Anaerobic and Aerobic digestion

Introduction

- Organic matter is the vast array of carbon compounds in nature.
- Originally created by plants, microbes, and other organisms, these compounds play a variety of roles in nutrient, water, and biological cycles.
- Organic matter can be divided into two major categories: **stabilized organic matter** which is highly decomposed and stable, and the **active fraction** which is being actively used and transformed by living plants, animals, and microbes. Two other categories of organic compounds are living organisms and fresh organic residue.

Stabilized organic matter

- Many soil organisms decompose plant and animal tissues, and transform the organic matter into new compounds. After years or decades of these transformations, what remains are large, complex compounds that few microbes can degrade.
- These hard-to-decompose, or stabilized, substances make up a third to a half of soil organic matter. These hard-to-decompose, or stabilized, substances make up a third to a half of soil organic matter.
- Stabilized organic matter are often divided into three chemical groups: humic acids, fulvic acids, and humins.

Humic Substances

- Soil humic substances (HS) are defined as amorphous, polymeric, brown coloured substances that are differentiated on the basis of solubility properties into humic acids (HAs, precipitated when aqueous alkaline extracts from soil are adjusted to pH 1), fulvic acids (FAs, soluble in aqueous media at all pH values) and humins (insoluble in aqueous media).
- Humins are considered to be the major components of HS, and to compose 50% and more (Stevenson, 1994) of the transformed or humified components (that bear no morphological resemblances to the structures from which they were derived) of organic materials in soil organic matter (SOM).

Humus

- **Humus** (coined 1790–1800; *Latin*: earth, ground) refers to any organic matter that has reached a point of stability, where it will break down no further and might, if conditions do not change, remain as it is for centuries, if not millennia.
- Humus is separated from the non-humic substances such as carbohydrates (a major fraction of soil carbon),fats, waxes, alkanes, peptides, amino acids, proteins, lipids, and organic acids by the fact that distinct chemical formulae can be written for these non-humic substances.
- Most small molecules of non-humic substances are rapidly degraded by microorganisms within the soil. In contrast soil humus is slow to decompose (Degrade) under natural soil conditions. When in combination with soil minerals soil humus can persist in the soil for several hundred years.
- Humus is the major soil organic matter component, making up 65% to 75% of the total. Humus assumes an important role as a fertility component of all soils, far in excess of the percentage contribution it makes to the total soil mass.

Humic and Fulvic acids

- **Humic acid**: It is a principal component of humic substances, which are the major organic constituents of soil. It is produced by biodegradation of dead organic matter; is a complex mixture of many different acids containing carboxyl and phenolate groups.
- **FULVIC ACIDS** - are a mixture of weak aliphatic and aromatic organic acids which are soluble in water at all pH conditions (acidic, neutral and alkaline). Their composition and shape is quite variable. The size of fulvic acids (FAs) are smaller than humic acids (HAs), with molecular weights which range from approximately 1,000 to 10,000.
- Fulvic acids (FAs) have an oxygen content twice that of humic acids (HAs). They have many carboxyl (-COOH) and hydroxyl (-COH) groups, thus fulvic acids (Fas) are much more chemically reactive. The exchange capacity of fulvic acids (FAs) is more than double that of humic acids (HAs). This high exchange capacity is due to the total number of carboxyl (- COOH) groups present.

Stabilized organic matter…

- In general there are two ways to stabilize organic matter in nature:
  - Composting: decomposes waste aerobically into CO_2, water and a humic fraction; some carbon storage also occurs in the residual compost
  - Anaerobic Digestion: anaerobic digestion produces biogas (CH_4 + CO_2) and biosolids.
- Anaerobic digestion is particularly appropriate for wet wastes, while composting is often appropriate for drier feedstocks.
- The two methods form part of biological digestion of waste.
- Compost products and digestion residuals can have potential horticultural or agricultural applications

Compost

- Composting is a managed aerobic (i.e. in the presence of oxygen) microbial process that breaks down organic wastes into compost.
- The process is focused on breaking down or decomposing those parts of the waste stream that are most easy to decompose. This includes sugars, starches, fats and proteins. At the end of the process all that is left are the parts of the waste stream that are more resistant to composting.
- Composting is said to stabilize waste. This means that the resultant compost will continue to break down but at a very slow rate.
- A key advantage of the composting process is that its high temperature essentially kills all pathogens and weed seeds that might be found in wastes.
- Bacteria, fungi and actinomycetes are the microorganisms responsible for the composting process. While they all play different roles they have essentially the same requirements.
- Composting is about creating a suitable environment for the microorganisms.

