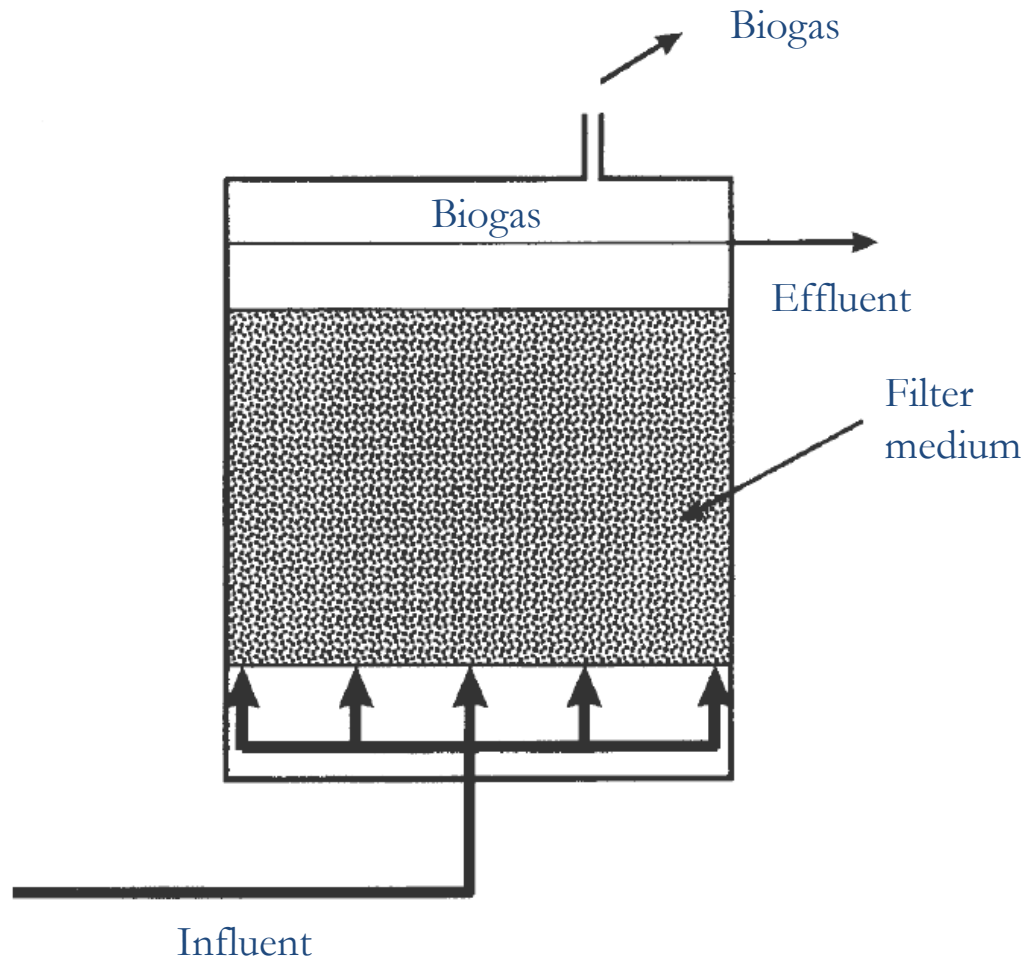
# Anaerobic Filter (Packed Bed)

- ❖ Various types of support material can be used, such as plastics, granular activated carbon (GAC), sand, reticulated foam polymers, granite, quartz and stone.
- ❖ These materials have exceptionally high surface area to volume ratios ( $400 \text{ m}^2/\text{m}^3$ ) and low void volumes.
- ❖ Its resistance to shock loads and inhibitions make anaerobic filter suitable for the treatment of both dilute and high strength wastewaters.

# Anaerobic Filter (Packed Bed)

- ❖ Limitations of anaerobic filter are mostly physical ones related to deterioration of the bed structure through a gradual accumulation of non-biodegradable solids.
- ❖ This leads eventually to channelling and short-circuiting of flow, and anaerobic filters are therefore unsuitable for wastewaters with high solids contents.
- ❖ Additionally, there is a relatively high cost associated with the packing materials.

# Anaerobic Filter (Packed Bed)





# Anaerobic Filter Packings

Random packings



Corrugated structured packings



# Fluidized Bed Reactor (FBR)

- ❖ FBR is a biological reactor that accumulates a maximum active attached biomass yet still handling fine suspended solids without blocking.
- ❖ By maximizing the surface area available for microbial attachment and minimizing the volume occupied by the media, a maximum specific activity of attached biomass may be achieved for a given reactor volume.
- ❖ A filter containing extremely small particles (0.5 mm) provides adequate surface area to achieve these benefits.

# Fluidized Bed Reactor (FBR)

- ❖ In order to achieve fluidization of the biomass particles, units must be operated in an upflow mode.
- ❖ Rate of liquid flow and the resulting degree of bed expansion determines whether the reactor is termed a fluidized bed or expanded bed system.
- ❖ Expanded bed reactors have a bed expansion of 10% to 20% compared to 30% to 90% in fluidized beds.

