
Dipartimento di Ingegneria Civile e Ambientale

Environmental section

POLITECNICO DI MILANO


    

# *Anaerobic Digesters for biogas production*


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# AD plants

AD plants are complex and technological installations designed to maximize biogas production. They normally include the following sections:

Substrate collection/ storage → Pretreatments → Anaerobic Digester → Post treatments/ disposal → Biogas valorization

## Substrate reception/Storage:

AIM: to guarantee the continuous feeding of discontinuously produced/delivered products

ISSUES: odours, licheate

# AD plants



## Pretreatments:

AIM: to remove extraneous materials, to make the substrate more easily degradable/transportable

ISSUES: energy request, odour, residues handling and disposal

## Digester:

AIM: ensure a favorable environment to anaerobic microorganisms,

ISSUES: mixing, temperature, gas capture

# AD plants

**Post-treatment:**

AIM: to make digestate compatible with its final disposal (N-content, stabilization, water content)

ISSUES: odours, energy request, residues handling

**Biogas valorization:**

AIM: to convert methane into usable energy (heat or power) depending on its final destination

ISSUES: safety, storage, efficiency

# ANAEROBIC DIGESTER

•It is the core of any AD plant.

•It is the *'container'* in which the anaerobic digestion process takes place in a controlled environment.

•It should be designed and operated to favor the AD process, by guaranteeing:

- Adequate and stable temperature
- Sufficient mixing to enhance the effective contact between bacteria and substrates
- Optimal residence time to support a stable microbial population and to achieve the expected degradation
- Reliable and effective biogas capture

# Anaerobic digester: design parameters

The following parameters are relevant in the design of any AD

## Organic Loading Rate (OLR):

It quantifies the mass of substrate that enters the digester per unit of time and per unit of digester volume :

$$OLR\left[\frac{kg_{VS}}{m^3_{digester} \times d}\right] = \frac{C_{org}\left[\frac{kg_{VS}}{d}\right]}{V_{digester}\left[m^3\right]}$$

$C_{org}$ = mass feeding rate

$V_{digester}$ = digester volume

- If too high: VFA accumulate, pH drops down, methanogens suffer, the degradation pathway may stop at the acidogenic step
- If too low: the digester is underloaded, biogas production is suboptimal and can be increased.

# Anaerobic digester: design parameters



## Organic Loading Rate (OLR):

Its optimal value depends on the type of substrate (its degradability) and on the type of reactors. OLR intervals:

- from 1 –3 kgVS/m3/d for agricultural digesters
- to as high as 50 kgVS/m3/d for highly loaded digesters fed on easily fermentable substrates

The higher the organic loading rate:

- the higher the specific biogas production (volume of biogas produced per volume of anaerobic reactor per day)
- The lower the amount of biogas produced per unit of feedstock, i.e. the lower the ratio between the operational and theoretical BMP.

# Anaerobic digester: design parameters

## Hydraulic residence time (HRT):

It quantifies the average time that a soluble molecule fed into the reactor remains inside it, that is also the time available to microrganisms to degrade it.

$$HRT[d] = \frac{V_{digester}\left[m^3_{digester}\right]}{Q_{IN}\left[\frac{m^3_{fed\ to\ digester}}{d}\right]}$$

$Q_{IN}$ = influent volumetric flow rate

- Too low: biodegradation is incomplete and degradable substrate remains in the digestate
- Too high: the digester is underloaded, biogas production is suboptimal and can be increased.

# Anaerobic digester: design parameters

## Hydraulic residence time (HRT):

Its optimal value depends on the type of substrate (its degradability) and on the type of reactor. HRT intervals:

- from 60 –90 d for agricultural digesters
- to as low as few hours for highly loaded digesters fed on easily fermentable substrates

The higher the HRT:

- the lower the specific biogas production
- the higher the ratio between the operational and theoretical BMP.

# Anaerobic digester: design parameters

## HRT vs OLR:

These two parameters are not independent, they are inversely proportional according to the following relationship:

$$OLR\left[\frac{kg_{VS}}{m^3_{digester}d}\right]=\frac{Conc_{IN}\left[\frac{kg_{VS}}{m^3_{digester}}\right]}{HRT[d]}$$

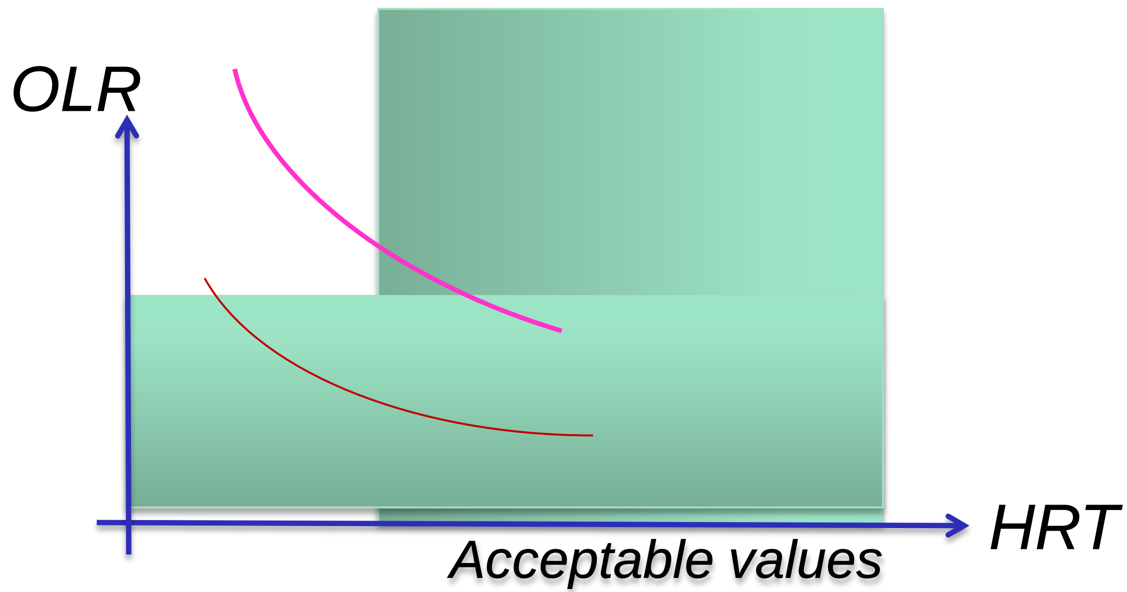
*$Conc_{IN}$ = volatile solid concentration in the influent to the digester*

In digester design, only one of these two parameters matters. The digester volume is based:

- on the desired OLR, for highly concentrated influent flows,
- on the desired HRT, for diluted influent flows

# Anaerobic digester: design parameters

**HRT vs OLR:**




highly concentrated influent flows: the minimum acceptable HRT corresponds to unacceptably high OLR → the design criteria is the OLR

Diluted influent flows: the maximum acceptable OLR corresponds to unacceptably low HRT → the design criteria is the HRT

## Sludge residence time (SRT):

It quantifies the average time that a particulate molecule/particles fed into the reactor spends inside it, that is also the time available to microrganisms to remain in the reactor.

$$SRT[d] = \frac{\text{Mass of solids in digester}\left[kg_{VS}\right]}{\text{Mass wasted per day}\left[\frac{kg_{VS}}{d}\right]}$$

Each time solids are withdrawn from digester, a fraction of the bacterial population is removed thus implying that the cell growth rate must at least compensate for the cell removal rate to ensure steady state and avoid process failure (bacteria wash-out)

When several microrganisms should cohexist, the SRT is fixed on the basis of the slowest growing ones *(=methanogens*).

# Anaerobic digester: design parameters

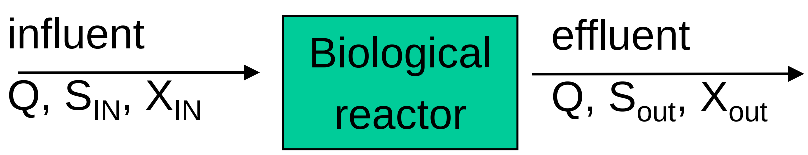
Digesters may include **a solid/liquid separation unit** (*settling tanks, filters, membrane, supports for the development of a microbial biofilm*) that selectively retains particulate matter (microorganisms included) in the system.