Compost…

- Compost is biologically active. An overabundance of soil organisms is responsible for transforming the organic matter in compost into carbon dioxide, water, humic substances capable of releasing inorganic plant nutrients and energy in the form of heat. These organisms are especially numerous and active in the initial phases of composting, but many remain in smaller numbers even in the finished product.
- In a mature compost, enough of the original organic material will have been consumed to prevent any substantial increase in the activity (and therefore heat-generating capacity) of the remaining microbes. This microbial stability is a prerequisite to compost maturity.
- Since stabilized compost is no longer subject to sudden chemical changes, it may be safely handled, stored and applied. Mature compost is normally dark brown in color and should have an even texture and a pleasant, earthy aroma.

Compost process

- It is an aerobic biological process which uses naturally occurring microorganisms to convert biodegradable organic matter into a humus like product.
- The process destroys pathogens, converts N from unstable ammonia to stable organic forms, reduces the volume of waste and improves the nature of the waste.
- It also makes waste easier to handle and transport and often allows for higher application rates because of the more stable, slow release, nature of the N in compost.
- The effectiveness of the composting process is influenced by factors such as temperature, oxygen supply (i.e. aeration) and moisture content.
- There are two fundamental types of composting aerobic and anaerobic:

Anaerobic Composting

- This is the decomposition of organic wastes in the absence of O_2, the products being methane (CH_4), CO_2, NH_3 and trace amounts of other gases and organic acids.
- Anaerobic composting was traditionally used to compost animal manure and human sewage sludge, but recently is has become more common for some municipal solid waste (MSW) and green waste to be treated in this way.
- *This method of composting is discouraged for un-enclosed decomposing matter due to foul smell.*

Aerobic Composting

- Composting is the decomposition of organic wastes in the presence of oxygen (air); products from this process include CO_2, NH_3, water and heat.
- This can be used to treat any type of organic waste but, effective composting requires the right blend of ingredients and conditions. These include moisture contents of around 60-70% and carbon to nitrogen ratios (C/N) of 30/1. Any significant variation inhibits the degradation process.
- Generally wood and paper provide a significant source of carbon while sewage sludge and food waste provide nitrogen.
- To ensure an adequate supply of oxygen throughout, ventilation of the waste, either forced or passive is essential.

Aerobic Composting

Key Parameter	Optimum values
Oxygen	10-15%
Moisture (supplementary moisture can also be added to composting mass)	50-55%
Carbon to nitrogen (C:N) ratio	30:1
pH	6-9
Porosity (spaces to allow air in compost)	1-5cm

Oxygen is supplied in two ways:

- by turning the compost, either by front-end loader or a specialized compost turner;
- by building the pile correctly, so surface air can diffuse into the center. When a pile gets too little oxygen, it will go anaerobic, and offensive odors may result.

Phases of composting

1. Mesophilic phase (I).
2. Thermophilic phase (II).
3. Cooling phase (III).
4. Maturing phase (IV).

Important Parameters of composting process

1. Water content.
2. Oxygen Demand.
3. Nutrients.
4. Temperature.
5. PH.
6. Time.

Suitable materials for composting

Can be composted	Cannot be composted
Sewage sludges	Coal ash
Industrial wastes (e.g. food, pulp & paper)	Metal, glass and plastic
Yard and garden wastes	Nappies.
Municipal solid wastes (up to 70% organic matter by weight)	The roots of persistent weeds, like bindweed and couch grass
Kitchen waste like fruit, peelings, teabags and egg shell.	Meat or fish
Paper shredded, mixed with grass cuttings	Cooked food, especially meat