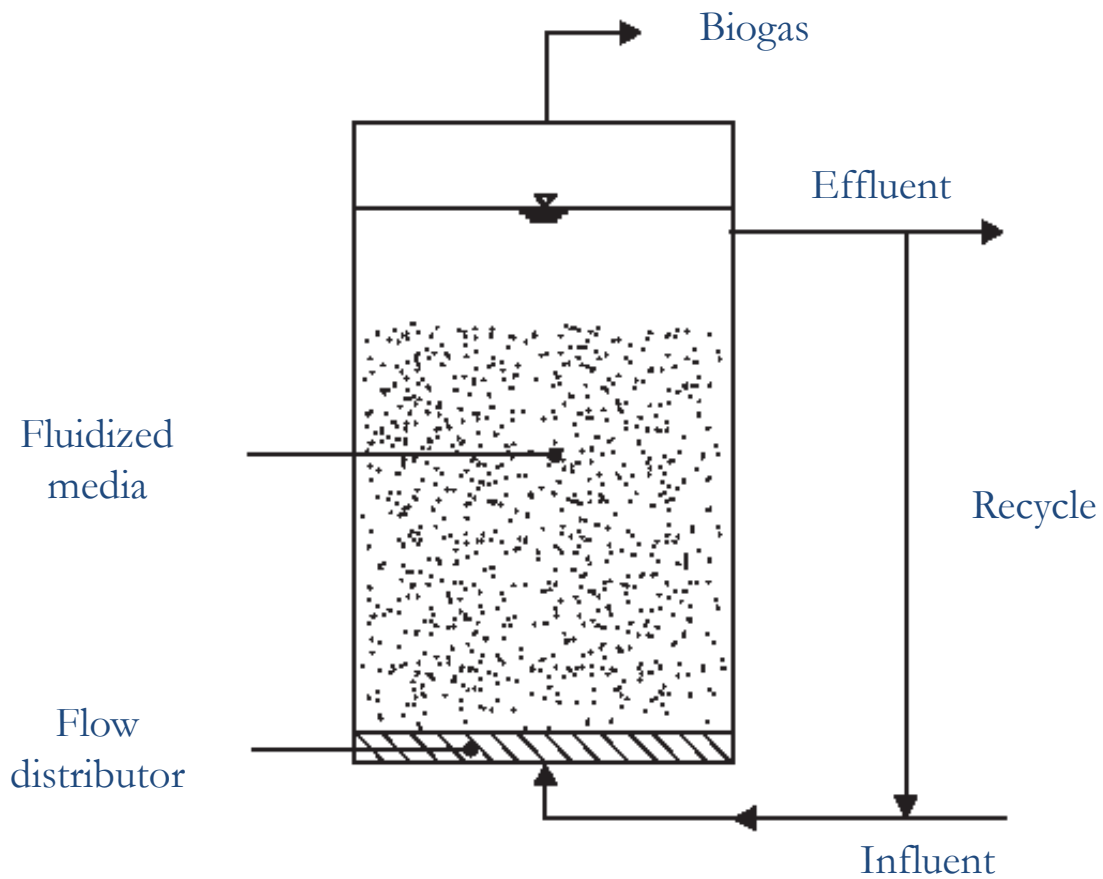
# Fluidized Bed Reactor (FBR)

- ❖ In FBR, biomass is attached to surface of small particles (*anthracite, high density plastic beads, sand* etc.) which are kept in suspension by upward velocity of liquid flow.
- ❖ Effluent is recycled to dilute incoming waste and to provide sufficient flow-rate to keep particles in suspension.
- ❖ Large surface area of support particles and high degree of mixing that results from high vertical flows enable a high biomass conc. to develop and efficient substrate uptake.
- ❖ Biomass concentration: 15-40 g/l

# Fluidized Bed Reactor (FBR)

- ❖ The greatest risk with FBR is the loss of biomass particles from the reactor following sudden changes in particle density, flow rate or gas production.
- ❖ If flow is interrupted and the bed allowed to settle, there is a tendency once flow is restarted for the entire bed to move upward in plug-flow rather than fluidizing.
- ❖ In practice, considerable difficulties were experienced in controlling the particle size and density of flocs due to variable amounts of biomass growth on particles.
- ❖ Therefore FBRs are considered to be difficult to operate.

# Fluidized Bed Reactor (FBR)



# Upflow Anaerobic Sludge Blanket (UASB) Reactor

- ❖ The problem associated with anaerobic filters and FBRs has led to development of unpacked reactors that still incorporate an immobilized form of particulate biomass.
- ❖ In 1970s, in the Netherlands, Lettinga *et al.* developed an unpacked high-rate reactor called UASB reactor.
- ❖ It is by far the most widely used high-rate anaerobic system for domestic & industrial wastewater treatment.
- ❖ UASB reactor is based on that anaerobic sludge exhibits inherently good settling properties, provided the sludge is not exposed to heavy mechanical agitation.