In those systems the retention time of the **soluble components** (and unretained matter, S) is different from that of **particulate components** (= retained matter, X):

→ **Particulate (or sludge) residence time (SRT)** > HRT

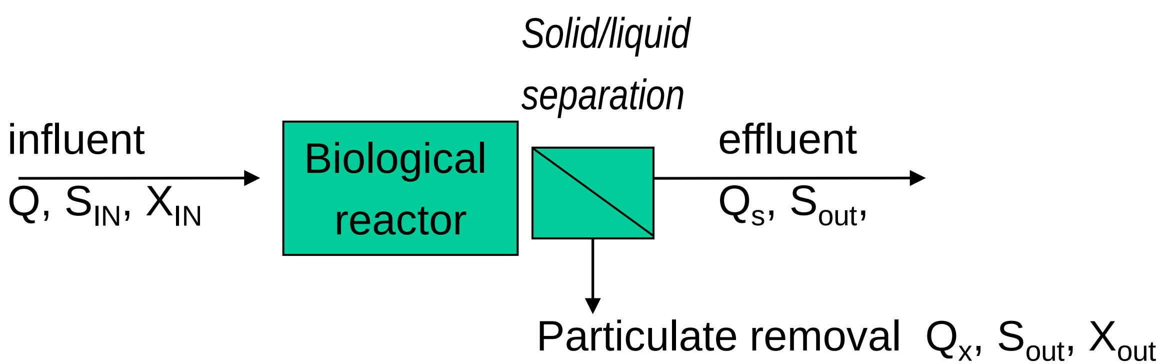
No retention:

HRT = SRT




retention of particulate matter:

SRT > HRT



# Anaerobic digester: design parameters

## Sludge residence time (SRT):

•For **low rate agricultural digesters**, no solid/liquid separation is applied → SRT = HRT and defined according to the rate of hydrolysis (the limiting step) → SRT is always sufficient long to retain methanogens

•For **high rate digesters** under mesofilic conditions → HRT<SRT and SRT should be defined according to the following observations:

- SRT< 5 d are insufficient for a stable digestion: VFA accumulate because of the washout of methanogenic bacteria,
- SRT = 5-8 d, unstable operational interval,
- SRT > 8–10 days: low VFA concentrations.

**In general:** the higher the amount of microrganisms retained, the higher the OLR that can be applied → the smaller the digester

## Efficiency parameters

*Ratio between the actual BMP and the BMP of the feedstock under optimal batch conditions*

- It depends only on the efficiency of the digester, i.e. it quantifies the efficacy of the reactor to promote the degradation of the organic matter in the feed.
- It can be verified only occasionally, because BMP evaluation is time consuming

*Volatile suspended solids degradation efficiency*

- It is a commonly used parameter, easy to estimate and to monitor in time
- It depends on both the inherent degradability of the  feed and the efficacy of the digester itself

$$\eta_{SV} = \frac{VS_{IN} - VS_{OUT}}{VS_{IN}} \cdot 100$$

Useful parameters to be assessed and monitored to check for proper operation:

- *Specific biogas production rate (SGP)*

$$SGP\left[\frac{m_{biogas}^{3}}{m_{digester}^{3}\times d}\right]$$

- *Percentage of methane in biogas*
- *VS degradation efficiency*
- *Alkalinity/VFA ratio*
- *pH*
- *VFA composition*

## Technological solutions

Broad range of alternatives

Simple systems:

- Low investment costs
- Widely applied, wide experience
- Low rate: Low specific biogas production, high volumes, high footprint

Advanced systems:

- Higher investment costs
- High rate:  high specific biogas production, low footprint

## Digesters classification

Solids content in the reactor:

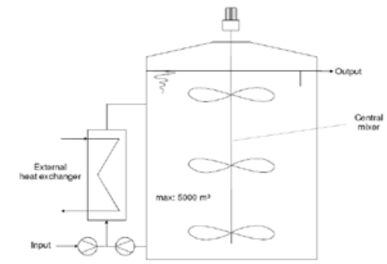
- Wet systems: in reactor TS  concentration < 10-15%;
- Dry systems : in reactor TS  concentration >20-25%;

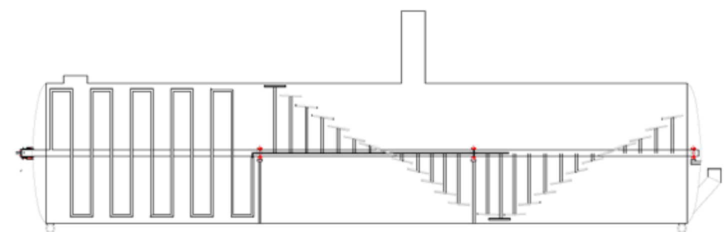
Feeding pattern:

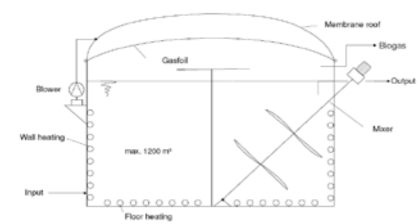
- Continuous
- Batch
- Semi-continuous

Fluid-dynamics:

- Completely mixed reactors
- Plug flow
- Mixed





## Digesters classification

Number of stages:

- Single stage
- Multi-stage, typically two-stage (optimizing the different bioreactions separately in different stages or reactors may lead to a larger overall reaction rate and biogas yield)

Temperature:

- Mesophilic
- Termophilic

Substrate complexity:

- Single substrate
- Co-digestion of various substrates (eg: maize + animal manure + organic fraction of municipal solid wastes, industrial waste)

Biomass retention:

- With
- without

## Examples :

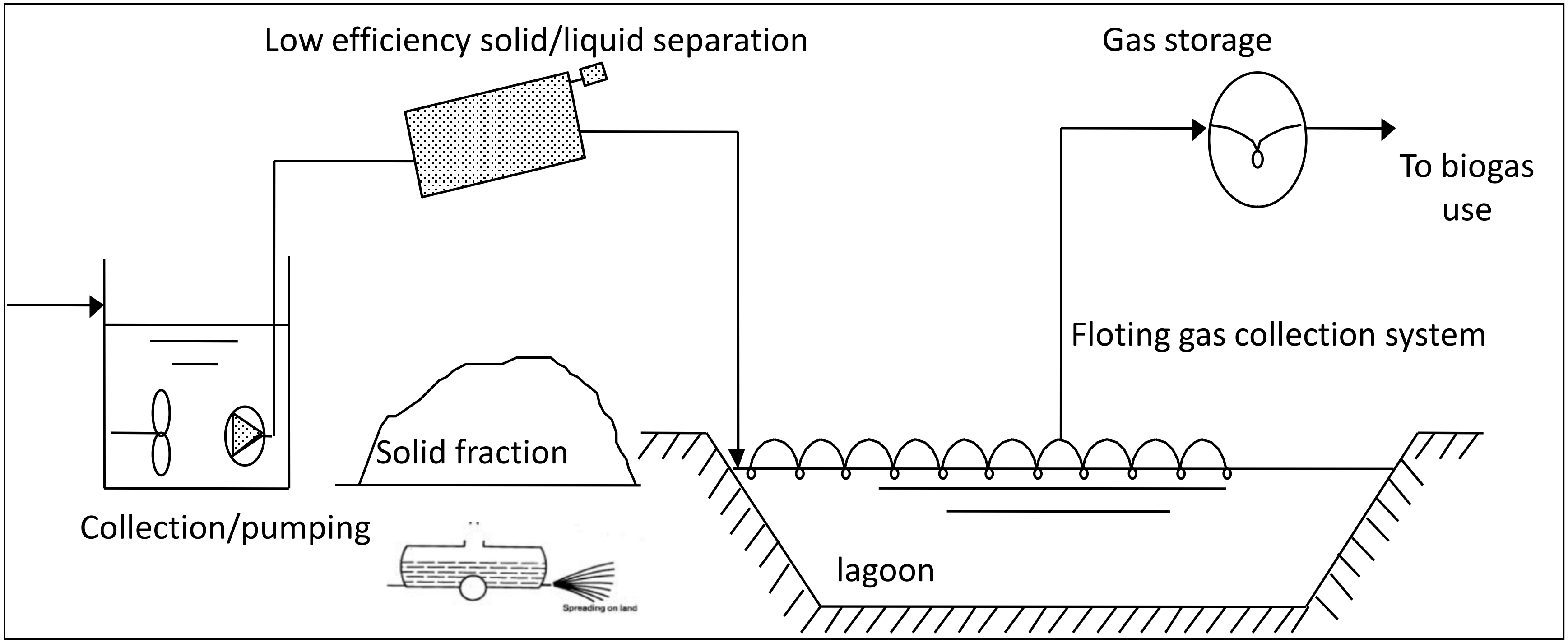
## Agricultural digesters

Treating:

