Treatment of wastewater solids III: sludge stabilisation

Applied wastewater engineering

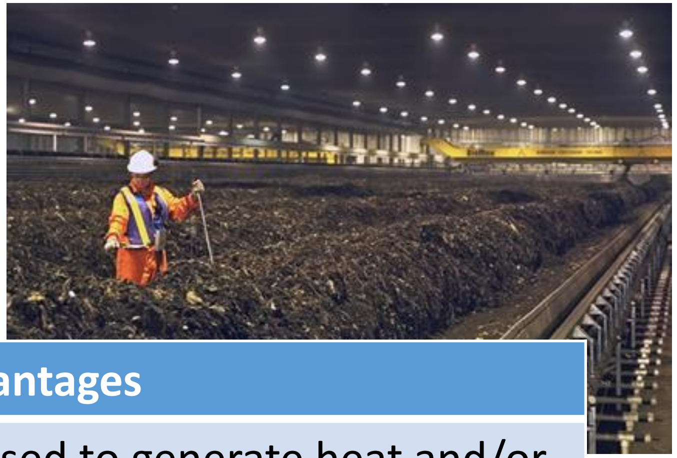
Michael Jon MATTLE

Sludge stabilisation

- eliminate offensive odours
- inhibit, reduce, or eliminate the potential for putrefaction
- reduce quantity of sludge to evacuate
- reduce pathogens content
- produce energy (digestion)

→ reduction of organic fraction (TVS)
  - transformation of organic fraction often produces bad odours (particularly under anaerobic conditions)
- production of biosolids that can further be used according to legislation
- the objective of sludge stabilisation is not volume reduction

Sludge stabilisation



process	description	advantages/disadvantages
anaerobic digestion	biological conversion of organic matter by fermentation in a (heated) reactor to produce methane gas and carbon dioxide	+ methane can be used to generate heat and/or electricity - requires skilled personnel
aerobic digestion	biological conversion of organic matter in the presence of air (oxygen)	+ simpler to operate than anaerobic digestion - energy-intensive process
composting	biological conversion of solid organic matter in an enclosed reactor or in piles (mostly aerobic conditions)	- addition of bulking agent to provide an environment suitable for biological activity - volume increase of compost as compared to sludge
alkaline stabilisation	addition of an alkaline material, usually lime, to achieve a high pH level to inactivate microorganisms (e.g. pathogens)	+ soil like product is produced + low pathogens content - product mass is increased

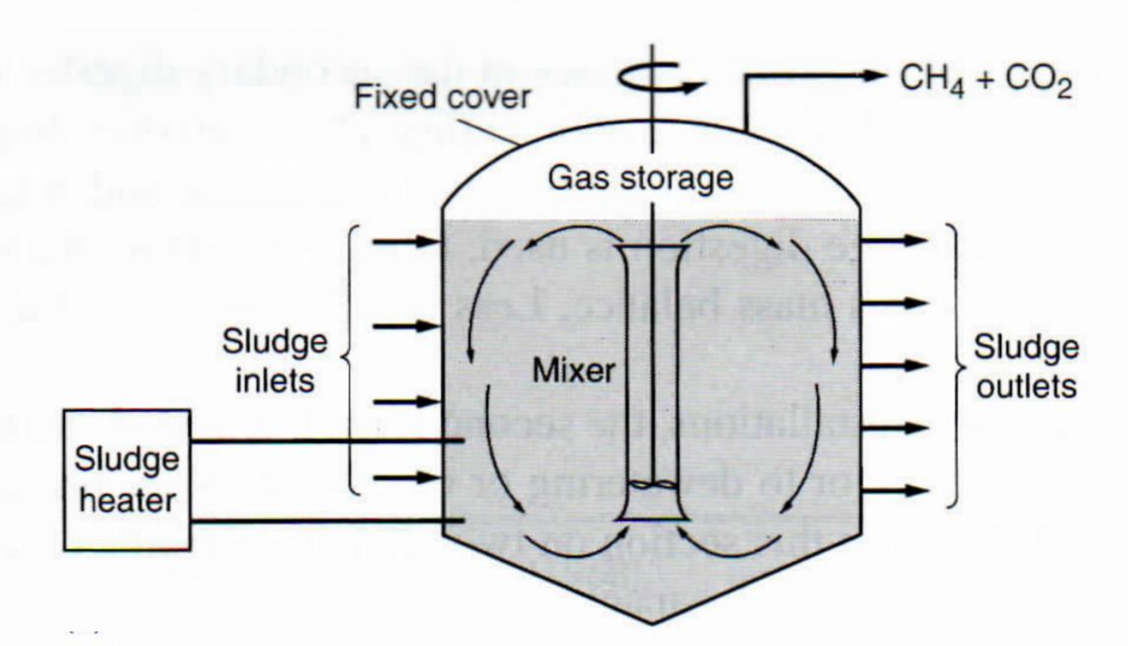
Sludge stabilisation

process	degree of attenuation		
	pathogens	putrefaction	odour potential
anaerobic digestion	fair	good	good
advanced anaerobic digestion (higher temperatures)	excellent	good	good
aerobic digestion	fair	good	good
alkaline stabilisation	good	fair	fair
composting	good	good	fair to good

- further use of sludge dictates the requirements of sludge stabilisation
- if sludge is reused (e.g. land application), pathogens have to be removed to a certain level (according to law and use)
- for easy sludge storage, putrefaction and odour potential should be low
- stabilised sludge is often called biosolid

Anaerobic digestion

- "Biological stabilisation process operated in the absence of oxygen in which biodegradable matter in primary and secondary sludge is converted to methane (CH_4), carbon dioxide (CO_2) and other end-products."
- process provides less energy to bacteria than oxidation processes (low free energy change under anaerobic conditions)
  - low biomass yields
  - high sludge age and elevated temperatures required to sustain anaerobic bacteria in reactor



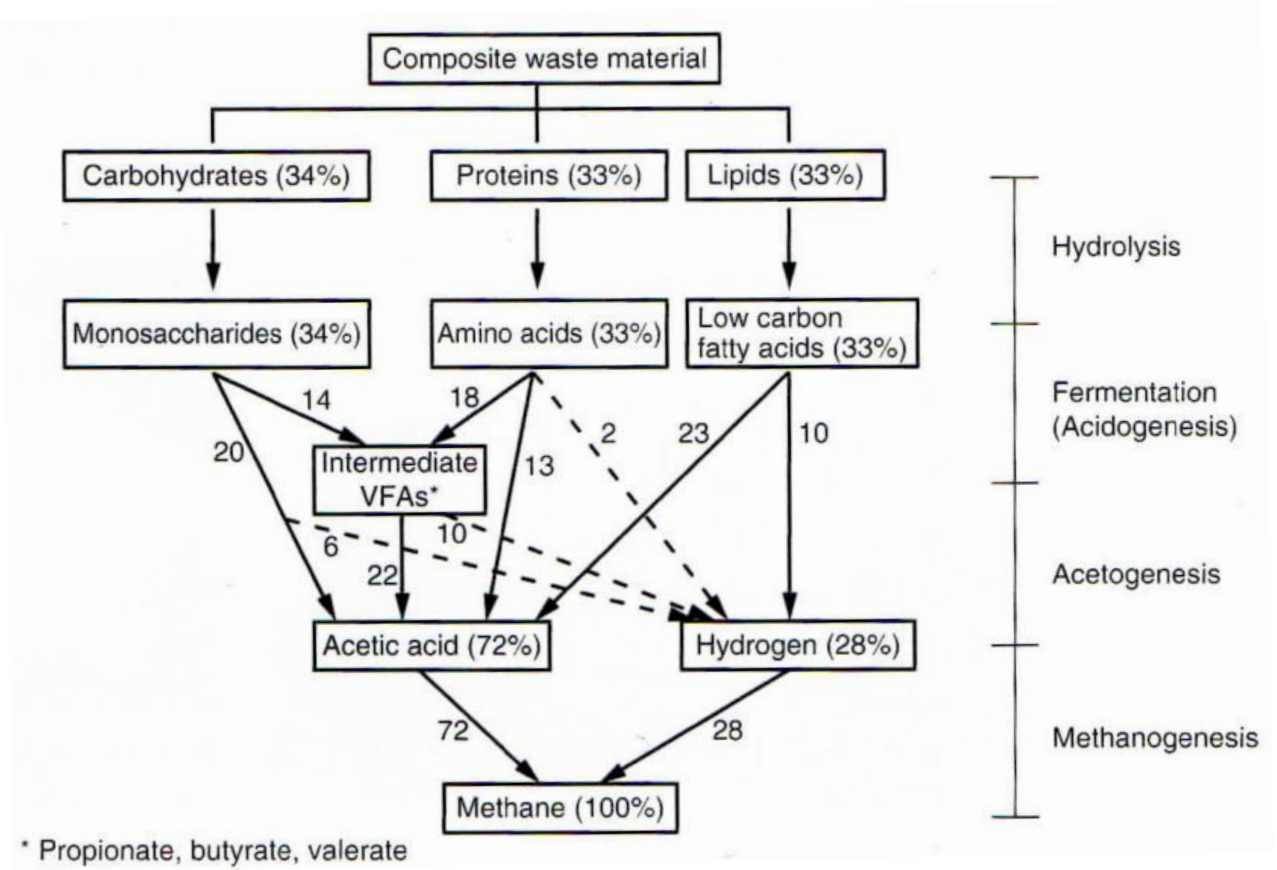
Anaerobic digestion

Onça wastewater treatment plant in Belo Horizonte, Brazil

- psychrophilic fermentation (below 30 °C)
- mesophilic fermentation (30 – 40 °C)
  - more than 90 % of primary and secondary sludge is digested mesophilically in Switzerland
- thermophilic fermentation (50 – 60°C)
  - higher pathogen inactivation
  - difficult to operate and high requirements on concrete
- mesophilic and thermophilic fermentation used to treat organic wastes
- psychrophilic/mesophilic fermentation also used to pre-treat communal wastewater in warm climates or industrial wastewater (higher concentrations of organic material, sometimes higher water temperatures)
- psychrophilic fermentation is used in certain older wastewater treatment plants in Switzerland