# Upflow Anaerobic Sludge Blanket (UASB) Reactor

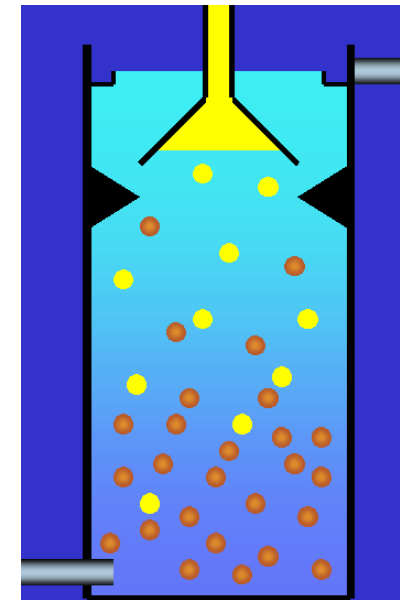
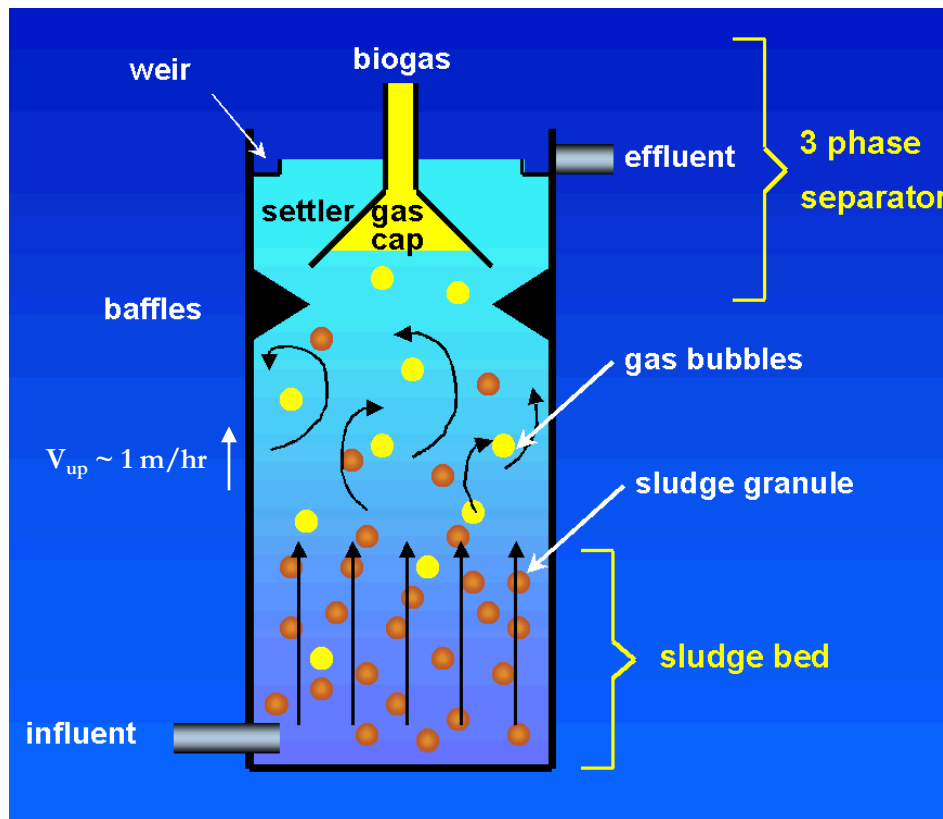
- ❖ Adequate mixing is provided by an even flow-distribution combined with a sufficiently high upflow velocity, and by agitation that results from gas production.
- ❖ Biomass is retained as a blanket or granular matrix, and is kept in suspension by controlling the upflow velocity.
- ❖ Wastewater flows upwards through a sludge blanket located in lower part of reactor, while upper part contains a three phase (solid, liquid, gas) separation system.



# Upflow Anaerobic Sludge Blanket (UASB) Reactor

- ❖ Three-phase separation device is the most characteristic feature of UASB reactor.
- ❖ It facilitates the collection of biogas and also provides internal recycling of sludge by disengaging adherent biogas bubbles from rising sludge particles.
- ❖ Superior settling characteristics of granular sludge allows higher sludge concentrations and consequently permitted UASB reactor to achieve much higher OLRs.
- ❖ Granular sludge development is now observed in UASB reactors treating many different types of wastewater.