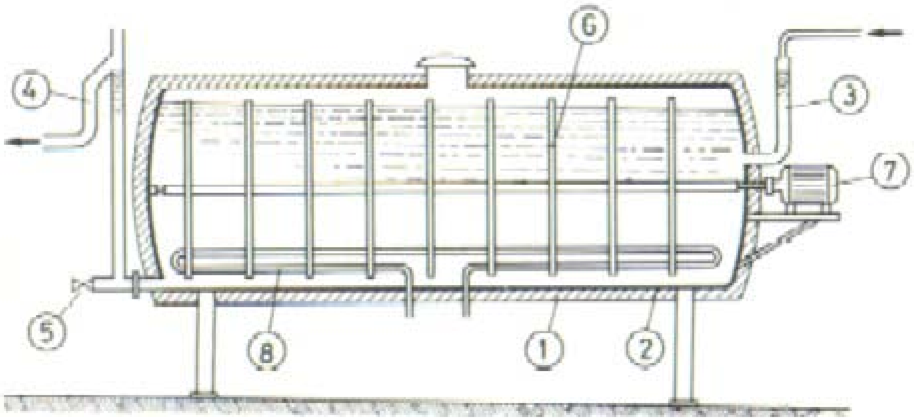
- Animal wastes (piggery /poultry manure),
- Agricultural feedstocks/residues (e.g. wheat straw, stalks)
- Energy crops (maize/sorgum/…)

# Agricultural digesters

Simple solutions that take advantage of in-farm already existing large storage tanks :



# Agricultural digesters

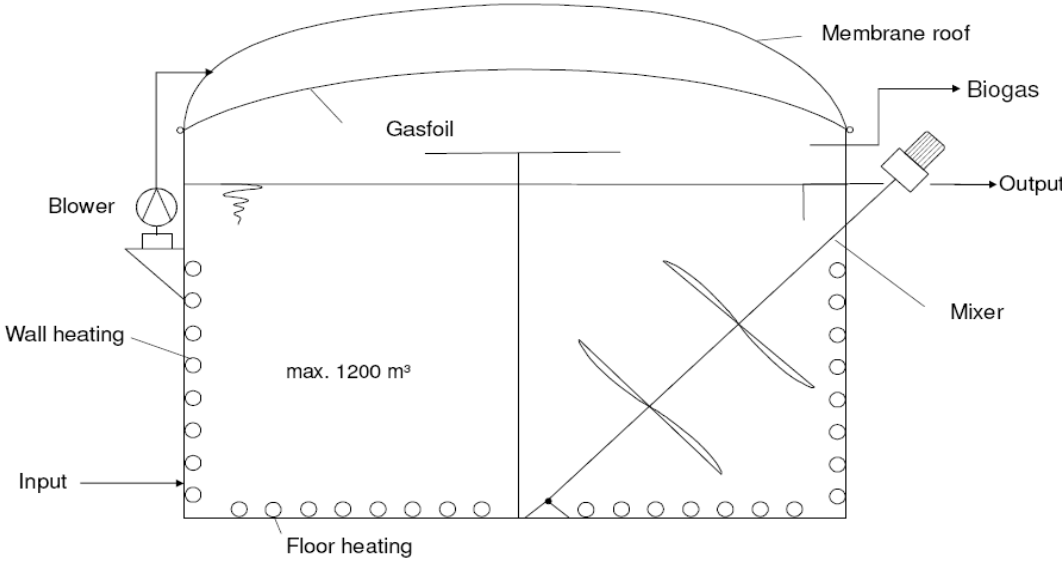



Horizontal digesters and gas holding tank

1. Stainless still tank
2. Insulation
3. Feeding inlet
4. Digestate outlet
5. Heavy particles outlet
6. Horizontal Mixer
7. Mixing engine
8. Heating system

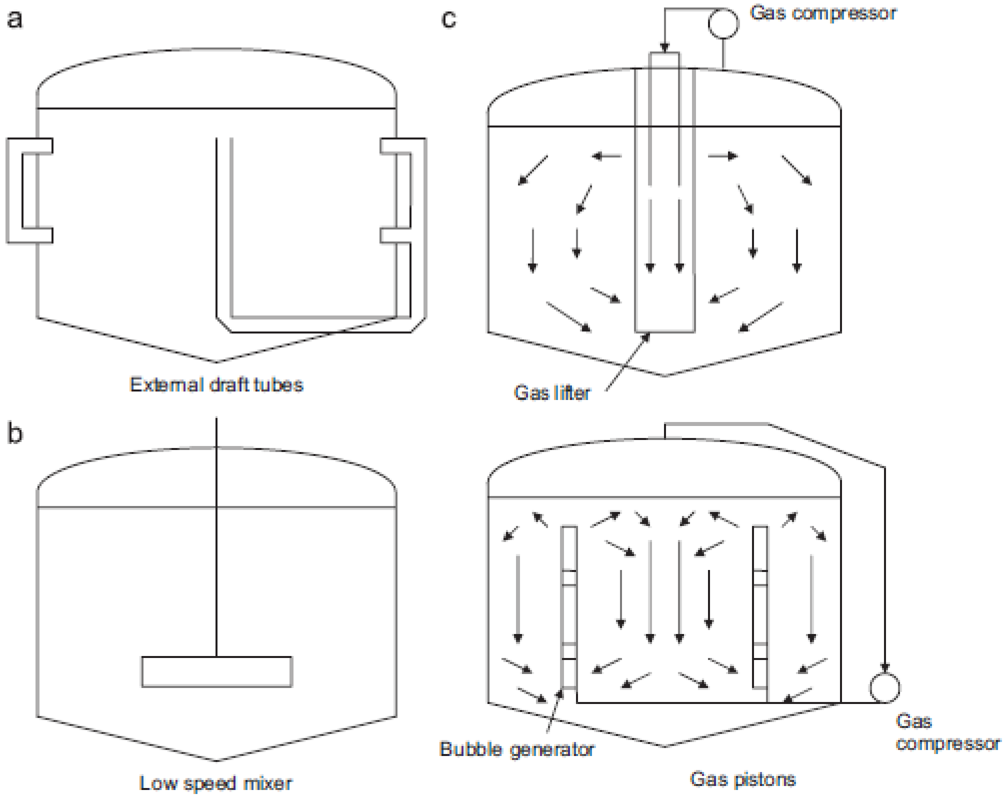
# Agricultural digesters: simple system with membrane covering

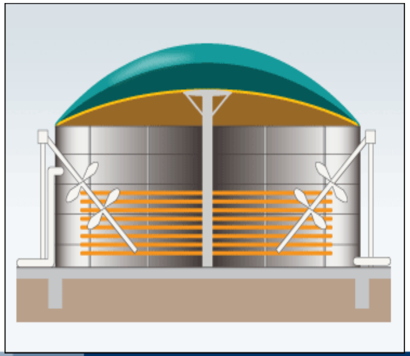
- Flexible membrane cover
- Wall/floor Heating
- Slow mixing with large pabbles




# Alternative mixing systems

- Gas recirculation (some l/m3/min),
- Mechanical mixing (some W/m3)
- Hydraulic recirculation