Anaerobic digestion

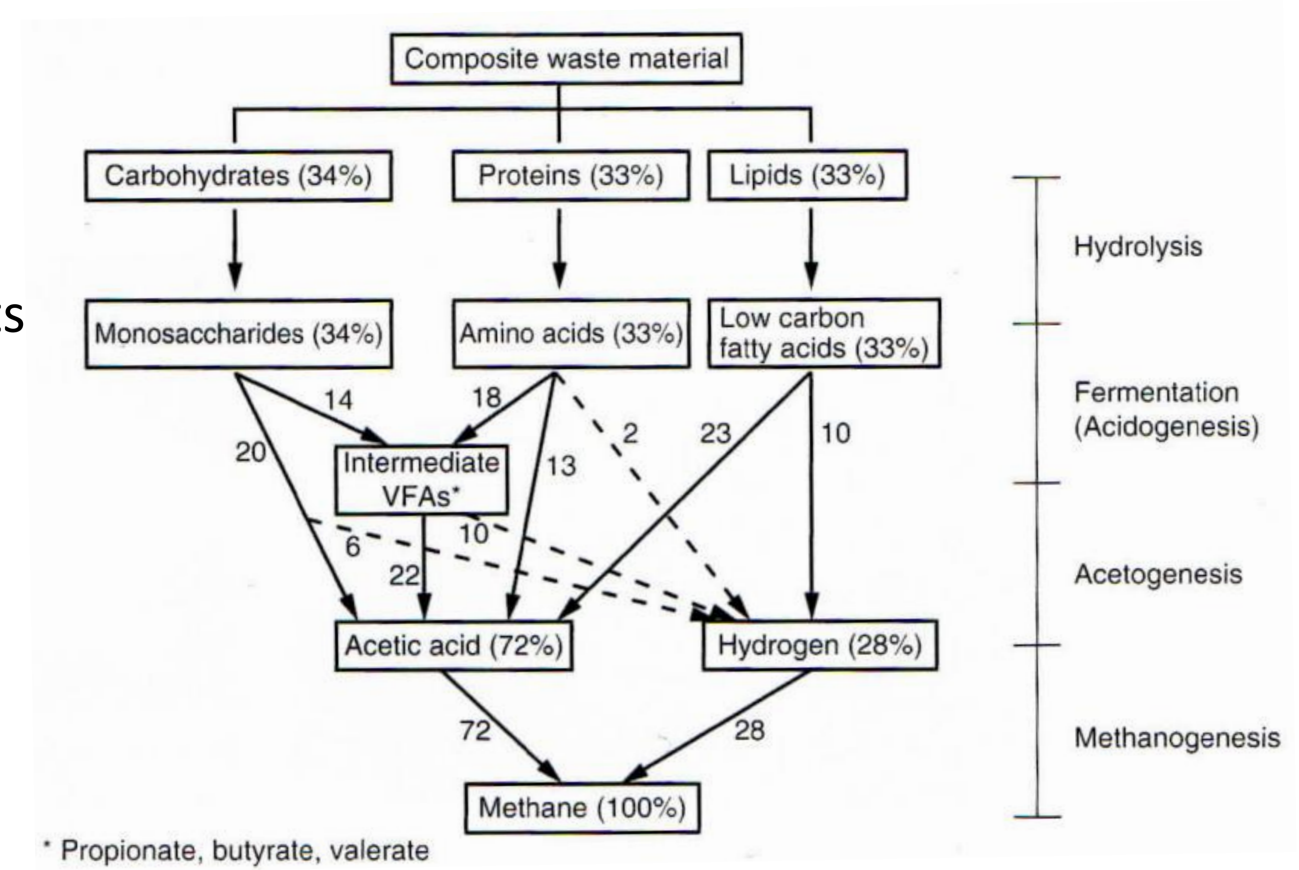
- anaerobic digestion includes several stages:
  - hydrolysis
  - fermentation (acidogenesis)
  - acetogenesis
  - methanogenesis



- hydrolysis
  - particulate material converted to soluble compounds and monomers (amino acids, monosaccharides and fatty acids)
  - performed by extracellular enzymes
  - often limiting step

Anaerobic digestion

- fermentation (acidogenesis)
  - bacteria produce volatile fatty acids (VFAs), CO_2 and hydrogen (H_2)
  - pH reduction
- Acetogenesis
  - bacteria convert intermediate products (intermediate VFAs) to acetate
- Methanogenesis
  - production of methane from acetate (or formate/methanol)
  - production of methane from CO_2 and H_2
  - acidity reduction
- Gas produced in sludge digesters generally contains about 65 % of methane and 35 % of CO_2



Anaerobic digestion (other reactions)

- sulphate reducing organisms

$$SO_4^{2-} + CH_3COO^- + H^+ \rightarrow H_2S + 2HCO_3^-$$
$$2HCO_3^- + 2H^+ \rightarrow 2CO_2 + 2H_2O$$

gas

  - sulphide (S^{2-}) is toxic to methanogenic bacteria at elevated concentrations
  - iron can be used to precipitate sulphites

$$Fe(II) + H_2S \rightarrow \mathrm{FeS} + 2H^+$$

precipitate

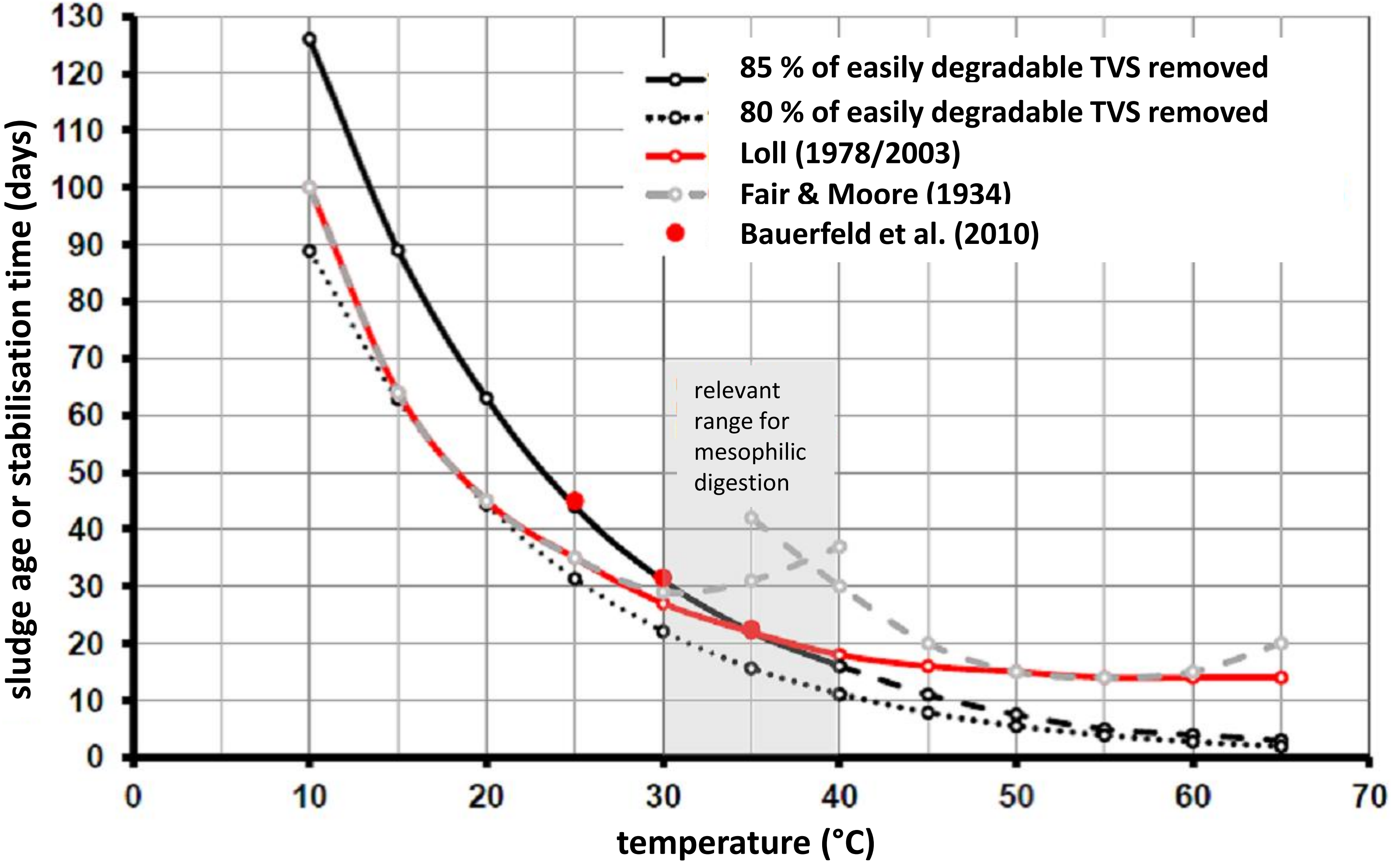
- nitrogen contained in organic matter (e.g. methylamine degradation)

$$4(CH_3)_3N + H_2O + 4H^+ \rightarrow 9CH_4 + 3CO_2 + 6H_2O + 4NH_4^+$$

  - ammonium returns to the wastewater (centrate after dewatering of digested sludge) and increases the influent N-loading rate by up to 10 – 20 %
  - centrate containing high ammonium concentration may be treated separately in large treatment plants (e.g. anaerobic ammonium oxidation (Anammox))

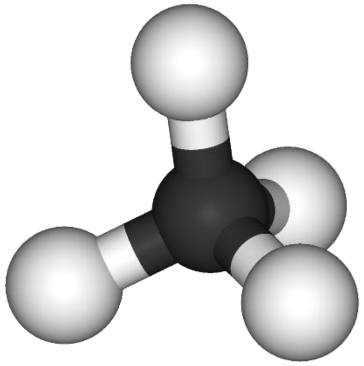
Anaerobic digestion

- increased temperatures reduce required sludge age
- temperatures above 40°C have little impact on required sludge age
- mesophilic range is most commonly used (requires heating)
- relatively high sludge age necessary to obtain a stable operation
- about 70 % of primary sludge total volatile solids (TVS) and 45 % of secondary sludge TVS are easily degradable



anaerobic sludge age required for single-staged digester using mixed sludge

Biogas production



- about 0.95 Nm^3 per kg of TVS removed for primary sludge
- about 0.85 Nm^3 per kg of TVS removed for waste activated sludge
- about 20 Nlitres (normal litres) per population equivalent (PE) and per day
- COD balance can also be used to compute methane produced

$$influent\ COD = effluent\ COD + COD\ of\ methane$$

- 1 mole of methane consumes two moles of oxygen

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

- how much gas (L) is produced if 1 g of COD is transformed in an anaerobic digestor?
  - under standard conditions (0°C and 1 atm) 1 mole of methane occupies 22.4 L

Biogaz production

- how much gas (L) is produced if 1 g of COD is consumed?