# Upflow Anaerobic Sludge Blanket (UASB) Reactor



# Upflow Anaerobic Sludge Blanket (UASB) Reactor

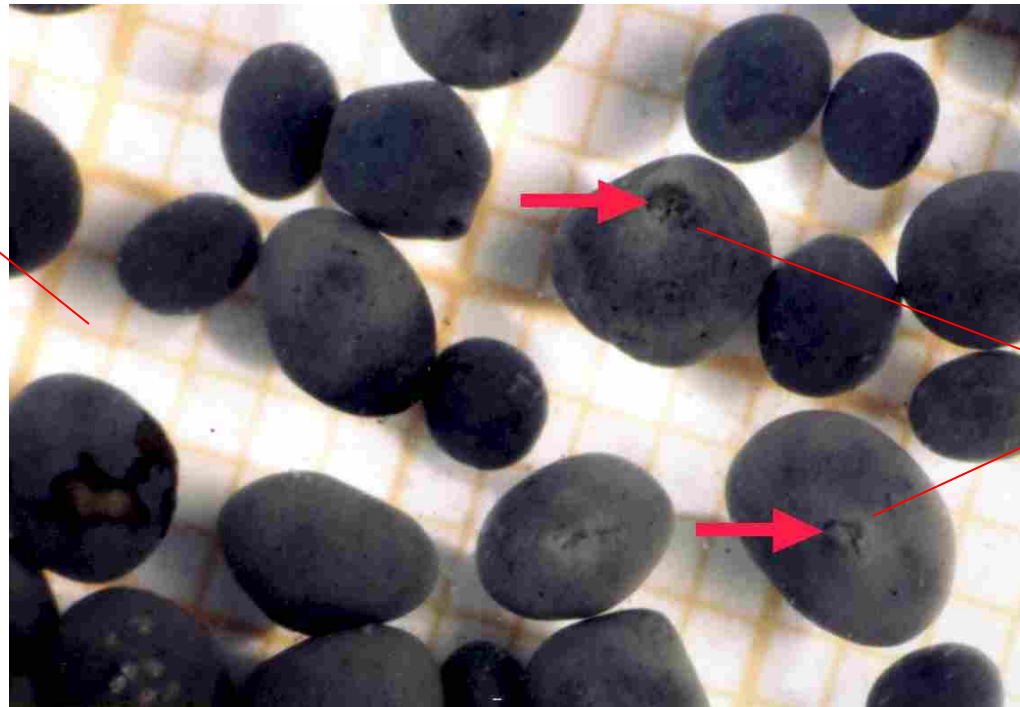


Two-stage UASB reactors, Tel Aviv, Israel

# Granulation

- ❖ Granulation is a process in which a non-discrete flocculent biomass begins to form discrete well-defined granules.
- ❖ These vary in dimension and appearance depending on the wastewater and reactor conditions, but generally have a flattened spherical geometry with a diameter of 1-3 mm.
- ❖ Mechanism of biomass granulation has been widely studied the objective being that the rate and extent of granule formation could be manipulated, particularly in wastewaters that show little intrinsic propensity to granulate (e.g. fat and oil containing effluents).

Millimeter paper  
indicating the size  
of the granules.



Gas vents in the  
granules, where  
biogas is released

Anaerobic sludge granules from a UASB reactor treating effluent from a  
Marmara  
Üniversitesi recycle paper mill (Roermond, The Netherlands).

# Consequences of Granulation

1. Leads to internal physicochemical gradients within granules
2. Leads to heterogeneous structured populations of syntrophic microorganisms
3. Affects overall stoichiometry, rates of growth & metabolism
4. Allows the manipulation of growth rate independent of the dilution rate
5. Allows the manipulation of biomass as a single phase
6. Generates a reactor effluent with low suspended solids
7. Allows high biomass concentrations in continuous reactors
8. Allows reactors to be operated continuously beyond normal washout flow rates.

# Development of Granulation

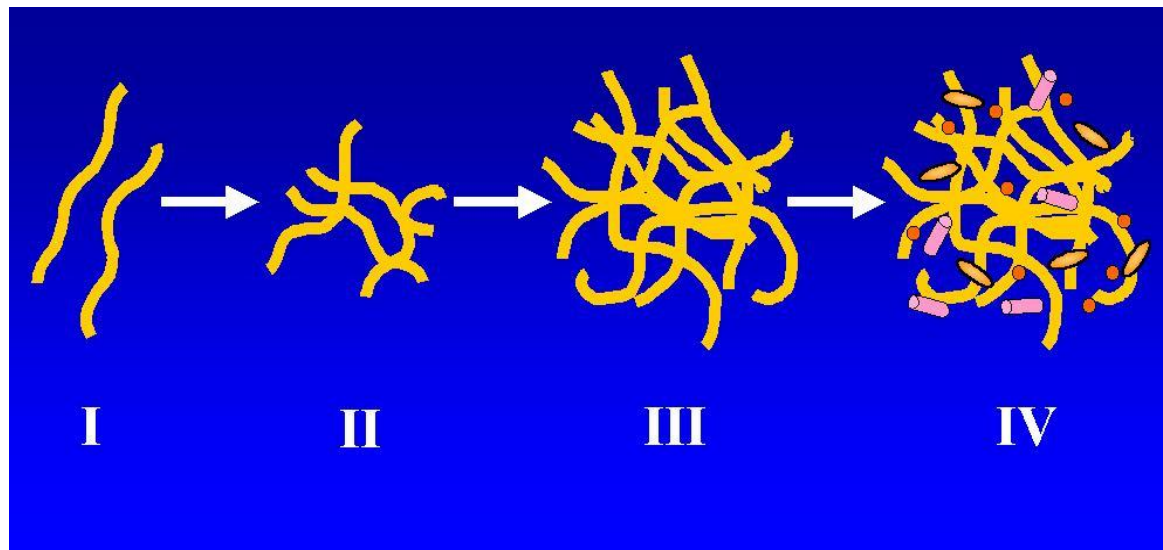
Granule formation is probably dependent on microorganisms participating in the same critical events.

- ❖ Transport of microbial cells to surface of an uncolonized inert material or other microbial cells (substratum)
- ❖ Initial reversible adsorption to the substratum by physicochemical forces
- ❖ Irreversible adhesion of cells to the substratum by microbial appendages and/or polymers attaching cell to the substratum.
- ❖ Replication of cells and the development of granules.