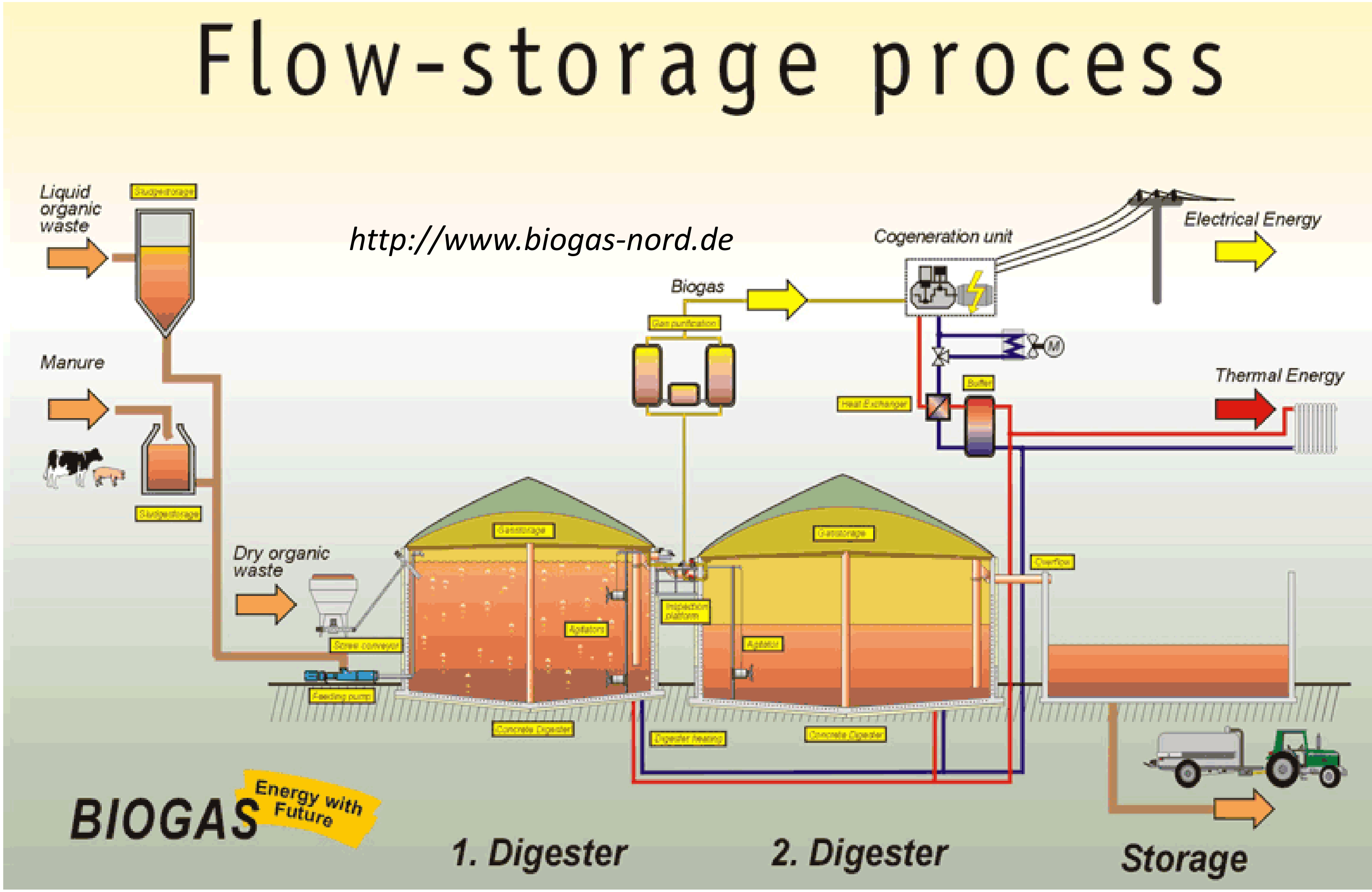


# Commun Agricultural digester configurations


1 Feeding
2 Digester
3 Pumping station
4 Biogas CHP
5 Digestate holding tank

# Commun codigestion systems

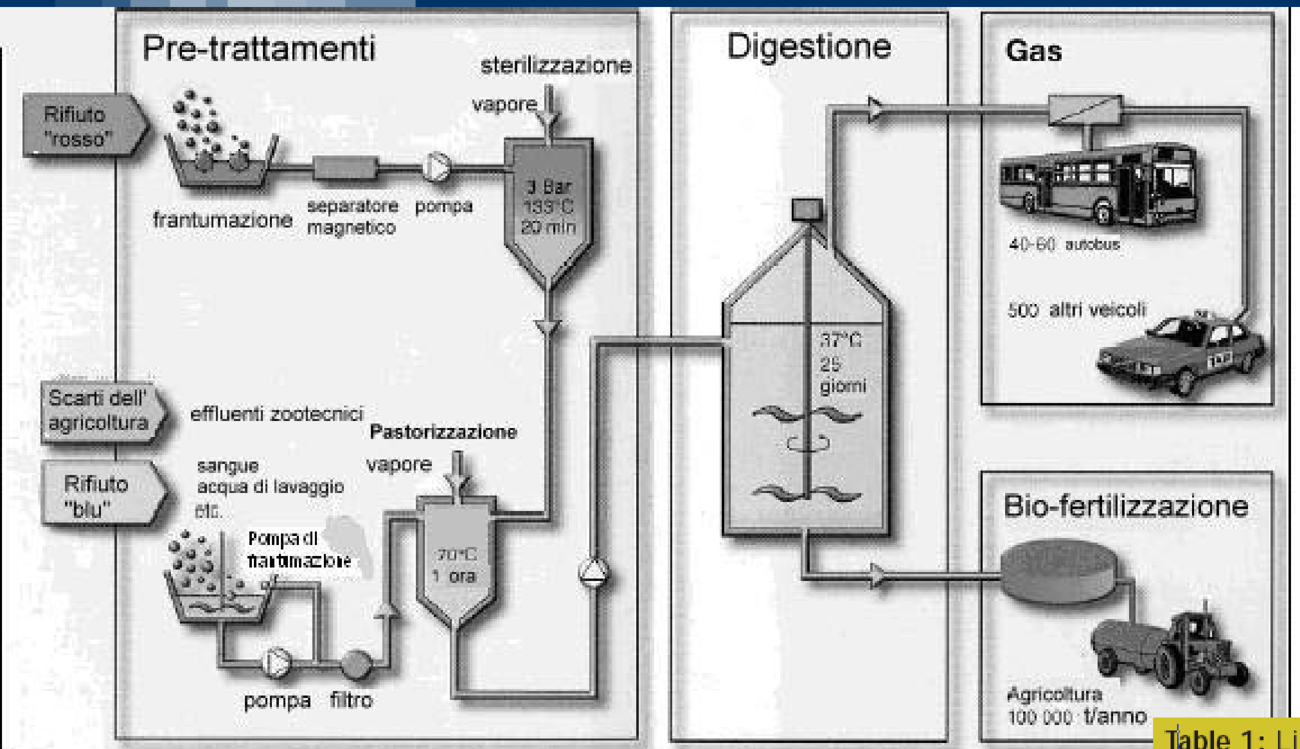


# Agricultural digesters

**Low loaded systems**

- Typical configurations include one or more heated and mixed fermenters followed by one or more unheated post-digesters
- Simple and low cost heating made of plastic tubing running around the inner part of the fermenter wall
- Membrane cover which acts also as gas-holding system
- Top wooden net serves as membrane floor and as support for $H_2S$ oxidising bacteria (limited amount of air is pumped into the headspace)
- Mechanical mixing systems with horizontal/vertical/bended axis.
- Working under mesophilic conditions (up to 40-42°C to favor the hydrolytic step, that is usually the limiting one)
- OLR = 1-2.5 kgCOD/m3/d,
- HRT around 60-90 d

# Co-digestion




*Linkoping, Sweden*

**Table 1:** Linköping biogas plant – inputs & outputs (2005)

| **Input** | tonnes/year |
|---|---|
| Manure for pigs and cattle | 2,000 |
| Abattoir waste | 30,000 |
| Industrial organic waste | 6,000 |
| Household waste | 250 |
| Others | 7,000 |
| **Total** | **45,000** |
| | |
| **Output** | |
| Certified bio-fertilizer to farming | 52,000 |
| Other | 0 |
| **Total** | 52,000 [1] |

[1] Water is added to the process to reduce the dry matter content in the digester