A) 0.05 L

B) 0.5 L

C) 5.0 L

D) 50 L

https://web.speakup.info/room/join/53199

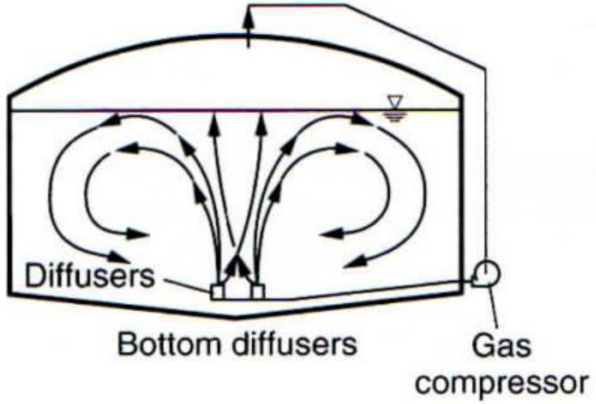
Design parameters for anaerobic digesters

Size of wastewater treatment plant		< 50’000 PE	50’000 – 100’000 PE	> 100’000 PE
sludge age	days	20 – 28	18 – 25	16 – 22
loading factor with easily degradable volatile solids	kg $TVS_{easily\ deg.}/(m^3 \cdot d)$	1.0 – 1.4	1.1 – 1.5	1.2 – 1.7
	kg $COD_{easily\ deg.}/(m^3 \cdot d)$	1.7 – 2.3	1.8 – 2.6	2.1 – 2.9

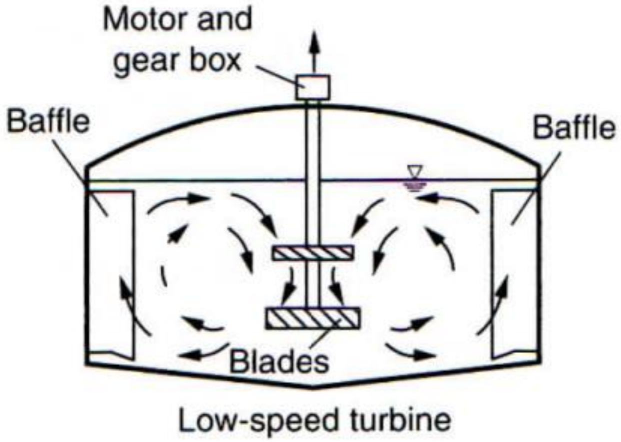
- larger plants have less fluctuations in sludge production
  - they can be designed with lower sludge ages
- the higher the sludge age, the higher the gas production
  - but also the higher the investment, heating (especially in winter) and maintenance cost

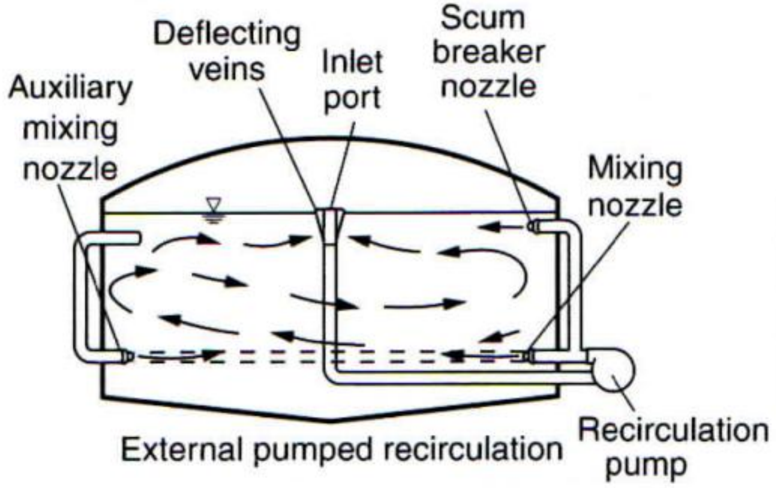
Mixing of digesters

- digesters have to be mixed to:
  - avoid concentration and temperature gradients
  - avoid short circuiting
  - avoid sedimentation and dead areas
  - enhance degassing
  - avoid floating sludge (e.g. grease)



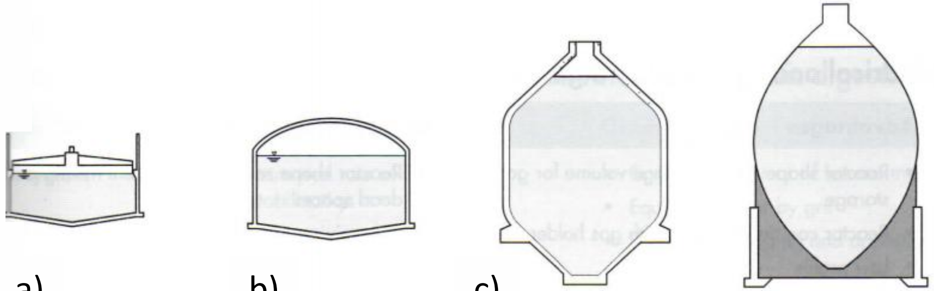
- ways of mixing digesters
  - mechanical stirring
  - gas injection (higher energy requirements)
  - mechanical pumping



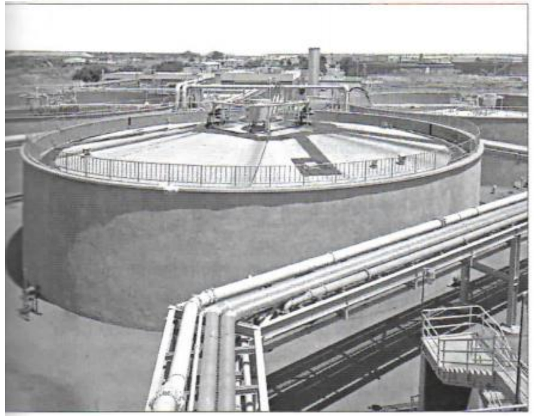


Shapes of digesters

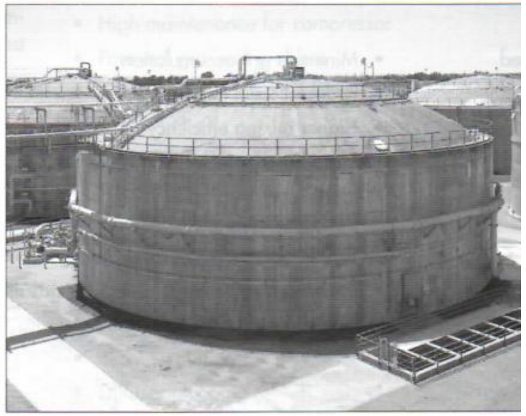
- a) cylindrical with floating cover
  - adaptable for gas storage
  - easier to construct than the German design
- b) cylindrical with fixed cover
  - common design in Switzerland
  - easier to construct than the German design
- c) conventional German design
  - steeper sloped top and bottom cones
  - better mixing
- d) egg-shaped with steel shell
  - easy mixing
  - used in large plants



a) b) c) d)



a)



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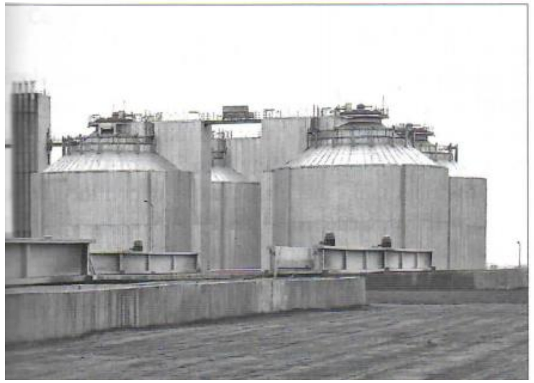

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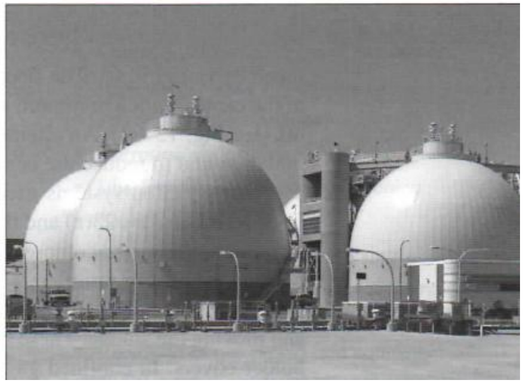
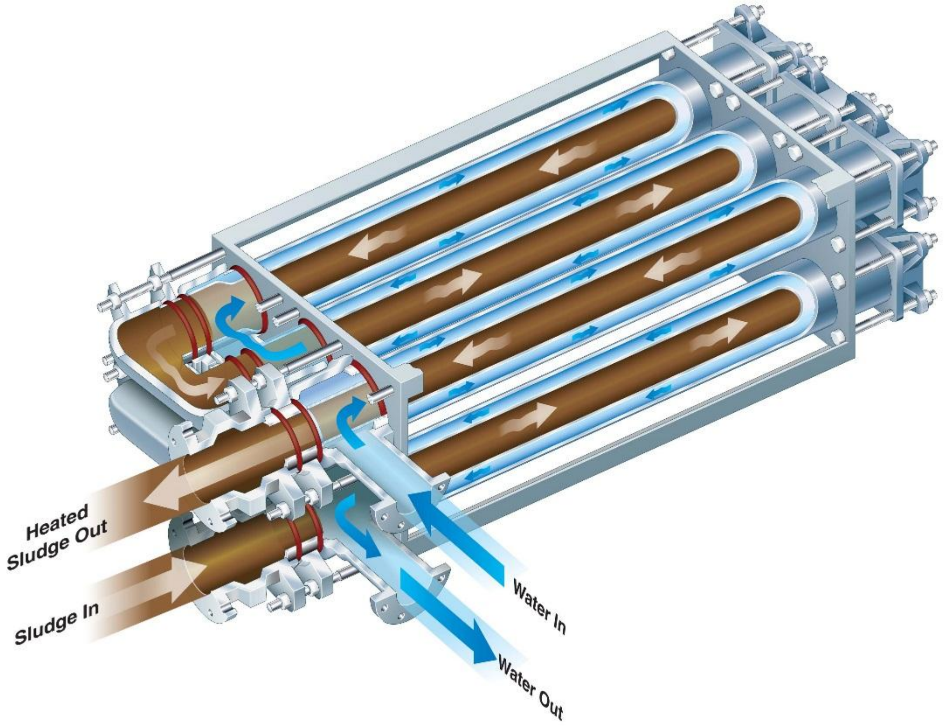


d)