# Development of Granulation

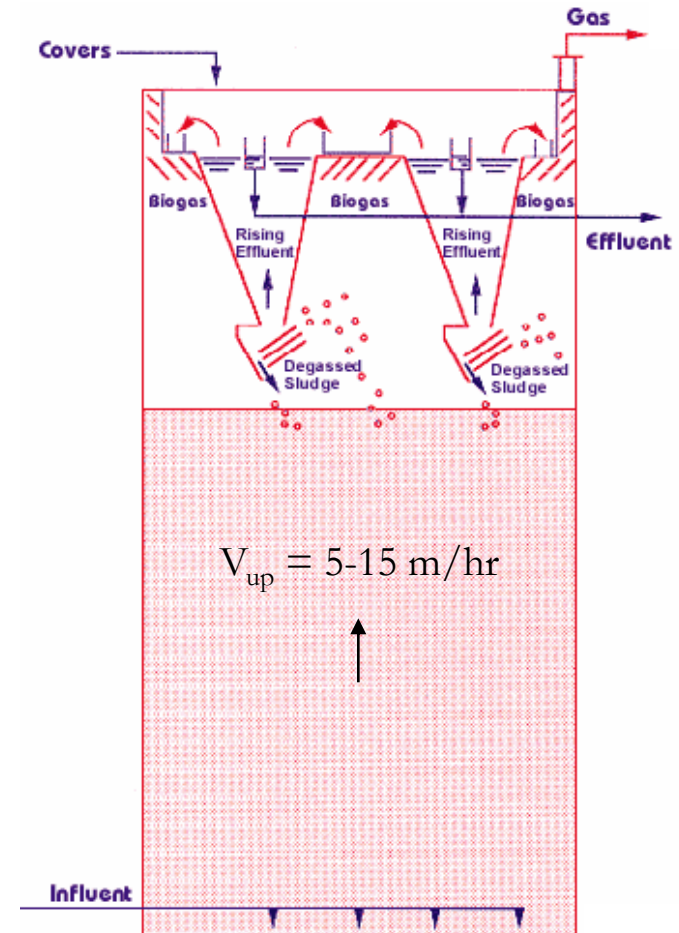
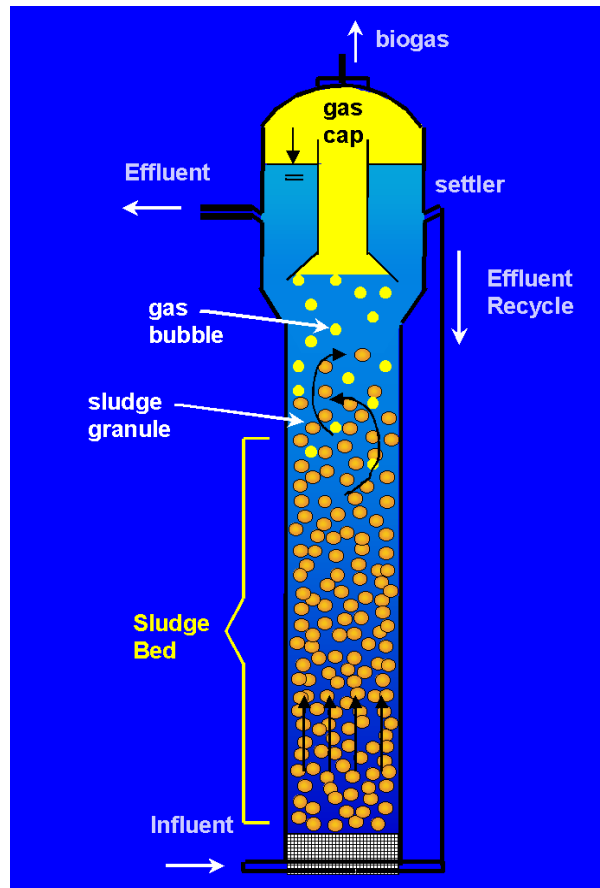
## Spaghetti theory of granulation



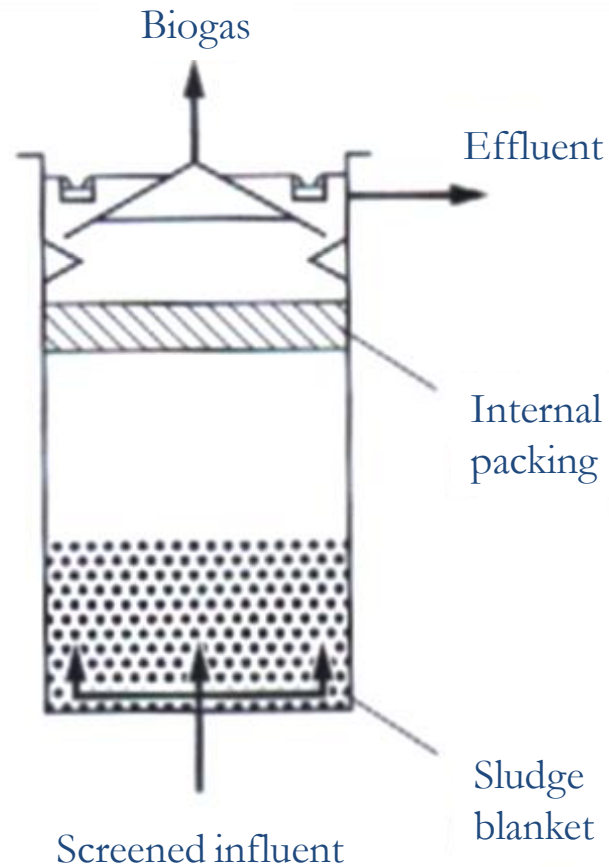
- I) Disperse methanogens (filamentous *Methanosaeta*)
- II) Floc formation via entanglement
- III) Pellet formation (spaghetti balls) and
- IV) Mature granules, with attachment of other anaerobic microorganisms onto the pellet.