Advantages of composting

- Reduces mass and volume: E.g. 50% reduction in mass and 80% reduction in volume
- Waste stabilization
- Pathogens are reduced
- Improves soil structure – makes it more 'friable' – i.e. gives it crumbly texture, beneficial for root growth.
- Improves water-retention in soils, helping to keep plants healthier for longer in dry conditions
- Provides a source of slow-release, organic fertilizer for your plants
- Boosts the community of microorganisms and other creatures beneficial for enhancing nutrient uptake and fighting plant diseases

Biological stabilization of liquid waste

- A lot of waste produced in nature, industry and in homes is in liquid form and cannot be composted.
- Under carefully controlled conditions, the waste can be stabilized under aerobic conditions known as “**aerobic digestion**” or in the absence of air known as “**anaerobic digestion**”.
- The latter method has economic value as it generates biogas rich in methane.

Anaerobic digestion (AD)

- In an anaerobic system there is an absence of gaseous oxygen; gaseous oxygen is prevented from entering the system through physical containment in sealed tanks.
- Anaerobes access oxygen from sources other than the surrounding air, which can be the organic material itself or may be supplied by inorganic oxides from within the input material.
- When the oxygen source in an anaerobic system is derived from the organic material itself, the 'intermediate' end products are primarily alcohols, aldehydes, and organic acids, plus carbon dioxide.

Anaerobic digestion

- The oxygen source for these microorganisms can be the organic material itself or alternatively may be supplied by inorganic oxides from within the input material.
- When the oxygen source in an anaerobic system is derived from the organic material itself, then the 'intermediate' end products are primarily alcohols, aldehydes, and organic acids plus carbon dioxide.

Types of Anaerobic Digesters: Mesophilic digestion

- It is an established and relatively simple technology.
- During this process decomposition of the organic matter takes 15 to 40 days and as a result requires a large tank.
- The tank is heated to a relatively low temperature of between 30 to 40°C.

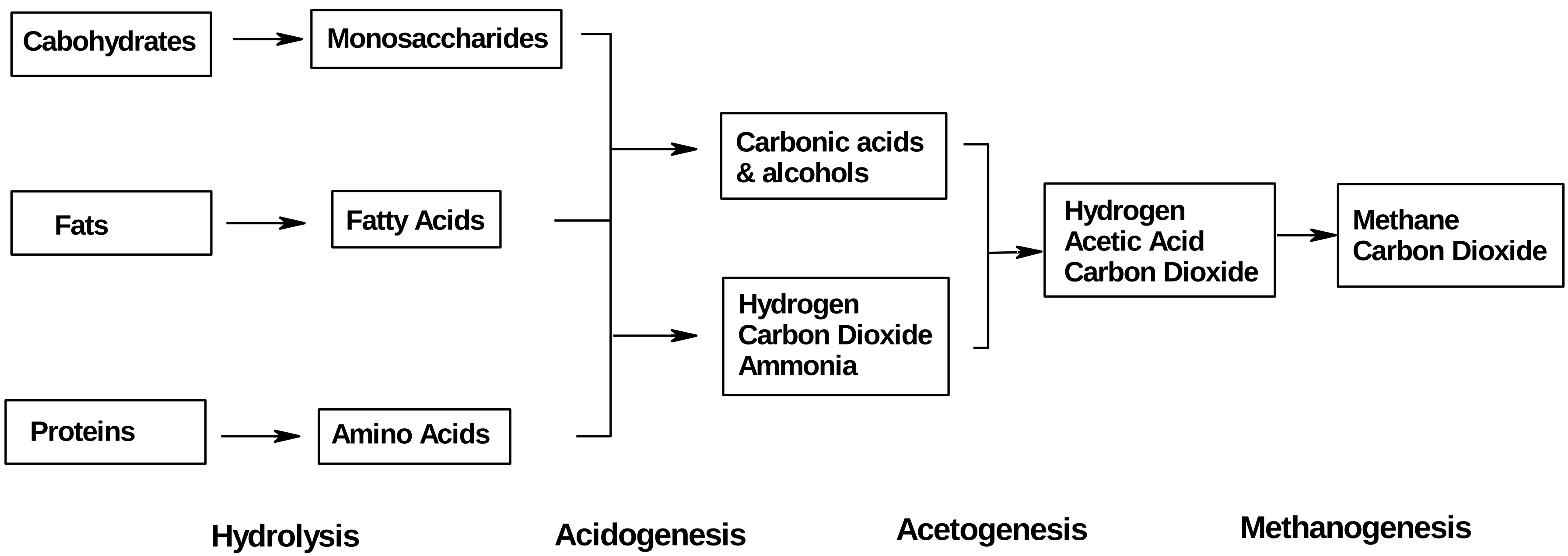
Types of Anaerobic Digesters: Thermophilic digestion