Heating of digesters

- sludge has to be heated to achieve mesophilic conditions
- good insulation of digester reduces heating requirements
- methane producing bacteria are very sensitive to temperature changes (> 2°C)
  - temperature has to be kept constant (in the short term)
- sludge is heated by external heat exchangers (water temperature below 68°C)
- heat may be produced by a cogeneration unit but a boiler is always required



Gas storage and pre-treatment

- gas production varies during the day and from day to day
  - gas storage required to produce constant gas flow
- gas can be stored in upper part of digester (e.g. floating cover) or in a separate gas tank (larger plants)

- gas contains water when it leaves the digesters (elevated temperature)
  - condensation occurs when gas cools down (equipment of piping system with appropriate traps required)
  - chilling of gas can be used to further reduce water content

- gas also contains H_2S which may corrode pipes and gas use equipment
  - condensation removes part of H_2S
  - additional removal can be obtained by various techniques (e.g. oxidation processes, biological scrubbers, chemical systems, adsorptive resins and activated carbon)

Gas use

- cogeneration is a system that produces electricity and another form of energy (e.g. heat)
- different co-generation systems (internal combustion engines, turbines) have different efficiencies
  - electricity generation: 26 – 42 %
  - heat recovery: 30 – 57 %
  - interesting if heat is really required (during summer?)
- gas can also be sold as natural gas
  - advanced purification often necessary (e.g. CO_2 removal)
  - heat generated only when needed (decoupling of processes)
  - interesting for larger wastewater treatment plants or if no purification is required
- excess gas has to be flared (e.g. cogeneration unit out of service)

Aerobic digestion

- “Biological stabilisation process operated in the presence of oxygen in which the biodegradable matter in primary and secondary sludge is oxidised to carbon dioxide and other end products.”
  - either directly in biological tank (extended aeration → higher sludge age in biological tank)
  - or separately in an aerobic digester
- bacteria start to consume ‘themselves’ as little/no food is available (oxic conditions)

$$C_5H_7NO_2 + 7O_2 \rightarrow 5CO_2 + 3H_2O + HNO_3$$

production of acid, alkalinity reduction

- under anoxic conditions, nitrate can be used as an oxygen source

$$C_5H_7NO_2 + 4NO_3^- \rightarrow 5CO_2 + 2N_2 + NH_3 + 4OH^-$$

production of base, alkalinity increase

- denitrification can be achieved by cycling the aerobic digester between aeration and mixing (similar to SBR operation)
  - improved pH control of sludge

Aerobic digestion (comparison with anaerobic digestion)

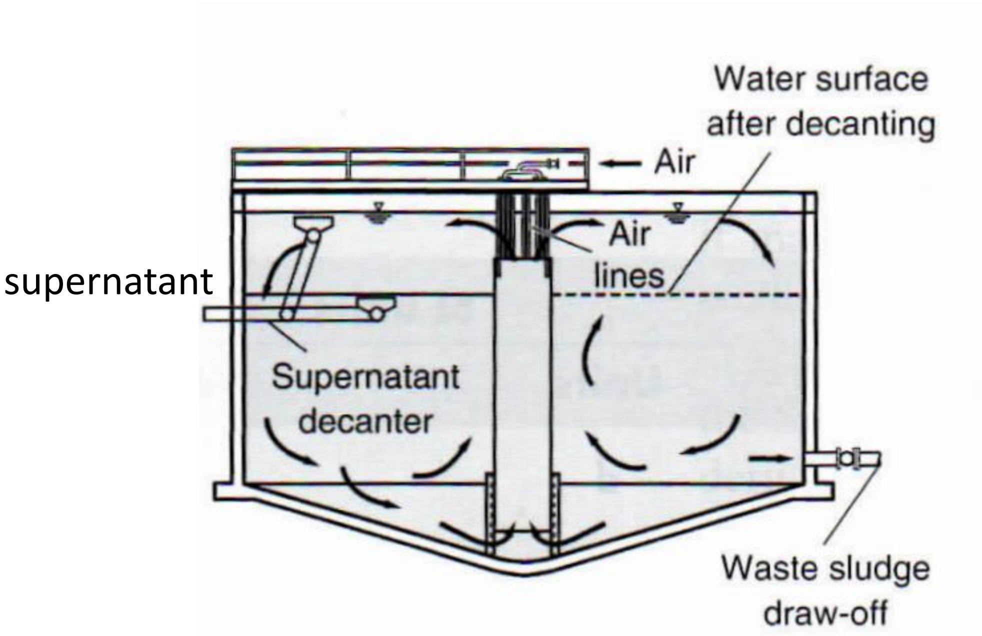
advantages	disadvantages
lower BOD and ammonia concentration in side streams	high power cost due to oxygen requirements
low capital cost for small utilities	does not produce methane gas (energy recovery)
no risk of explosions	aerobically digested biosolids have poorer mechanicals dewatering characteristics (as compared to anaerobically digested solids)
easy to construct and operate	process consumes alkalinity (limited denitrification)

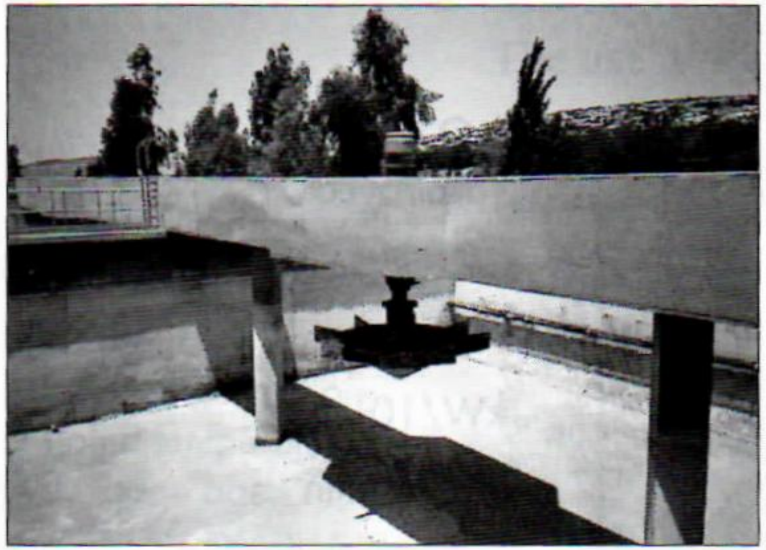
- used in smaller wastewater treatment plants
- used to reduce complexity of treatment (if skilled personal is difficult to find)
- constructed to reduce investment costs

→ technology unimportant in Switzerland

Design of aerobic digesters

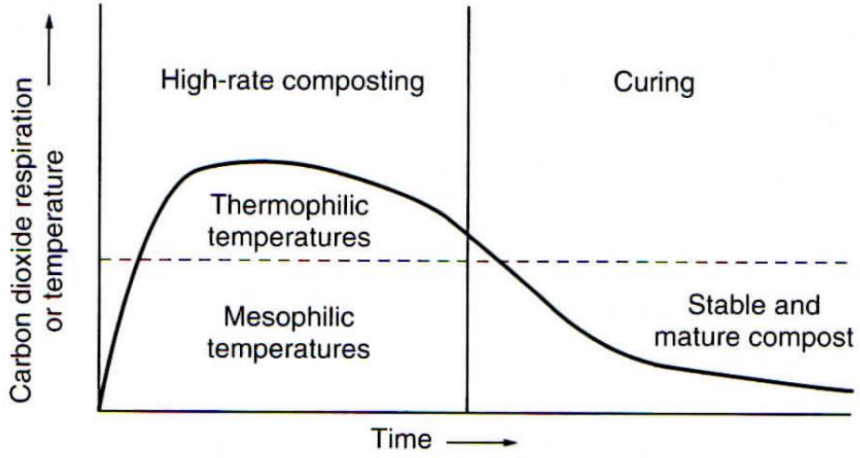
- sludge age ≥ 20 days at temperatures ≥ 10°C
- total solids (TS) between 2 % and 4 % in reactor
- oxygen requirements about ≈ 18 g/(PE·d) at 10°C and ≈ 24 g/(PE·d) at 20°C
- easily removable volatile solids reduction between 45 and 65 %
- reactors can be operated as batch or continuous flow systems



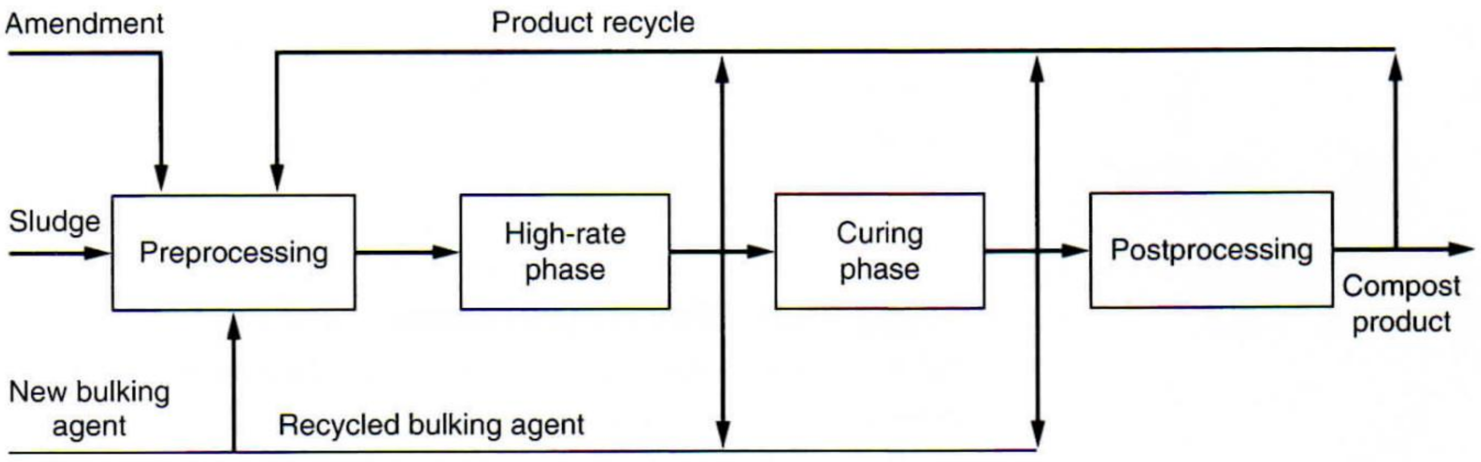


Composting

- "A stabilisation process that relies on the aerobic decomposition of organic matter in sludge and biosolids by bacteria and fungi"
- organic material undergoes biological degradation to a stable end-product
- under mostly aerobic conditions (composting is never completely aerobic)
- decomposition of organic material produces heat
  - compost heats to temperatures in the pasteurisation range of 50 to 70°C
  - pathogenic microorganisms are destroyed
- still largely applied if sludge can used for land application (depending on legislation)