# Examples:

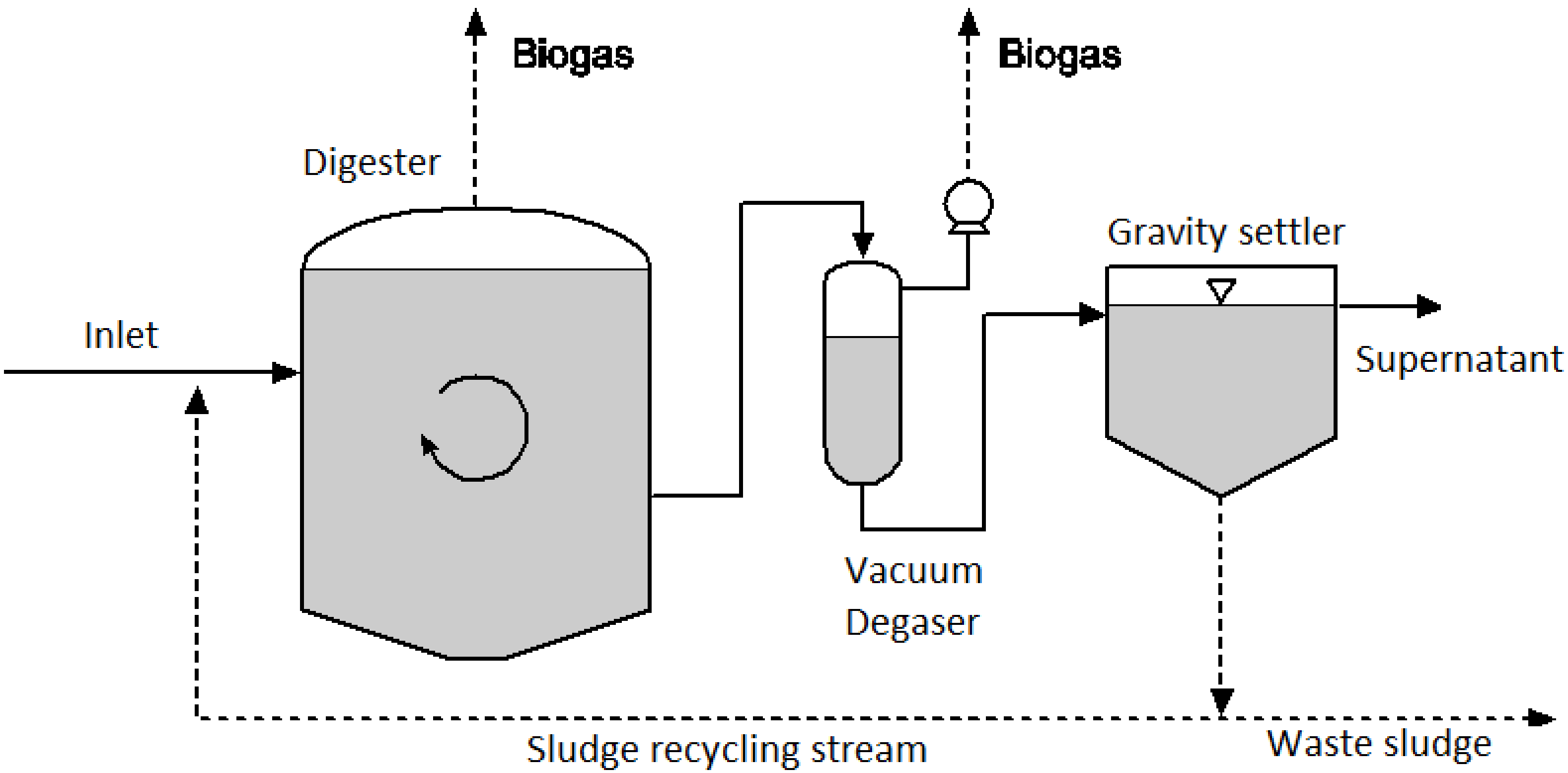
# Highly concentrated Industrial wastes

# High load digesters

**Suspended biomass with gravity settler**

Particulate matter (microrganisms+organic matter) is recycled to the digester

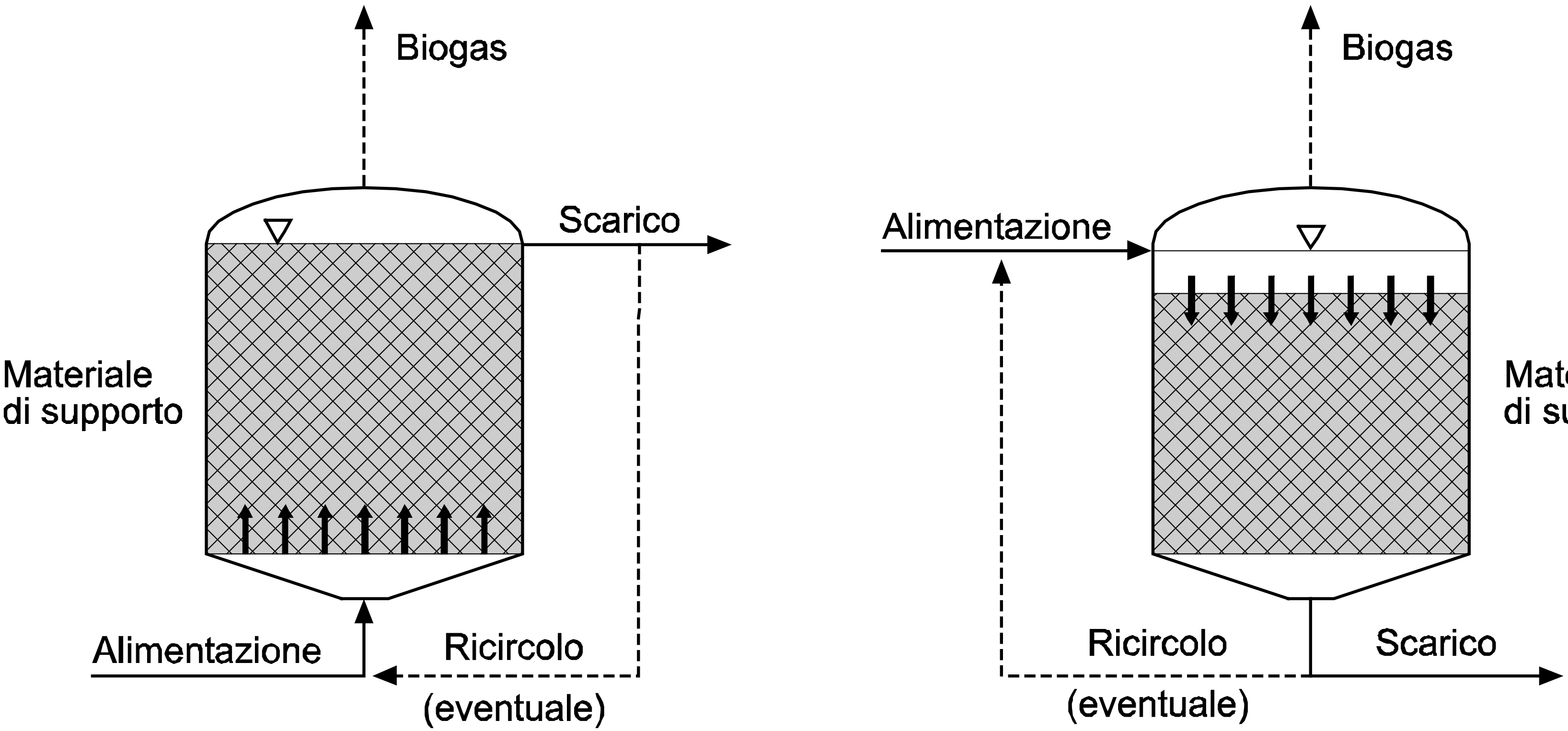
SRT>HRT → biomass concentration can be increased and so can the OLR



# High load digesters

## Attached biomass systems

*OLR = 5-10 kgCOD/m3/d,  HRT around 1 d*



# High load digesters

**Attached biomass systems**

- Fixed bed anaerobic filters
- Supports are plastic materials with high surface to volume ratio (around 100 $m^2$ $m^{-3}$) with high void index to avoid clogging
- Both up or downstream set-up are possible
- Limited velocity (< 0,5 m/h)
- Suspended biomass can also develop (→ hybrid systems)
- Backwashing is needed to limit the biofilm thickness
- Slow start-up (biofilm growth by slow growing bacteria)
- Less sensitive to load variations
- Suitable to deal with seasonal streams
- *OLR = 5-10 kgCOD/m3/d)*

# High load digesters

**Granular biomass systems**

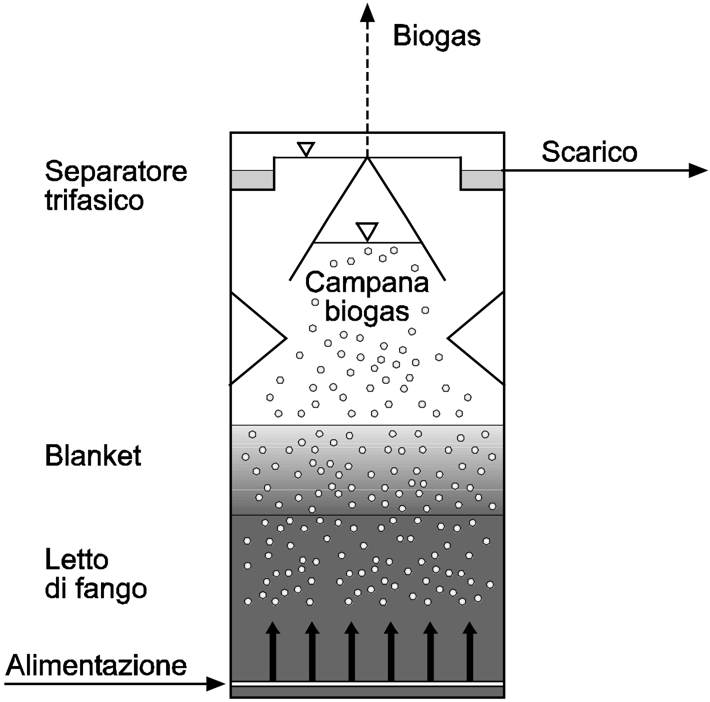
**(UASB: *Upflow Anaerobic Sludge Blanket* )**