- It is an emerging technology with a lower retention time (12 to 14 days) and with a faster and higher rate of biogas production.
- It also has the benefit that a smaller tank can be used.
- The tank needs to be heated to a higher temperature (55°C) therefore using more energy.
- The thermophilic digestion process is currently more expensive and is technically more complex.

Anaerobic digestion occurs in four steps

- Hydrolysis
- Fermentation or Acidogenesis
- Acetogenesis
- Methanogenesis

Stages of Anaerobic digestion



Anaerobic digestion:**Hydrolysis**

- Complex organic matter is decomposed into simple soluble organic molecules using water to split the chemical bonds between the substances
- Hydrolysis of the input materials occurs in order to break down insoluble organic polymers such as carbohydrates and make them available for other bacteria
- Through hydrolysis the complex organic molecules are broken down into simple sugars, amino acids, and fatty acids

Anaerobic digestion: Fermentation or Acidogenesis:

- The chemical decomposition of carbohydrates by enzymes, bacteria, yeasts, or molds in the absence of oxygen.
- Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids
- The process of acidogenesis is similar to the way that milk sours.

Anaerobic digestion: **Acetogenesis**

- Acetogenic bacteria then convert these resulting organic amino acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide

Anaerobic digestion: **Methanogenesis**

- methanogenic bacteria are finally are able to convert acetate, hydrogen to methane and carbon dioxide.

Anaerobic digestion: Two groups of methane forming bacteria

Methanobacterium

- Convert CO_2 and H_2 to CH_4
- Reductive methane formation
- About 30% of methane formed

Methanosarcina

- Convert acetate to CH_4 and bicarbonate
- Acetate decarboxylation
- About 70% of methane formed