Composting

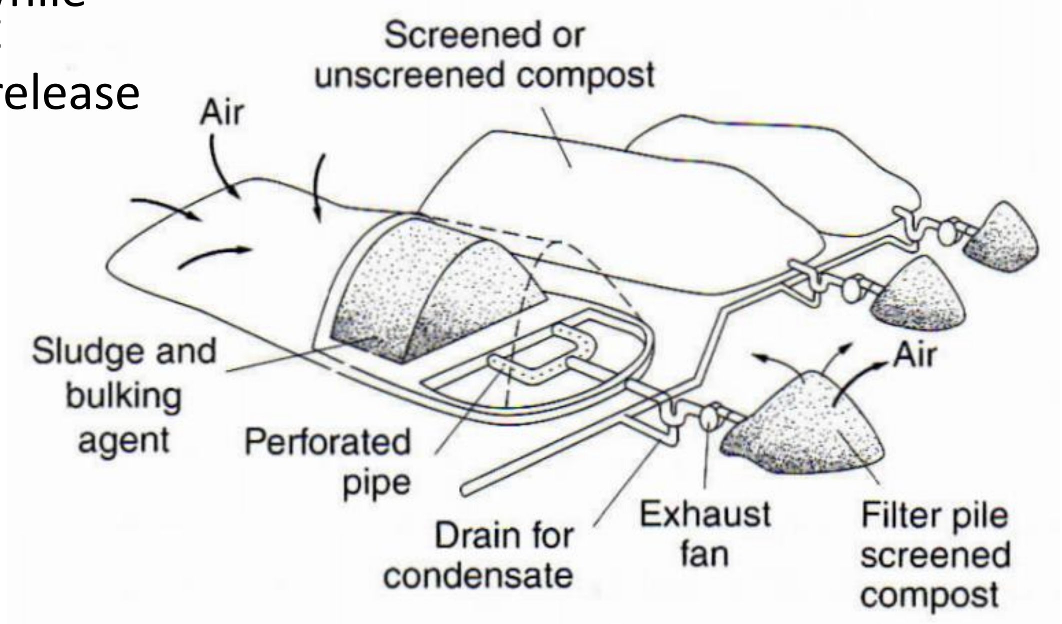


- sludge is dewatered prior to composting and ideally digested (reduced odour production)
- an amendment (an organic material) is added to the substrate to reduce the moisture content, and increase the air voids for proper aeration
  - e.g. sawdust, straw, recycled compost
- a bulking agent is used to provide structural support and to increase porosity of the mixture for effective aeration
  - e.g. wood chips
  - mostly recovered at the end of the process

Composting

- composting period about 21 to 28 days
- curing period 30 days or longer

- two composting systems:
  - windrow system
    - typically 1 to 2 m high and 2 to 4.5 m at the base
    - windrows are turned a minimum of five times while the temperature is maintained at or above 55°C
    - turning the windrows is often accompanied by release of offensive odours (especially when anaerobic conditions occur)
  - aerated static pile
    - grid of aeration piping over which sludge and bulking agent is placed
    - may or may not be covered
    - pile heights about 2 to 2.5 m



Alkaline stabilisation

- use of an alkaline material to render sludge unsuitable for survival of microorganisms
  - increase of pH value to 12 or higher
  - halts or retards microbial reactions
  - sludge will not putrefy or create odours (as long as pH remains at elevated values)
  - high pH values inactivate viruses, bacteria and other pathogenic microorganisms

- e.g. addition of quicklime

$$2CaO + H_2O \rightarrow 2CaOH$$

  - produces heat (exothermic reaction)
  - ‘consumes’ water
  - increases the pH (OH^-)

Alkaline stabilisation

advantages	disadvantages
well proven process	the volume of stabilised sludge is increased by approximately 15 % to 50 % in comparison to other stabilisation techniques
simple technology	potential of odour generation both at processing and end use site
easy to install	nitrogen content in final product is lower due to ammonia volatilisation (less nutrients)
small footprint	resulting product is not suitable for use on all soils (especially high alkaline soils)

- technology employed to reduce investment costs and to keep the process simple
- may be employed with other stabilisation techniques in order to achieve increased stabilisation and disinfection of sludge
- not used in Switzerland for wastewater sludge stabilisation

Treatment of wastewater solids IV: dewatering of sludge

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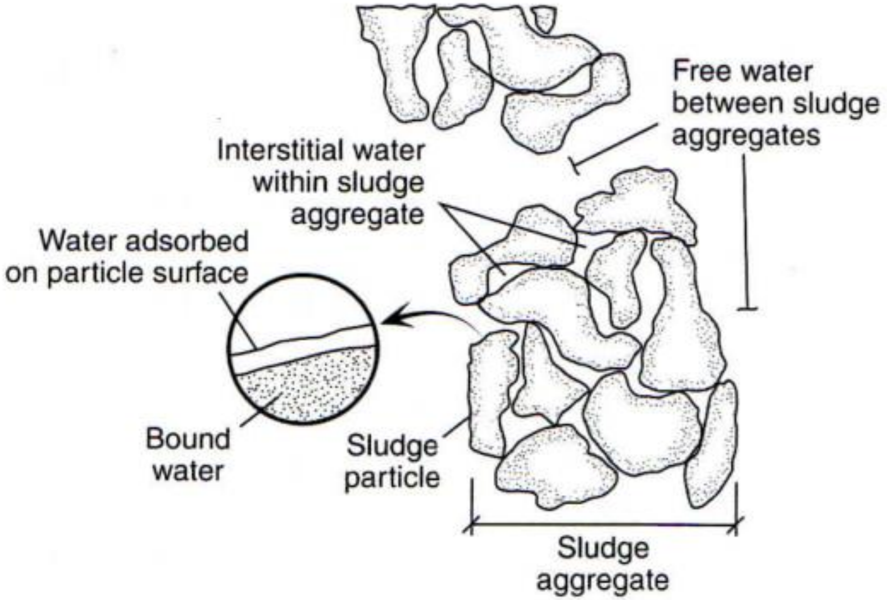
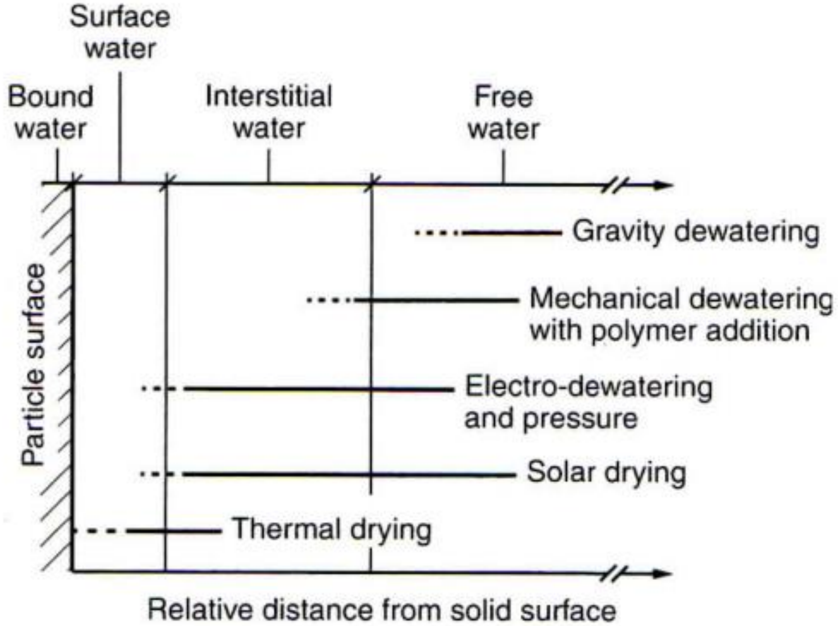
Dewatering of sludge

- "A process that removes a portion of water contained in solids. Dewatering is distinguished from thickening in that the resulting dewatered cake may be handled as a solid, not as a liquid."
    - reduction of transportation costs to final destination of sludge
    - increase in calorific value (incineration)
    - required for composting (reduction of required supplementary bulking agents)
    - reduction of energy needed for drying (dewatering and drying requires less energy than only drying)
    - necessary before landfilling sludge to reduce leachate production at landfill site
    - generally easier to handle than thickened sludge





Dewatering of sludge

- mechanically assisted physical means are used to dewater sludge more quickly (sludge is pressed together)
- certain dewatering applications rely on heat energy and electric energy (not treated in this course)

- for effective solid-liquid separation, chemical conditioning is required
- liquid stream (centrate or filtrate) is typically returned to the wastewater treatment but can also be treated separately
- dewatered cake can be handled as a solid although water content is still around 70 – 80 %

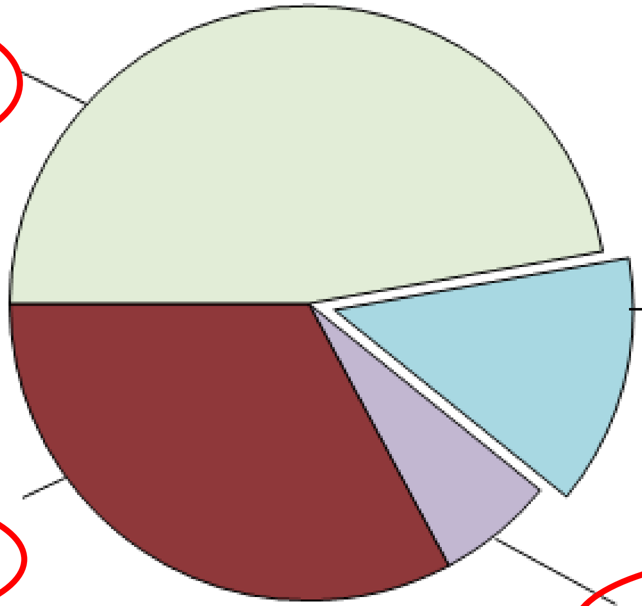
Dewatering of sludge

- dewatering characteristics of sludge depends on many criteria (e.g. sludge origin, composition (primary, waste activated, digested sludge or external sludge), concentration,…

- dewatering is required for the final disposal of sludge:
  - co-incineration and deposition in landfills
  - mono-incineration and deposition in special landfills (future phosphorous-removal)
  - use in agriculture or landscape building
  - direct deposition in landfills

Dewatering of sludge

- in Switzerland screw presses are also quite often used
- however, filter presses are being replaced by other technologies