Up flow systems

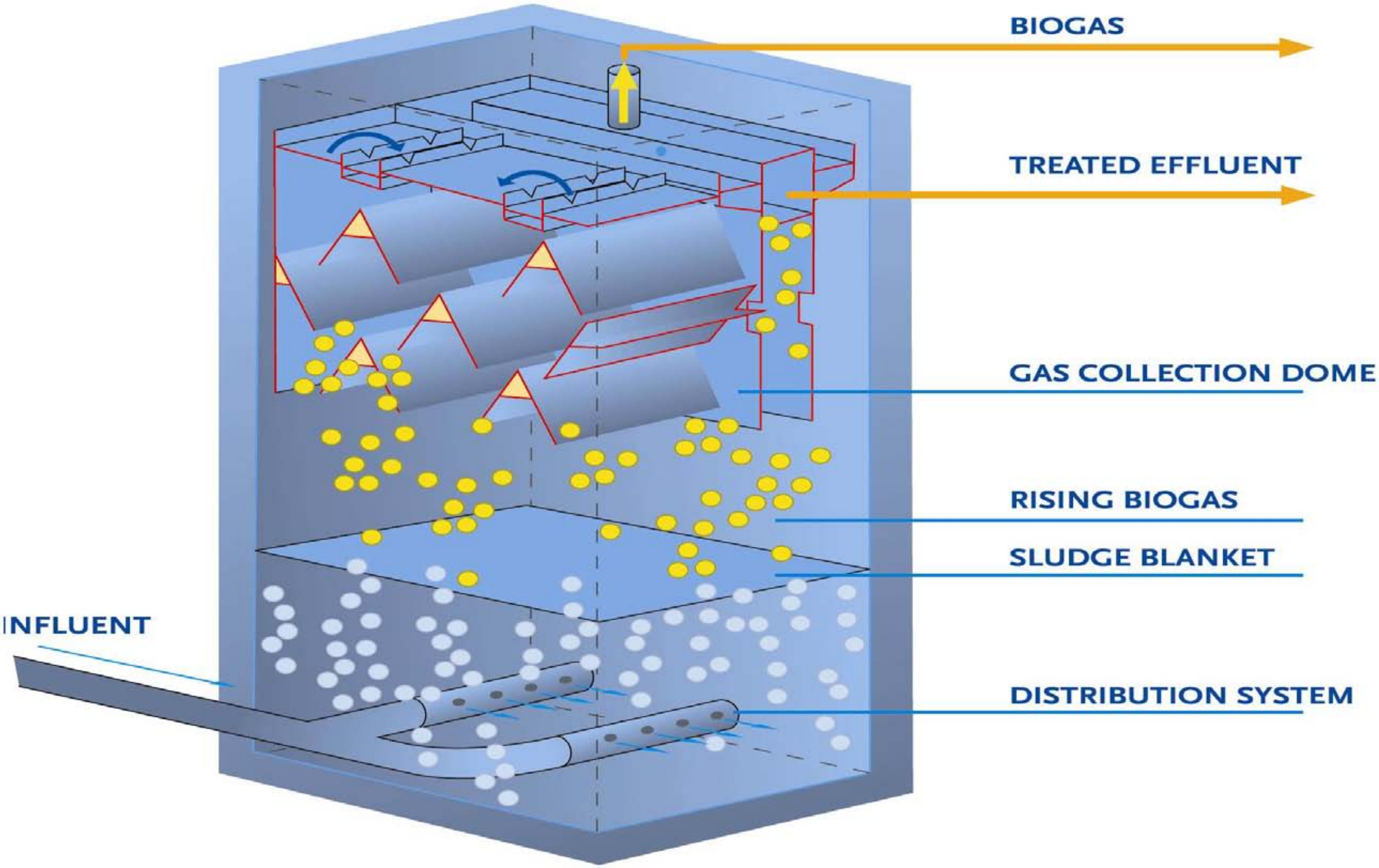
The bottom zone is packed with granules which is kept mixed/expanded by biogas production

In the middle a less dense zone is formed *(blanket)* where gas bubbles are detached from granules surface, granules tend to settle;

A tri-phase separation system cover the blanket where gas is collected, the liquid moves up to the weir, granules are separated and settle back towards the bottom bed.




# High load digesters



# High load digesters

## UASB systems

- The up-flow velocity is the key parameter to favor granules formation. It varies within 0.5 and 3 m/h (increases with COD concentration and degradability) → microorganisms that can aggregate are favored
- Granules are formed with average diameter 1-3 mm and excellent settleability
- Very high biomass concentrations can be achieved (50-100 gSS/L)
- Granules are onion-like complex structures:
  - in the outer layers: hydrolytic and acidogenic microrganisms
  - In the inner layers: acetogens and methanogens
- The start-up is slow but can be shortened when pre-formed granules are inoculated

# High load digesters

## UASB: design criteria

- Typically applied to highly concentrated streams (5-10 gCOD/L)
- OLR =12-20 kgCOD/m3/d referred to the bed volume (with pre-acidifier)
- HRT = 6 -12 h
- Bed height (bed) = 3 -10 m
- Blanket accounts for 10-20% of the bed volume and is to be added to the bed volume

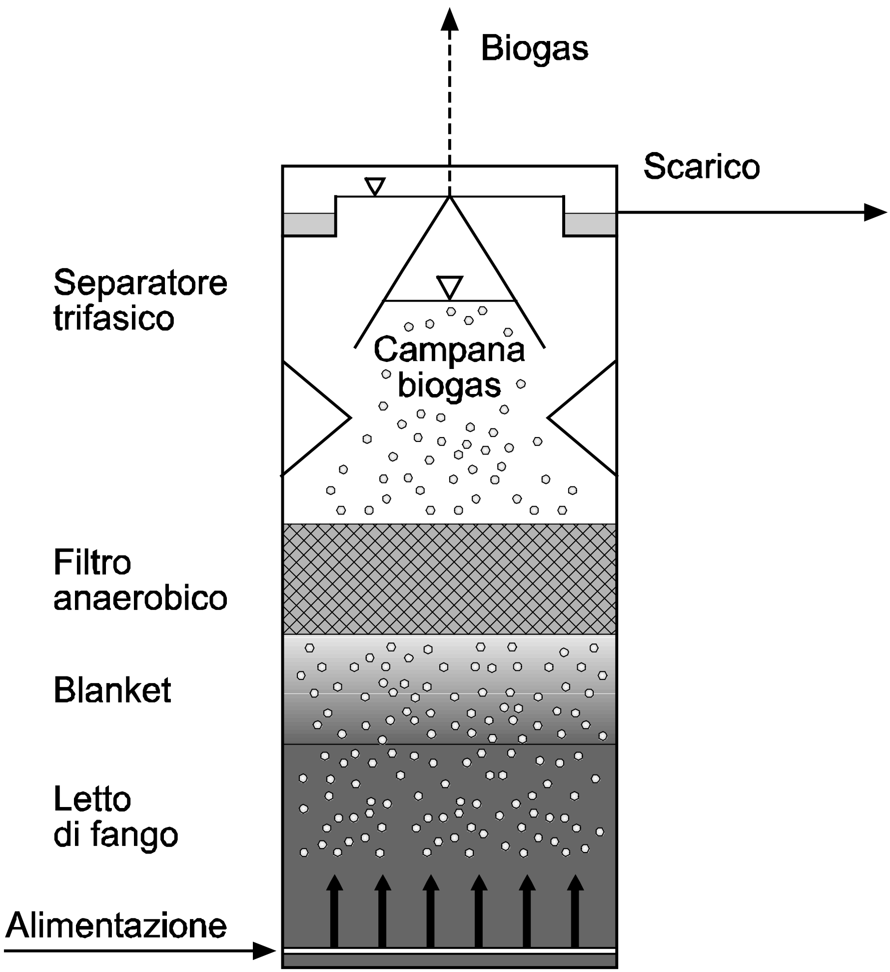
# High load digesters

**Other alternatives**

**Upflow fixed bed anaerobic reactor**

Including:

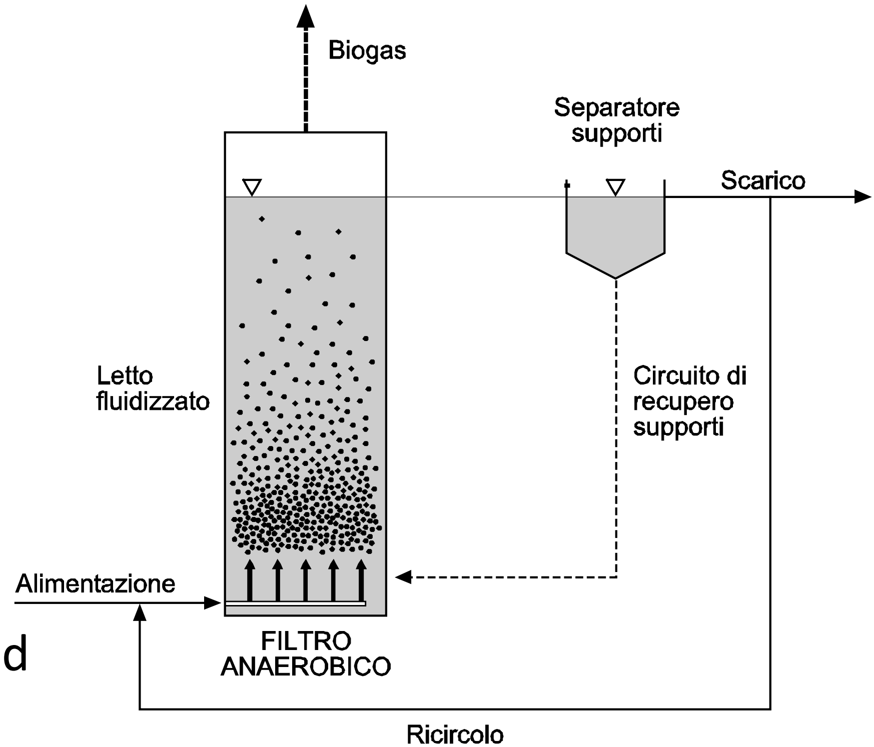
- A typical granules bed in the bottom part
- A filter bed on the top that also favor granules separation