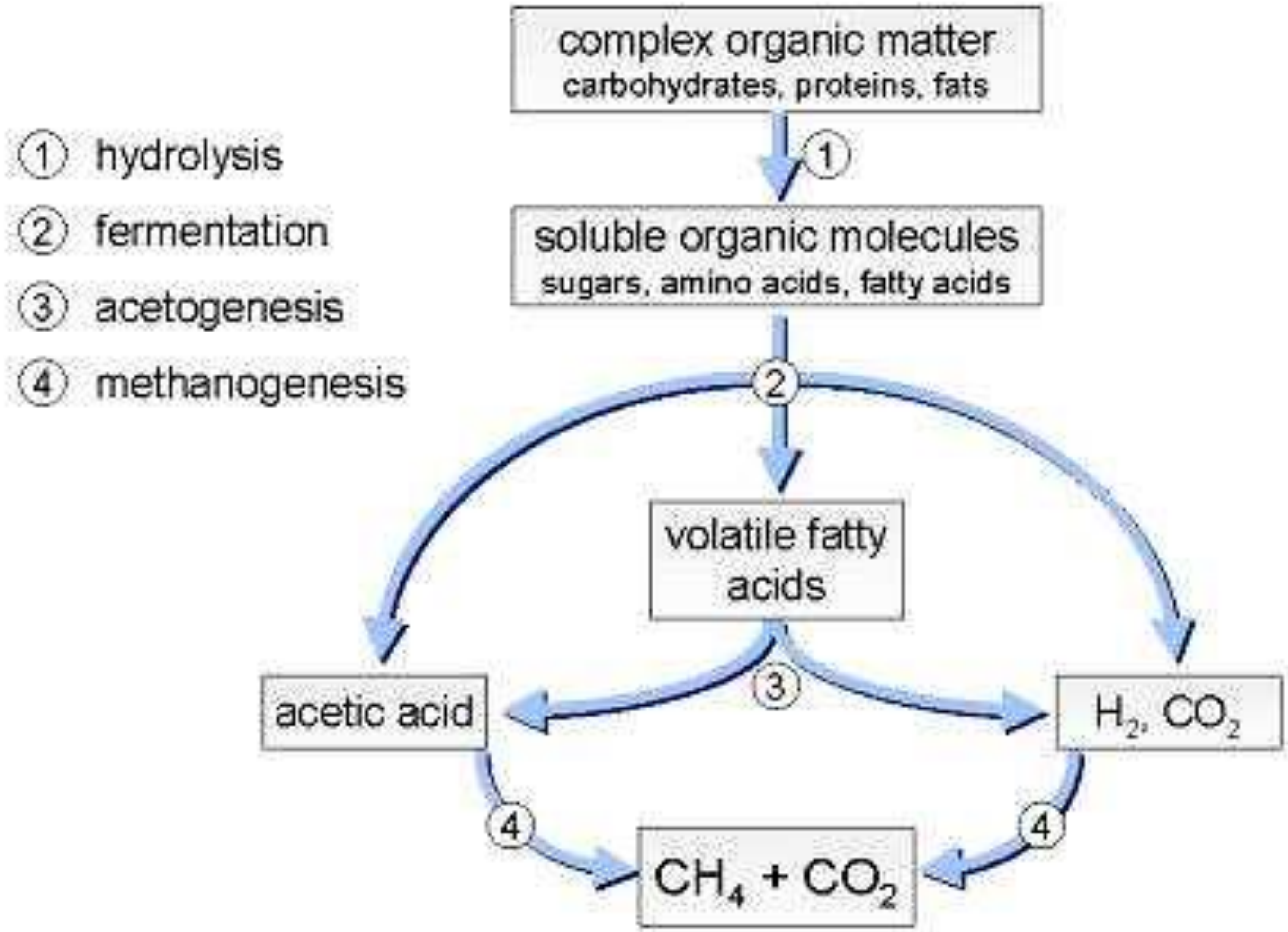
Anaerobic digestion: Methane Formers

Methane forming bacteria control the anaerobic digestion process.

- Sensitive to environmental changes
- Reproduce slowly
- Easy to kill and hard to grow
- Methane formers
- Strict anaerobes
- No stabilization until methane is formed.

AD Process revolves around methane formers.

Path of Anaerobic Digestion



Bacteria involved in Anaerobic digestion

Types of bacteria involved in each step of polymeric organic material digestion

Degradation process	Bacterial group	Type of conversion	Type of bacteria
Hydrolysis	Hydrolytic bacteria	Proteins to soluble peptides and amino acids	*Clostridium*, *Proteus vulgaris*, *Peptococcus*, *Bacteriodes*, *Bacillus*, *Vibrio*
		Carbohydrates to soluble sugars	*Clostridium*, *Acetovibrio cellulilticus*, *Staphylococcus*, *Bacteriodes*
		Lipids to higher fatty acids or alcohols and glycerol	*Clostridium*, *Micrococcus*, *Staphylococcus*
Fermentation	Acidogenic bacteria	Amino acids to fatty acids, acetate and NH_3	*Lactobacillus*, *Escherichia*, *Staphylococcus*, *Bacillus*, *Pseudomonas*, *Desulfovibrio*, *Selenomonas*, *Sarcina*, *Veillonella*, *Streptococcus*, *Desulfobacter*, *Desulforomonas*
		Sugars to intermediary fermentation products	*Clostridium*, *Eubacterium limosum*, *Streptococcus*
Acetogenesis	Acetogenic bacteria	Higher fatty acids or alcohols to hydrogen and acetate	*Clostridium*, *Syntrophomonas wolfeii*
		Volatile fatty acids and alcohols to acetate or hydrogen	*Sytrophomonas wolfei*, *Sytrophomonas wolinii*
Methanogenesis	Carbon dioxide-reducing methanogens	Hydrogen and carbon dioxide to methane	*Methanobacterium*, *Methanobrevibacterium*, *Methanoplanus*, *Methanospirillum*
	Aceticlastic methanogens	Acetate to methane and carbon dioxide	*Methanosaeta*, *Methanosarcina*,