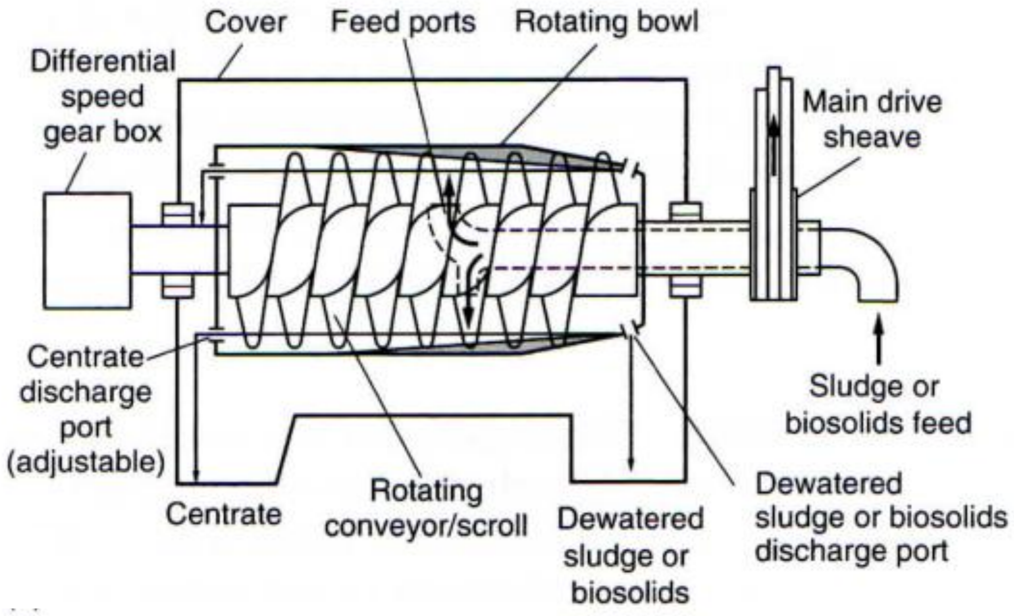
based on 97 million PE

statistical analysis of German dewatering of sludge (2003): fraction of sludge treated related to PE

Centrifuges (dewatering)

- rotation of bowl generates centrifugal forces that sediment the sludge on the outer part of the bowl
    - centrifugal force > 2’800 g (gravity force)
- rotating scroll pushes sludge in direction of the exit
    - rotation is either slightly slower or faster than the bowl rotation
- continuous operation

- optimising the functioning of a centrifuge is complicated and often requires the intervention of an expert
    - technology less ‘ideal’ in areas where such experts are not locally present



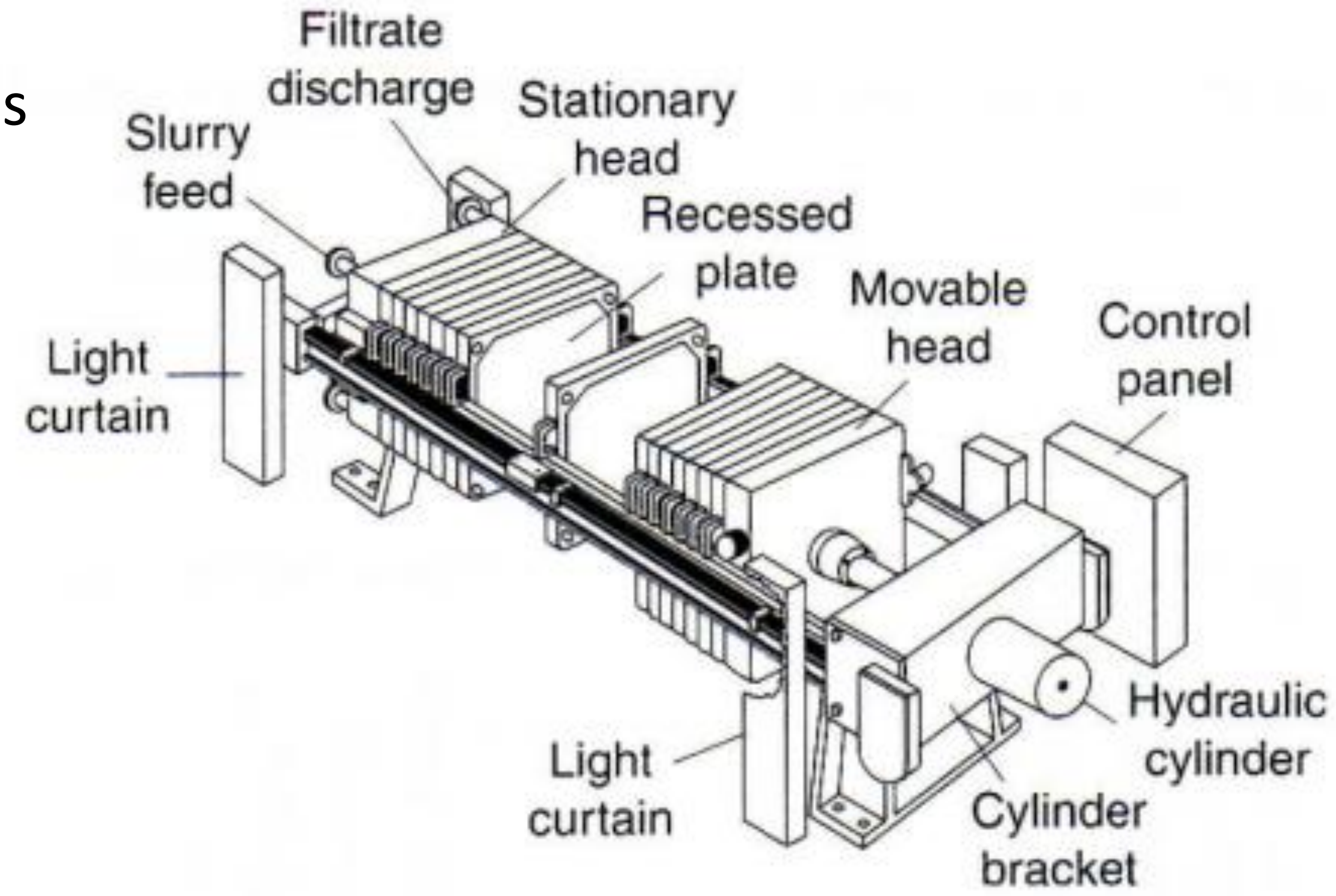
Centrifuges (dewatering)

advantages	disadvantages
high sludge cake concentration	skilled maintenance personnel required
low capital cost to capacity ratio	requires grit removal and possibly sludge screening/grinder in the feed stream
easy to install	moderately high suspended solids content in centrate
fast start-up and shut-down capacities	scroll wear potentially a high maintenance problem
enclosed design contains odours and aerosols	observation of dewatering zone not possible to optimise/adjust performance
clean appearance	high electricity consumption

- even waste activated sludge can be directly dewatered, however it is recommended to thicken sludge first

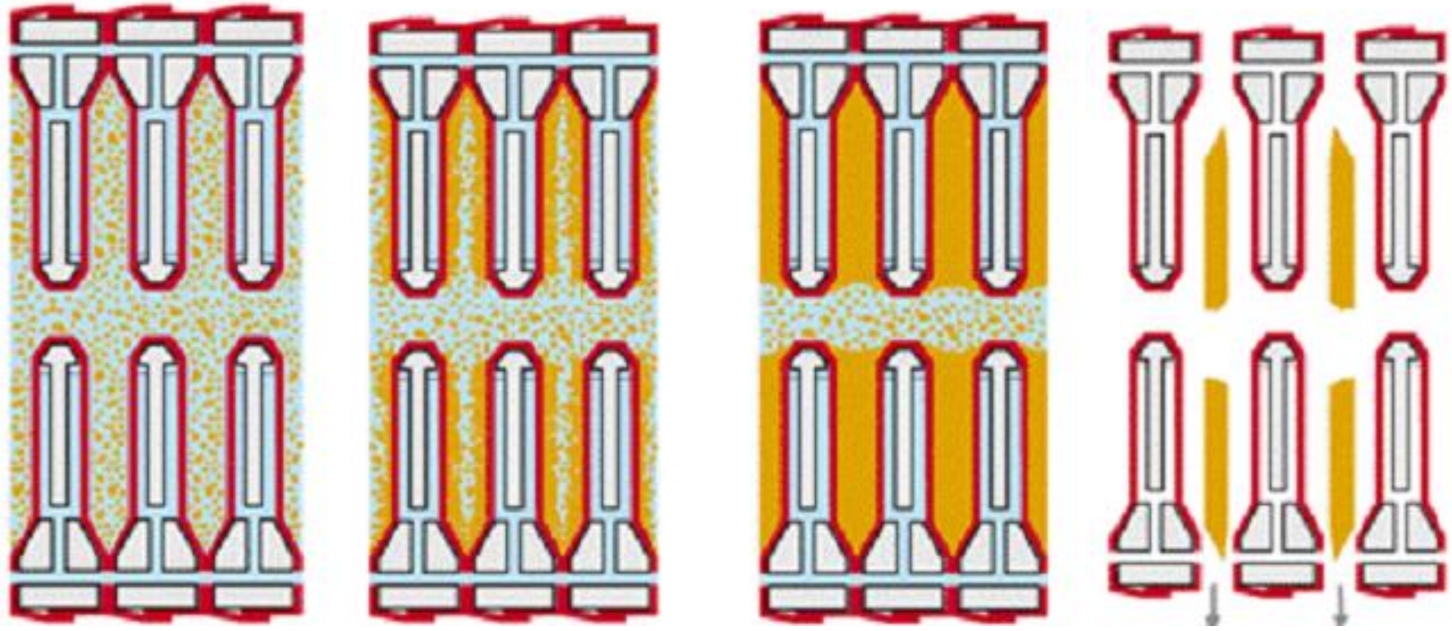
Filter press

- dewatering is achieved by retaining the sludge or biosolids with a filter (cloth/membrane)
- high pressure applied (700 to 2’100 kPa)
  - can achieve very high solid contents, especially if treated with iron salts or lime
  - high solids capture rate: close to 100 %
- cyclic operation