# Expanded Granular Sludge Bed (EGSB) Reactor



# Hybrid (UASB+Packed Bed) Reactor



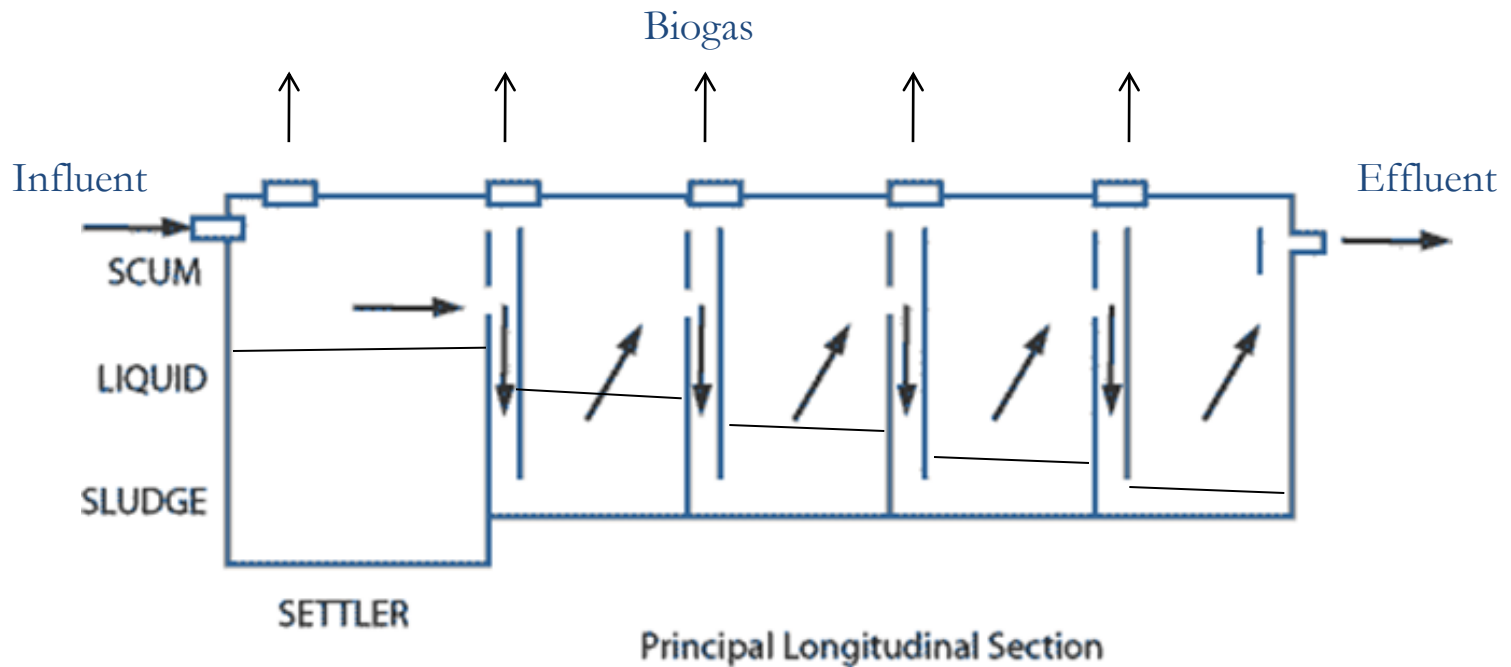
# Anaerobic Baffled Reactor

- ❖ Anaerobic baffled reactor (ABR) consists of a number of UASB reactors connected in series.
- ❖ In ABR, wastewater passes over and under the staggered vertical baffles as it flows from inlet to outlet.
- ❖ Unique baffled design enables ABR to reduce biomass washout, hence retain a high active biomass content.
- ❖ It can recover remarkably quickly from hydraulic and organic shock loads.
- ❖ No special gas or sludge separation equipment is required

# Anaerobic Baffled Reactor

- ❖ Owing to its compartmentalized configuration, it may function as a two-phase anaerobic treatment system with separation of acidogenic and methanogenic biomass.
- ❖ ABR has a simple design and requires no special gas or sludge separation equipment. It can be used for almost all soluble organic wastewater from low to high strength.
- ❖ Considering its simple structure and operation, it could be considered a potential reactor system for treating municipal wastewater in tropical and sub-tropical areas of developing countries

# Anaerobic Baffled Reactor



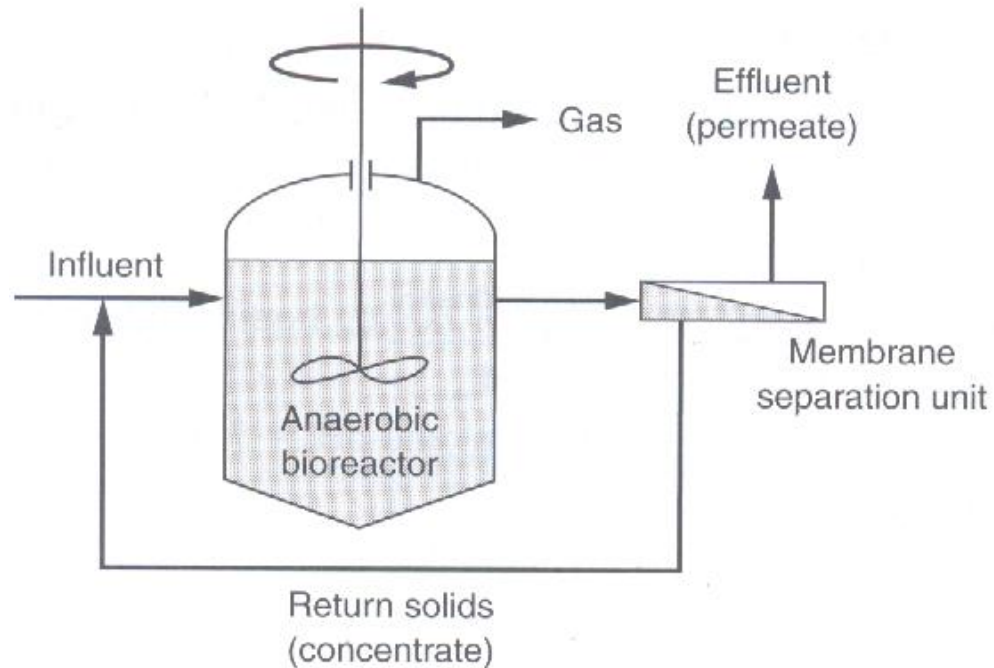
# Anaerobic Membrane Bioreactor (AMB)

- ❖ AMB is still in development stage.
- ❖ Higher biomass concentrations in AMB reduce the size of reactor and increase organic loadings.
- ❖ Almost complete capturing of solids (much longer SRT) results in maximum removal of VFAs and degradable soluble organics and provide a higher-quality effluent.
- ❖ Maximum capture of effluent SS improves greatly the effluent quality.
- ❖ Longer SRT and low effluent SS concentration allow AMB to compete with aerobic treatment processes.