Anaerobic Digestion: Digestate

- Digestate is the solid remnants of the original input material to the digesters that the microbes cannot use.
- It also consists of the mineralised remains of the dead bacteria from within the digesters.
- Digestate can come in three forms: fibrous, liquor, or a sludge-based combination of the two fractions.

Anaerobic Digestion: Digestate

- The acidogenic digestate is a stable organic material consisting largely of lignin and cellulose, but also of a variety of mineral components in a matrix of dead bacterial cells; some plastic may be present.

Anaerobic Digestion: Digestate

- The solid digestate can also be utilized as feedstock for ethanol production.
- The methanogenic digestate is a liquid that is rich in nutrients and can be used as a fertiliser dependent on the quality of the material being digested.

Anaerobic Digestion

- The final output from anaerobic digestion systems is water.
- This water originates both from the moisture content of the original waste that was treated but also includes water produced during the microbial reactions in the digestion systems.
- This water may be released from the dewatering of the digestate or may be implicitly separate from the digestate.

Anaerobic Digestion

- The wastewater exiting the anaerobic digestion facility will typically have elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD).
- These are measures of the reactivity of the effluent and show an ability to pollute.
- If this effluent were put directly into watercourses, it would cause eutrophication.
- As such, further treatment of the wastewater is often required.

Some Definitions in Anaerobic Digestion

- **Biochemical oxygen demand** or **B.O.D.** is a chemical procedure for determining the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic material present in a given water sample at certain temperature over a specific time period.
- It is most commonly expressed in milligrams of oxygen consumed per litre of sample during 5 days of incubation at 20 °C and is often used as a robust surrogate of the degree of organic pollution of water.
- Moderately polluted rivers may have a BOD value in the range of 2 to 8 mg/L. Untreated sewage varies, but averages around 600 mg/L .

Some Definitions in Anaerobic Digestion

- **Chemical oxygen demand** (**COD**) test is commonly used to indirectly measure the amount of organic compounds in water. Most applications of COD determine the amount of organic pollutants found in surface water (e.g. lakes and rivers), making COD a useful measure of water quality. It is expressed in milligrams per liter (mg/L), which indicates the mass of oxygen consumed per liter of solution.

Conditions for Anaerobic Digestion

- Environmental conditions: Neutral pH (actually between 6.8- 7.2)
- Below 6: unionized volatile acids become toxic to methane formers.
- -Above 8: unionized ammonia becomes toxic.
- Alkalinity 2,000 –5,000 mg/L
- Volatile acids 50 – 300 mg/L
- Volatile acid/alkalinity ratio Range: 0.2 –0.3 (Increase above 0.3 – 0.4 indicate upset)

Conditions for Anaerobic Digestion

- Temperature: Mesophilic 32 - 38°C
- Thermophilic range 50 - 60 °C

**Tank temperature must not change more than 1° C per day.

- Causes of Toxicity
  - Organic compounds
  - Heavy metals
  - Ammonia
  - Sulfide
  - Oxygen
  - Salts

Important factors in AD of solid waste

- Several factors can affect the performance of the anaerobic digestion, either by process enhancement or inhibition, influencing parameters such as specific growth rate, degradation rates, biogas production or substrate utilisation.
- These factors are: pH, temperature, substrate, retention time, organic loading, mixing condition and inhibitory substances.