Filter press

- cycle of operation (2 to 5 hours)
  - closing of press
  - filling the press (filtration)
  - stop supply pump of sludge
  - open the press
  - wash and discharge the sludge cake (often requires intervention of personal)



filter press full with sludge suspension

sludge cake partially built (pressure increases)

sludge cake fully built (high pressure)

water core removed, then cake removal

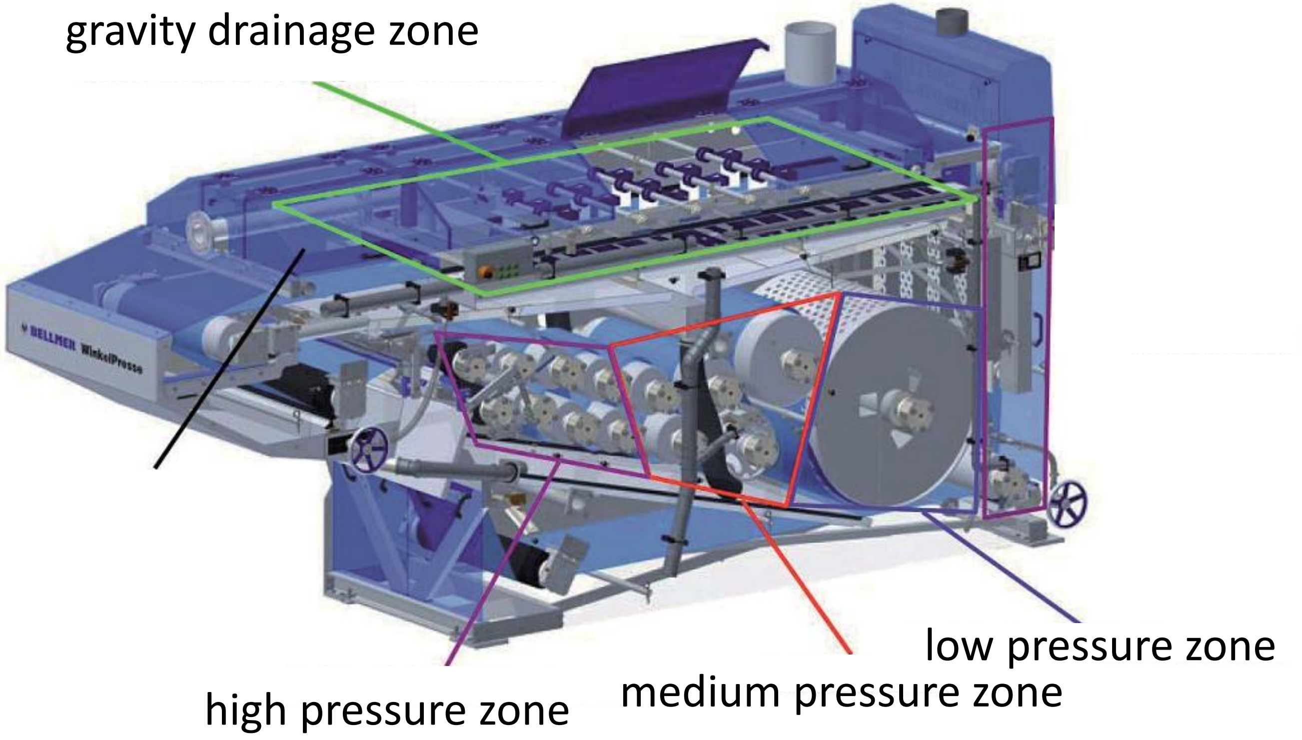
Filter press

advantages	disadvantages
high cake solids concentration	high labour cost
low suspended solids in filtrate	high pressures used → danger
simple operation	high equipment cost
	batch operation
	large floor area required
	skilled maintenance personnel required

→ high labour requirements (uncomfortable (smell) and potentially dangerous work) and landfilling restrictions (alkaline stabilised sludge) reduced the use of this technology in Switzerland

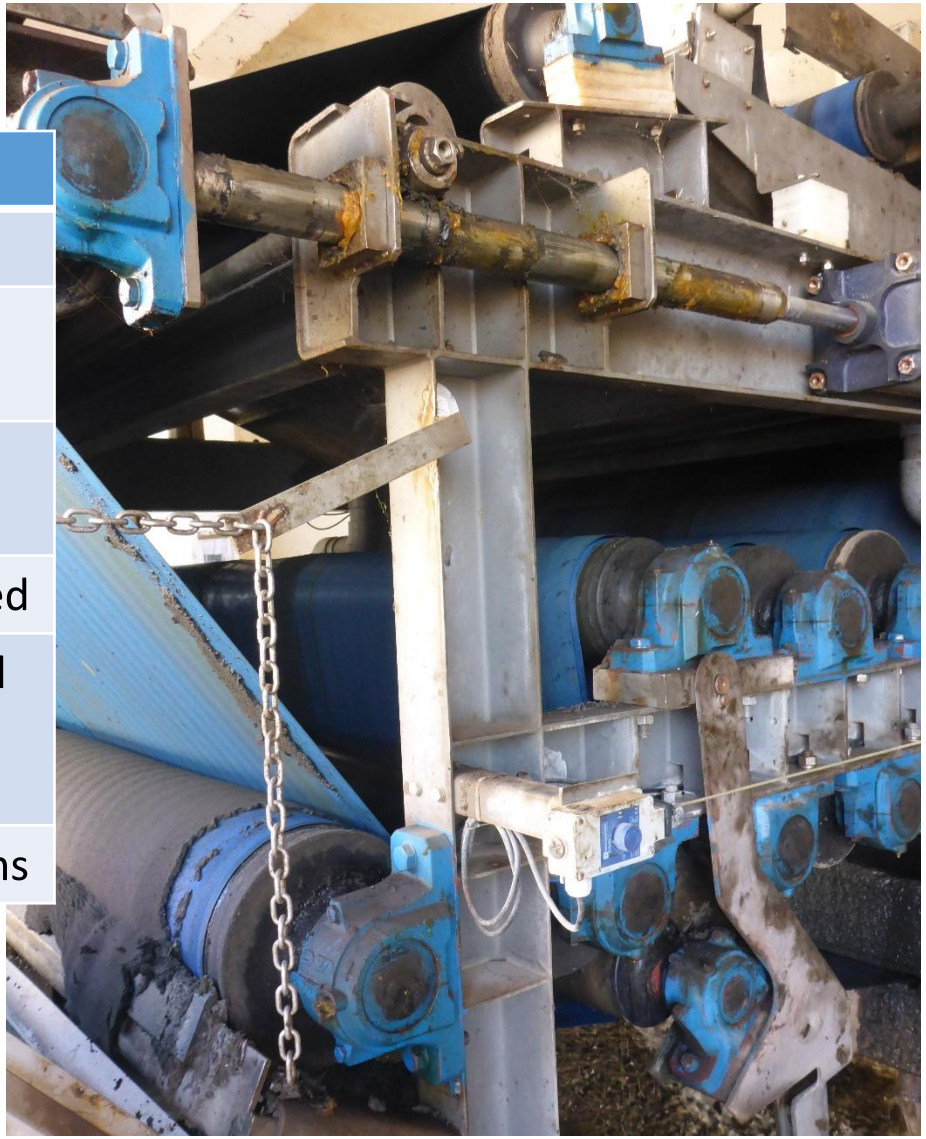
Belt-filter press

- gravity drainage and mechanically applied pressure dewatering
- sludge is kept between two porous cloth belts
- machine has various zones (pressure is inversely proportional to drum size):
  - gravity drainage
  - low pressure zone (large drum)
  - medium pressure zone (medium drum)
  - high pressure zone (small drum)
- operation has to be constantly adapted to entering sludge consistency (sludge should be homogenous)
- dewatering capacity rather low for sludge containing little structure forming materials (e.g. waste activated sludge from activated sludge plants)
- continuous operation



Belt-filer press

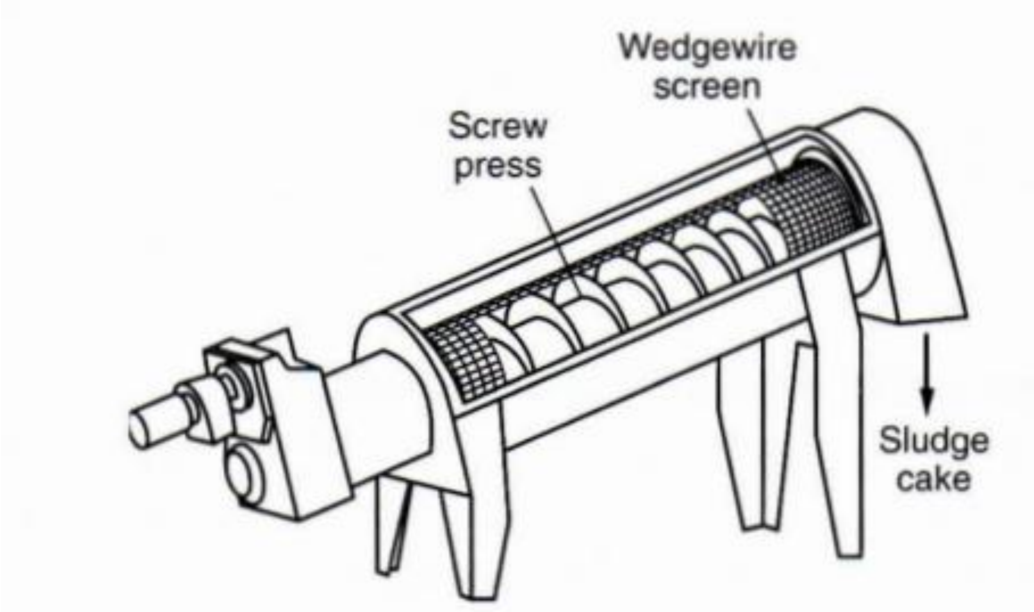
advantages	disadvantages
low energy requirements	hydraulically limited in throughput
relatively low capital and operation costs	very sensitive to incoming sludge feed characteristics
less complex from a mechanical point of view	short media life as compared to other devices
relatively easy to maintain	automatic operation generally not advised
minimal effort required for system to shut down	requires sludge screening/grinder in feed stream
	aerosol formation due to cleaning systems



➡ technology little used in Switzerland or Germany but otherwise still widely used (easy to repair and maintain)

Screw press

- low-speed, enclosed cylindrical unit
- sludge fed at a relatively low pressure into a stationary wedge wire screening basket
- rotating screw transfers the sludge through the wedge wire screening basked
- the pressure increases as sludge moves to exit depending on the outlet restriction (back pressure)
  - different zones (thickening zone, intermediate (formation of filter cake) and dewatering zone)
- wash-water required to clean the wedge wire screening assembly
- continuous operation