# Anaerobic Membrane Bioreactor (AMB)

- ❖ High liquid velocities across the membrane and gas agitation systems might be used to minimize fouling.
- ❖ Organic fouling problems are typically caused by accumulation of colloidal material and bacteria on the membrane surface.
- ❖ High pumping flowrates across the membrane may lead to the loss of viable bacteria due to cell lysis.
- ❖ Inorganic fouling is due to formation of struvite ( $\text{MgNH}_4\text{PO}_4$ )
- ❖ Developments in membrane design and fouling control measures could make AMR a viable technology in future.

# Anaerobic Membrane Bioreactor



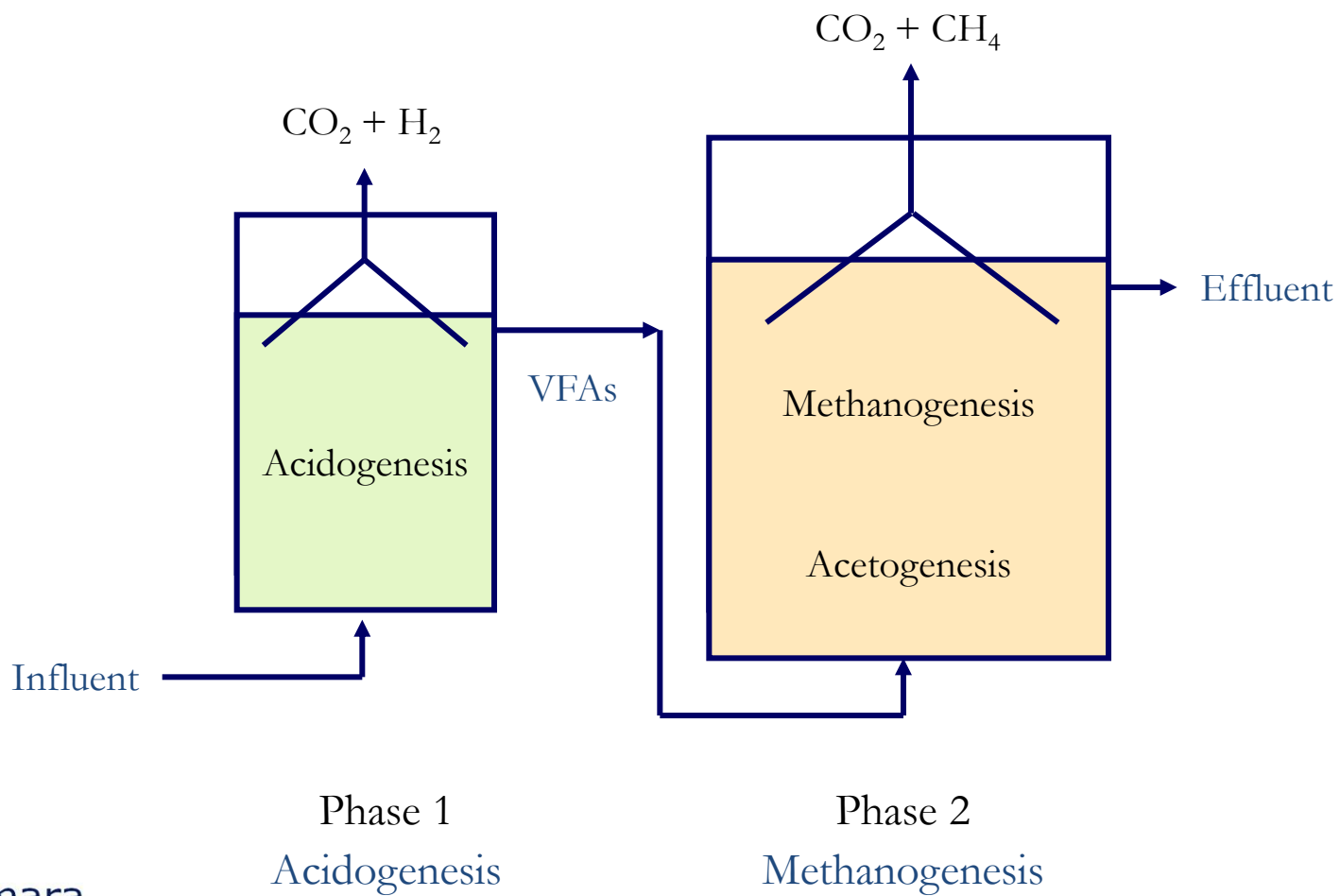
Anaerobic bioreactor with external membrane separation of solids in effluent stream



## 2-Phase AD Process

- ❖ Two-phase AD implies a process configuration employing separate reactors for acidification and methanogenesis.
- ❖ These are connected in series, allowing each phase of digestion process to be optimized independently since the microorganisms concerned have;
  - ❖ Different nutritional requirements
  - ❖ Physiological characteristics
  - ❖ pH optima
  - ❖ Growth and nutrient uptake kinetics and
  - ❖ Tolerances to environmental stress factors

# 2-Phase AD Process



# Advantages of Two-Phase AD

- ❖ Improvement in process control
- ❖ Disposal of excess fast growing acidogenic sludge without any loss of slow growing methanogens
- ❖ Degradation and attenuation of toxic materials in the first phase (protects the sensitive methanogens)
- ❖ Precise pH-control in each reactor
- ❖ Higher CH<sub>4</sub> content in biogas from methanogenic phase
- ❖ Increased loading rate possible for methanogenic stage
- ❖ Balancing tanks in existing treatment plants might be readily converted to acidification tanks

# Disadvantages of Two-Phase AD

- ❖ Possible disruption of syntrophic relationships
- ❖ High sludge accumulation in the first phase
- ❖ Lack of process experience and so more difficult to operate
- ❖ Difficulty maintaining a balanced segregation of the phases.