Important factors in AD: PH

- The pH value of the digester content is an important indicator of the performance and the stability of an anaerobic digester. In a well-balanced anaerobic digestion process, almost all products of a metabolic stage are continuously converted into the next breaking down product without any significant accumulation of intermediary products such as different fatty acids which would cause a pH drop.
- Many aspects of the complex microbial metabolism are greatly influenced by pH variations in the digester. Although acceptable enzymatic activity of acid-forming bacteria can occur at pH 5.0, methanogenesis proceeds only at a high rate when the pH is maintained in the neutral range.
- Most anaerobic bacteria including methane forming bacteria function in a pH range of 6.5 to 7.5, but optimally at a pH of 6.8 to 7.6, and the rate of methane production may decrease if the pH is lower than 6.3 or higher than 7.8
- Anaerobic digestion of kitchen wastes with controlled pH value at 7.0 resulted in a relatively high rate of hydrolysis and acidogenesis with about 86 % of TOC and 82 % of COD were solubilized.

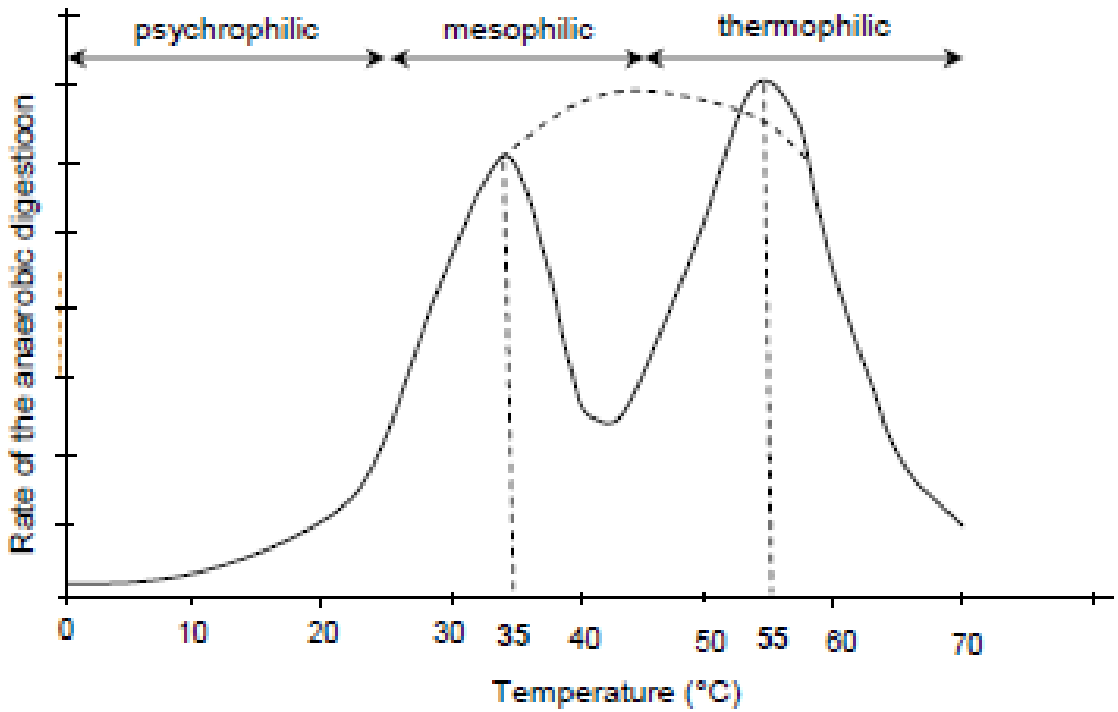
Important factors in AD: PH

- Alkalinity and pH in anaerobic digestion can be adjusted using several chemicals such as sodium (bi) carbonate, potassium (bi) carbonate, calcium carbonate (lime), calcium hydroxide (quick lime) and sodium nitrate. Addition of any selected chemical for pH adjustment should be done slowly to prevent any adverse impact on the bacteria.
- Because methanogenic bacteria require bicarbonate alkalinity, chemicals that directly release bicarbonate alkalinity are preferred (*sodium bicarbonate and potassium* bicarbonate are more preferred due to their desirable solubility, handling, and minimal adverse impacts).
- Lime may be used to increase digester pH to 6.4, and then either bicarbonate or carbonate salts (sodium or potassium) should be used to increase the pH to the optimum range