Screw press

advantages	disadvantages
low speed 0.3 to 1.5 rpm	capacity limitations will require multiple units for large wastewater facilities
low noise < 68 dB	cannot observe dewatering zone to optimise/adjust performance
enclosed design contains odours and aerosols	wash-water required periodically throughout operating cycle
low energy use drive motor	
low shearing force reduces odours in dewatered cake	
overdosing of polymer does not clog screen and hinder dewatering	

→ interesting technology for small to middle size treatment plants

Summary of mechanical dewatering technologies

sludge type	unit	centrifuge	belt-filer press	filter press	screw press
final solids content % [kg TS/kg]					
primary sludge	%	32 – 40	30 – 35	32 – 40	30 – 40
mixed sludge	%	26 – 32	24 – 30	26 – 32	24 – 30
extended aeration sludge (no primary decantation)	%	18 – 24	15 – 22	18 – 24	18 – 24
anaerobically digested sludge	%	22 – 30	20 – 28	22 – 30	20 – 28

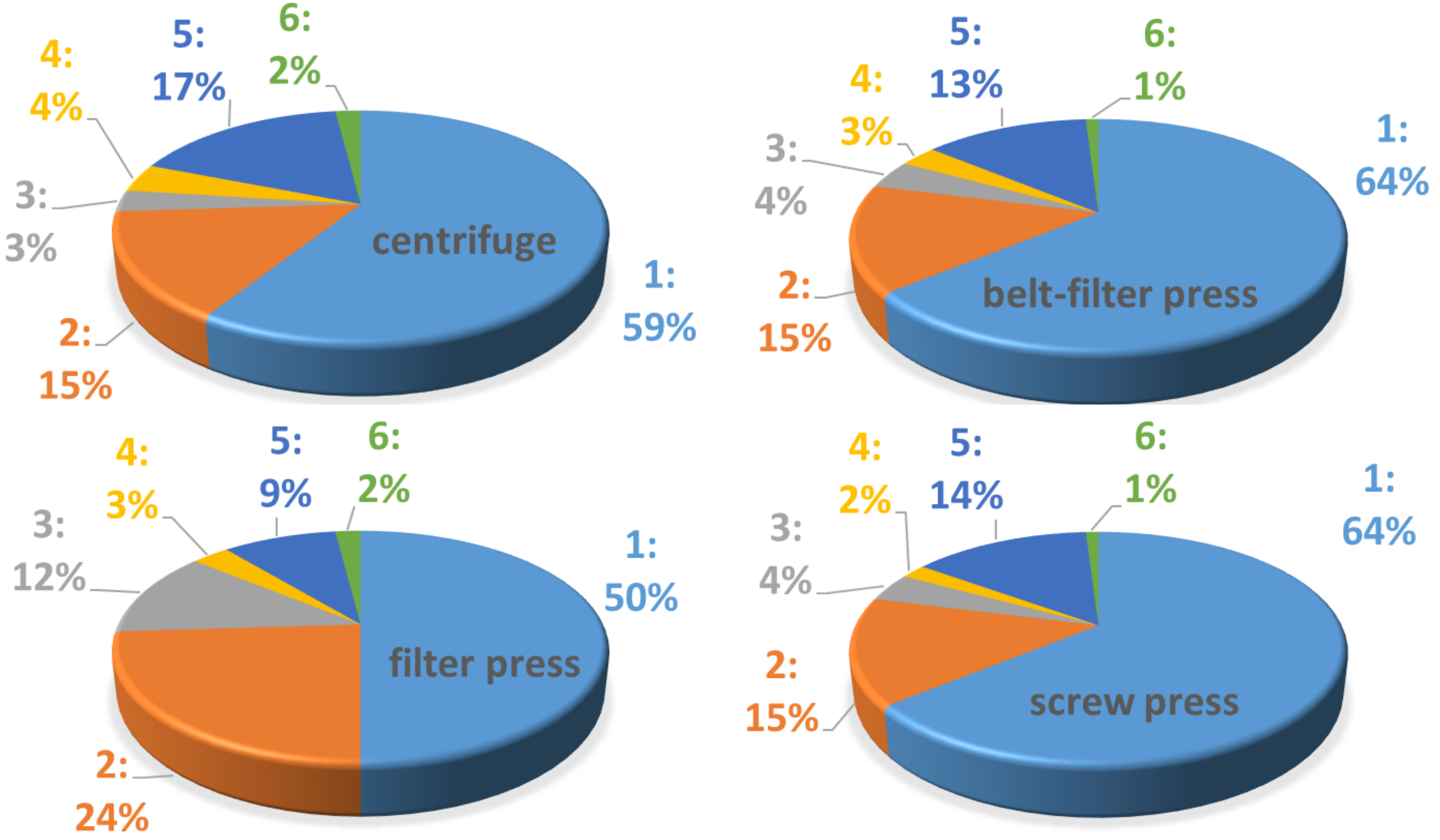
- centrifuges and filter presses achieve the highest solids content in the filter cake
- variation of final solids content is strongly dictated by characteristics of sludge to be dewatered
- constant optimisation of the dewatering unit is crucial for good dewatering results

Summary of mechanical dewatering technologies

sludge type	unit	centrifuge	belt-filer press	filter press	screw press
energy consumption (including conditioning and feed pump)					
specific energy consumption	kWh/m³	1.6 – 2.2	1.1 – 1.4	1.5 – 1.8	0.6 – 1.0
specific energy consumption	kWh/t TS	60 – 90	40 – 50	60 – 70	20 – 40
polymer use					
polymer consumption	kg/t TS	8 – 14	6 – 12	6 – 12	6 – 12

- screw press has clearly the lowest energy demand
- centrifuges have the highest energy demand
- polymer use depends less on technology used but rather on characteristics of sludge to be dewatered

Costs related to mechanical dewatering technologies (expressed in % of total cost)



- study of DWA (German prizes)
- for wastewater treatment plants with 100’000 PE

- 1: disposal
- 2: investment
- 3: personal
- 4: electricity
- 5: conditioning
- 6: maintenance

Cost of mechanical dewatering technologies

- main cost due to disposal (at least 50 %)
  - final total solids content is highly important for total cost
- conditioning (polymers) is more expensive than electricity costs
- costs related to personal is rather limited as compared to total cost
  - however, filter press has relatively high personal costs
- investment cost should not influence choice as it has little influence on total cost (for large wastewater treatment plants: 100’000 PE)
- however, investment costs may be much more important for small wastewater treatment plants

Other dewatering technologies: sludge drying beds

"Devices used for dewatering and drying of sludge and biosolids in which a semi-solid solution is spread over a porous (e.g. sand) or impervious medium and allowed to separate and air dry or decant."

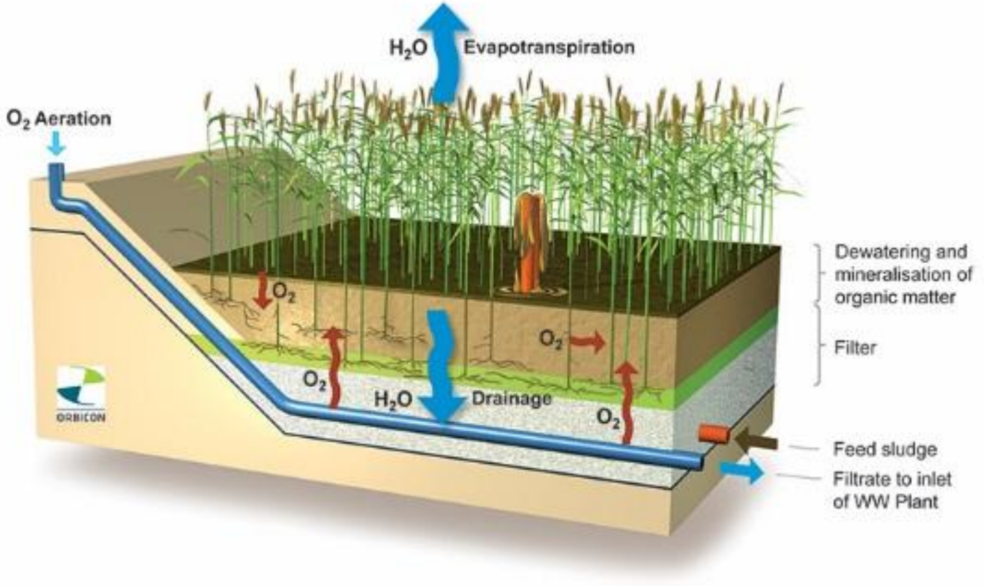
- functioning of sludge drying beds
  - thickened sludge put onto a (sand) bed
  - sludge is dried (weeks)
  - sludge is removed (often manually)
  - sand bed is refilled with thickened sludge
  - …
- drained water has to be returned to the wastewater treatment

Other dewatering technologies: sludge drying beds

- high space requirements (depends strongly on climatic conditions)
- often labour-intensive
- odour problems should not be underestimated
- sand has to be replaced as part of it is removed with the dried sludge
- solid content of dried sludge is highly variable and depends on climatic conditions
- efficiency of process can be increased by covering the drying bed

Other dewatering technologies: reed beds

- functioning of reed beds
  - thickened sludge is applied regularly on reed bed
  - water is either drained or consumed/ evaporated by planted reed or grass
  - sludge is not only dried but also stabilised (reduction in total volatile solids)
  - before harvesting of stabilised sludge, no thickened sludge is applied for several months (maturation process)



- very high space requirements (higher than drying beds)
- relatively low labour required apart from initial phase (planting of reed) and final phase (stabilised sludge evacuation after several years)
- high total solids content of stabilised sludge (up to 40 %)

Other dewatering technologies: heat drying

- "Application of heat to evaporate water and reduce the moisture content in biosolids below that achievable by conventional dewatering methods."
- sludge (dewatered) is dried to very high solids content
  - reduced transportation costs
  - significant pathogen inactivation
  - enhanced heat value of sludge/biosolids
  - small footprint (as compared to other drying technologies)
- however,
  - large fuel/electricity requirements (heat)
  - bad odour potential
  - relatively complex system, requires highly trained operating staff
  - relatively high capital cost

Treatment of the liquid stream

- during dewatering process solids are separated from the liquid phase
- liquid phase still contains
  - solids (separation process is not 100 % efficient)
  - ammonia, especially if dewatered sludge was previously anaerobically stabilised
  - and other pollutants (BOD, COD, phosphorous,…)
  - ➡ liquid phase has to be treaded before it can be discharged

- liquid phase is generally returned to main liquid treatment train
- specific treatments (e.g. Anammox) can be applied if liquid contains a lot of ammonium:
  - reduces load to main treatment train (particularly ammonium)
  - reduces energy consumption of whole wastewater treatment plant
  - increased complexity of wastewater treatment plant operation