# High load digesters

**Expanded/fluidized bed systems**

- These systems limit clogging problems that are typical of anaerobic filters
- Granular supports are applied, such as:
  - Silica sand Ø = 0,2-0,5 mm,
  - Granular activated carbon (Ø = 0,6-0,8 mm)
  - Expanded clay  (Ø = 0,4-0,5 mm)
- The liquid flux is recycled to fix the up-flow velocity that keeps the granular bed expanded/fluidised




| Parameter | Expanded bed | Fluidized bed |
|---|---|---|
| Up-flow velocity (m $h^{-1}$) | | |
| -Silica sand | 2-3 | 20-24 |
| -expanded clay | - | 5-10 |
| OLR (kgCOD $m^3$ $d^{-1}$) | 10-15 | 15-30 |

# High load digesters

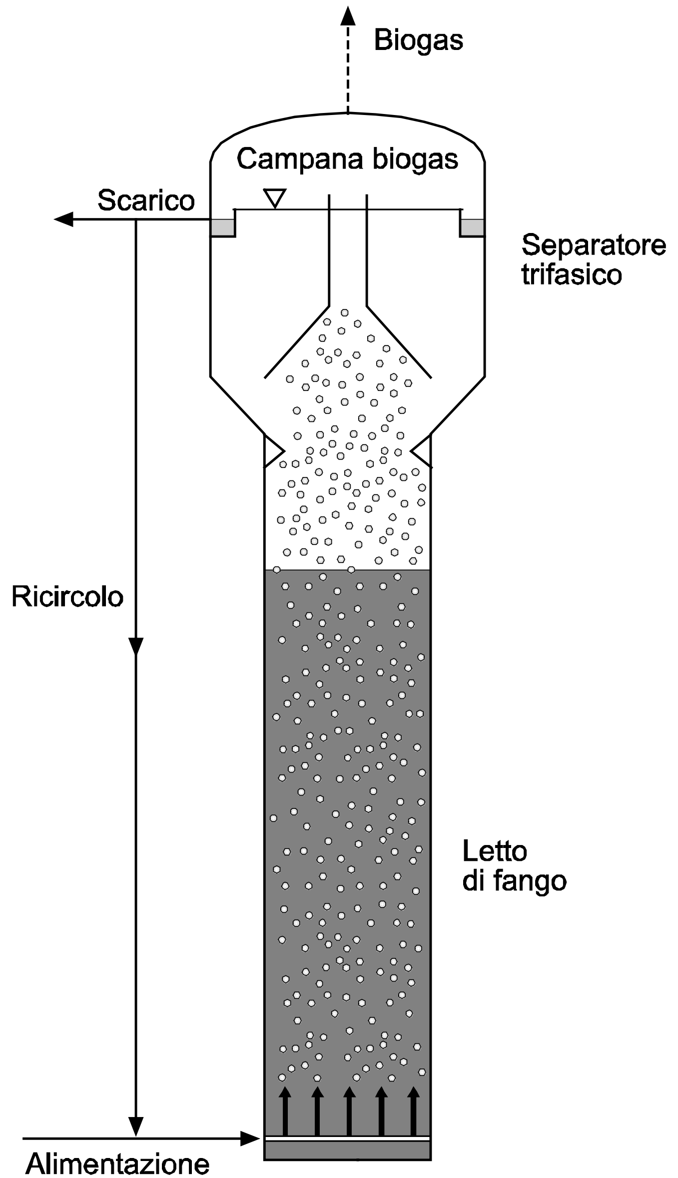
## Other alternatives

### Expanded granular sludge bed reactor

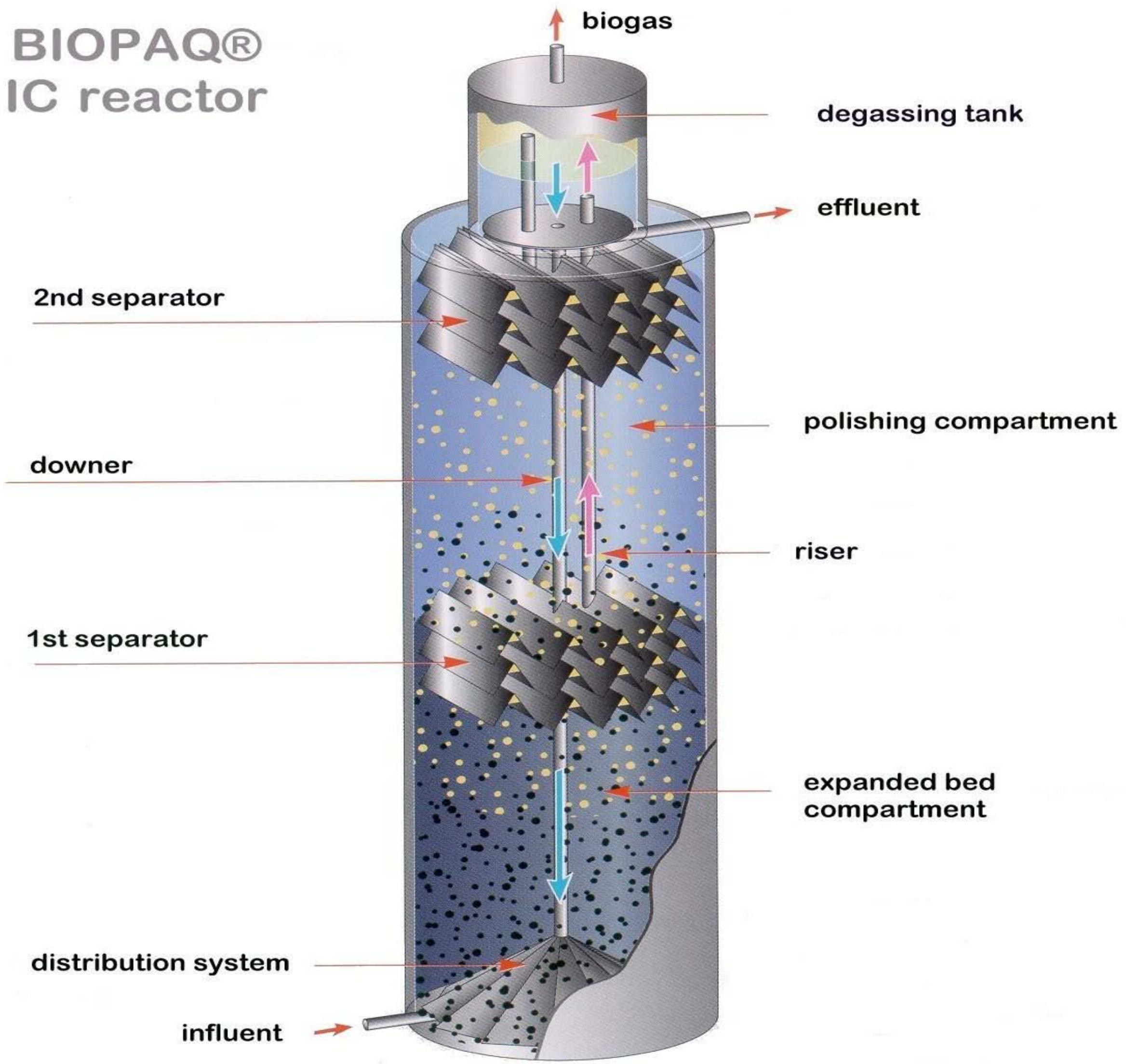
- Higher up-flow velocities are achieved thanks to a recycling line
- Higher velocity (>8 m/h) causes the granules bed to expand
- Better contact between substrate and granules
- Denser granules

- Higher load can be achieved

(OLR up to 50 kgCOD/m3/d)