# Comparison of anaerobic reactors

Typical operating conditions of various AD configurations

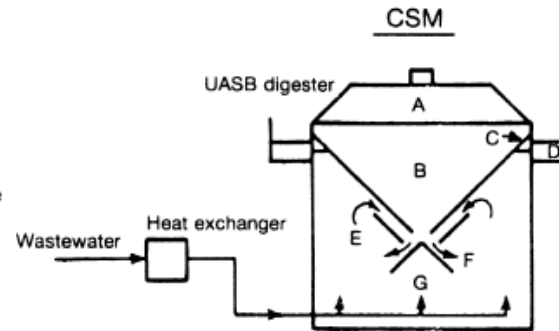
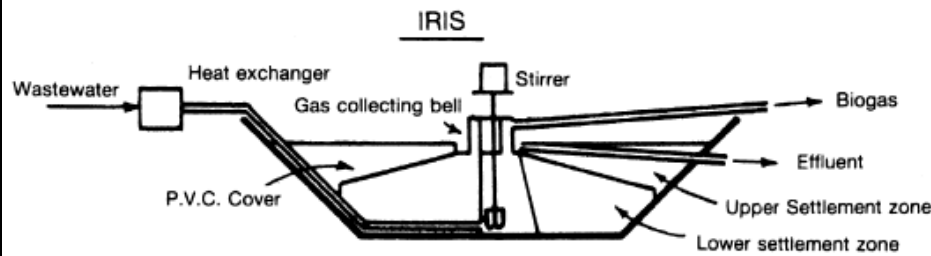
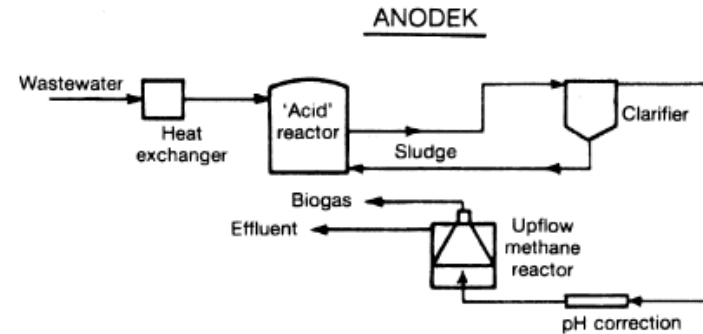
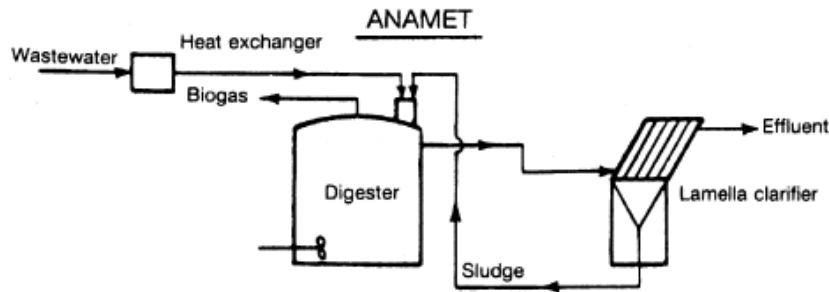
<i>Reactor type</i>	<i>Load (kg COD/m<sup>3</sup>day)</i>	<i>HRT (hour)</i>	<i>COD removal (%)</i>
Conventional anaerobic reactor	1–5	240–360	60–80
Anaerobic contact reactor	1–6	24–120	70–95
Anaerobic sequencing batch reactor	1–10	6–24	75–90
Anaerobic filter	2–15	10–85	80–95
Fluidized bed	2–50	1–4	80–90
UASB	2–30	2–72	80–95
Anaerobic baffled reactor	3–35	9–32	75–95
Two phase anaerobic digestion	5–30	20–150	70–85

# Comparison of anaerobic reactors

Type of unit	Range
<i>Anaerobic filter</i>	
Organic load (kg COD/m <sup>3</sup> . d)	2–10
Retention period (h)	10–15
COD removal (%)	70–80
Critical solids concentration in feed (mg/l)	450–1050
<i>Upflow anaerobic sludge blanket reactor</i>	
Load (kg COD/m <sup>3</sup> . d)	2–15
Retention period (h)	10–50
COD removal (%)	70–90
<i>Expanded bed</i>	
Load (kg COD/m <sup>3</sup> . d)	2–50
Retention period (h)	0.5–24
COD removal (%)	70–80

# Industrial wastewater treatment

## Anaerobic treatment of sugar industry wastewaters



- A - Gas chamber
- B - Sedimentation chamber
- C - Gas catcher
- D - Purified effluent
- E - Wastewater and sludge
- F - Sludge return
- G - Active sludge chamber