# High load digesters



# High load digesters

**Comparison among treatment capacities**

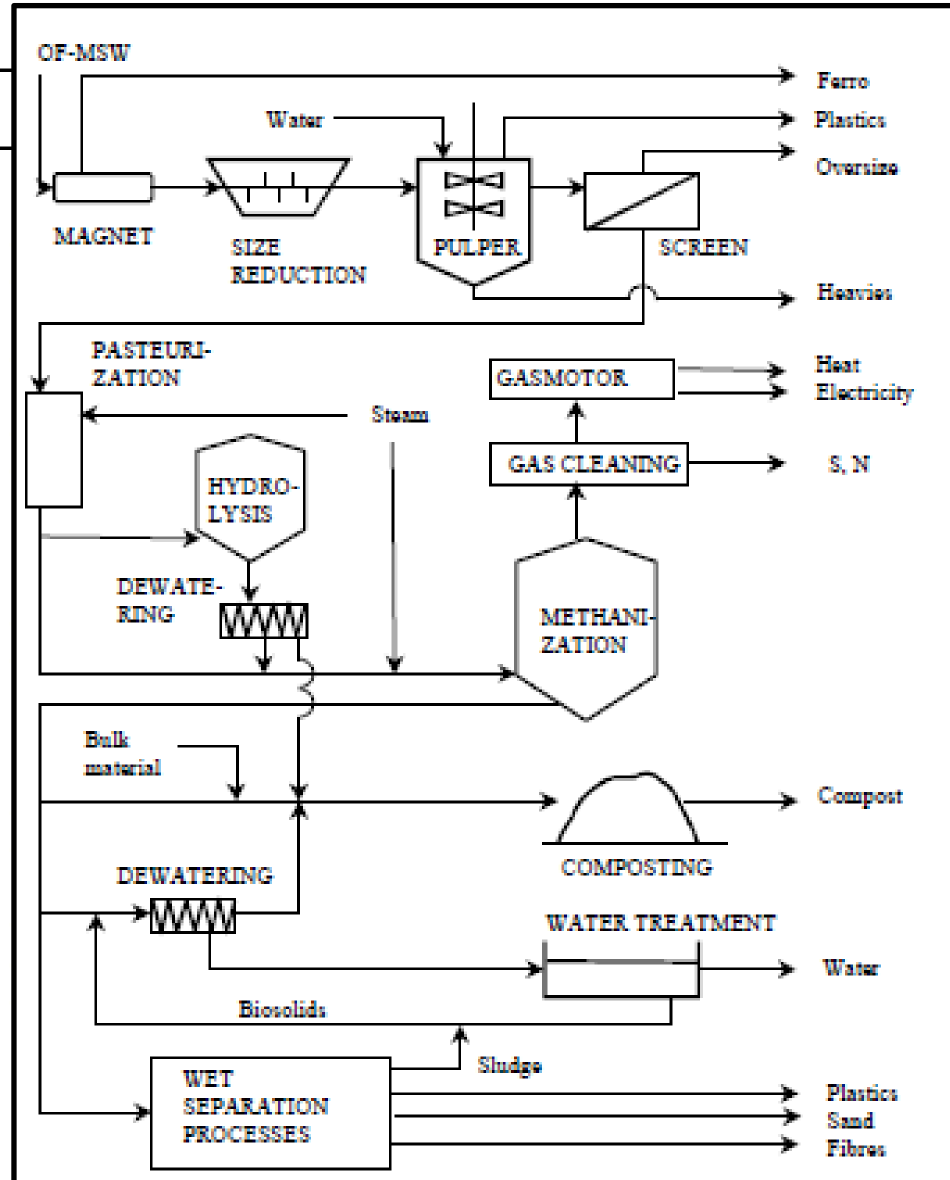
| | |
|---|---|
| Conventional mixed reactor (CSTR) | =1 |
| Mixed reactor with settling and recycle | =5 |
| UASB or anaerobic filters | =25 |
| EGSBR or IC | =75 |

**Typical applications of high loaded systems**

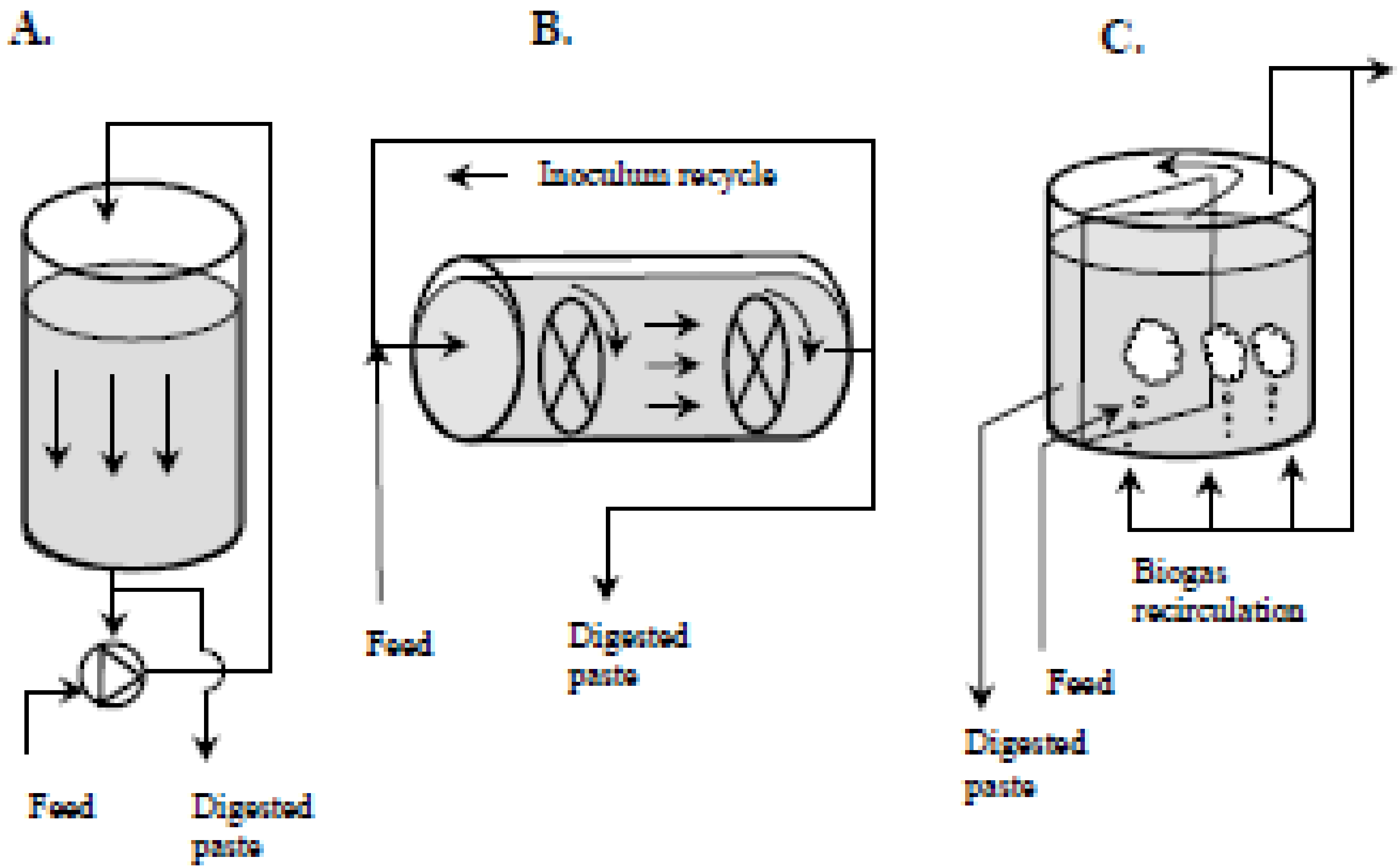
- Agro-food industry (starch, sugar, potato, yeast, pectin, citric acid, cannery, dairy, fruit, vegetables, confectionary)
- Beverage (beer, soft drinks, wine, fruit juice, cofte)
- Alcohol distilleries (Sugar cane, grape, grain, fruit)
- Pulp and paper
- Miscellaneous (chemical, wastes, landfills, pharmaceutical)

# Digestion of OFMSW

| Unit processes | Reusable products |
|---|---|
| **PRE-TREATMENT** | |
| - Magnetic separation | - Ferrous metals |
| - Size reduction (drum or shredder) | |
| - Pulping with gravity separation | - Heavy inerts reused as construction material |
| - Drum screening | - Coarse fraction, plastics |
| - Pasteurization | |
| **DIGESTION** | |
| - Hydrolysis | |
| - Methanogenesis | - Biogas |
| - Biogas valorization | - Electricity<br>Heat (steam) |
| **POST-TREATMENT** | |
| - Mechanical dewatering | |
| - Aerobic stabilization or Biological dewatering | - Compost |
| - Water treatment | - Water |
| - Biological dewatering | - Compost |
| - Wet separation | - Sand<br>Fibres (peat)<br>Sludge |



# Digestion of OFMSW




**A. Dranco; B. Kompogass; C. Valorga**

# Digestion of OFMSW

| **Design parameters** | **Interval** |
|---|---|
| Influent, (%TS) | 25-40 |
| OLR (kgVS/m3/d) | 8-12 |
| HRT (d) | 25-30 |
| **Yields** | |
| Biogas yields, (m3/t waste) | 90-150 |
| Specific biogas yield (m3/kgVS) | 0.2-0.3 |
| GPR, (m3/m3/d) | 2-3 |
| %CH4 | 50-60 |
| VS reduction yield (%) | 50-70 |