Important factors in AD: Temperature

- Temperature is one of the major important parameters in anaerobic digestion. It determines the rate of anaerobic degradation processes particularly the rates of hydrolysis and methanogenesis.
- Moreover, it not only influences the metabolic activities of the microbial population but also has a significant effect on some other factors such as gas transfer rates and settling characteristics of biosolids.
- Anaerobic digestion commonly applies two optimal temperature ranges: mesophilic with optimum temperature around 35 °C and thermophilic with optimum temperature around 55 °C.

Influence of temperature on the rate of anaerobic digestion process.



- Optimum temperature for mesophilic around 30 – 40 °C and for thermophilic 50 – 60 °C

Mesophilic AD

- Mesophilic bacteria are supposed to be more robust and can tolerate greater changes in the environmental parameters, including temperature.
- Smaller digesters, poorly insulated digesters, or digesters in cold climates are susceptible for extreme temperature fluctuations thus these would be beneficial if the digester is being run in the mesophilic range to minimize system crashing.
- Although it requires longer retention time, the stability of the mesophilic process makes it more popular in current anaerobic digestion facilities

Thermophilic AD

- Thermophilic process offers faster kinetics, higher methane production rates and pathogen removal. This method, however, is more sensitive to toxic substances and changes of operation parameters.
- A study comparing the performance of thermophilic and mesophilic treating mechanically sorted municipal solid waste (by Cecchi in 1991) found that thermophilic process yielded 100 % more methane production and better volatile solids elimination compared to mesophilic process.
- However, thermophilic process is sometimes considered as less attractive from the energy point of view since it requires more energy for heating

Heat Exchangers in AD

- The most common method for maintaining the temperature in anaerobic digester is an external heat exchanger. This method has the benefit of enabling to mix recirculating digestate with raw slurry before heating, and in seeding the raw slurry with anaerobic microorganisms.
- Among three types of external heat exchangers frequently used (water bath, tubular and spiral exchangers), both tubular and spiral exchangers are mostly preferred for their countercurrent flow design and heat transfer coefficients. The hot water used in the heat exchangers is commonly produced in a boiler fueled by biogas that comes from the digester.
- At the startup and/or under conditions of insufficient biogas production, an alternative fuel source such as natural gas must be provided

Psychrophilic AD

- Reasonable methane yields still can be expected from anaerobic digestion at low temperatures (14 – 23 °C) if the organic loading of the digester is reduced by mean of extending the hydraulic retention.
- A relative stable operation of an anaerobic digester treating mixture of animal manure can be achieved at low temperature (18 – 25 °C) with an optimum OLR of 4 – 6 kg VS m^{-3} d^{-1} and a methane content of 47 – 55 % in the biogas.

Anaerobic Digestion: Substrate Characteristics

- The characteristics of solid wastes determine the successful anaerobic digestion process (*high biogas production potential and degradability).*
- *In municipal solid* waste, substrate characteristics may vary due to the method of collection, weather season, cultural habits of the community .

Anaerobic Digestion: Substrate Characteristics

- The degradability and biogas production potential from solid waste in an anaerobic digester are dependent on the amount of the main components: lipids, proteins, carbohydrates such as cellulose and hemicelluloses as well as.
- Among them lipids are the most significant substances in the anaerobic digestion, since the methane yield from lipids is higher than from most other organic materials.

Anaerobic Digestion: Substrate Characteristics

- Lignocellulosic (cellulose and hemicelluloses which are tightly bound to the lignin) waste can be found in abundant amount in the form of garden waste, paper residue or agricultural waste. Due to the presence of lignin, lignocellulosic waste is considered to be quite resistant to anaerobic digestion and hydrolysis is the rate limiting step in the overall process.
- In order to improve the rate of enzyme hydrolysis and increase yields of fermentable sugars from cellulose or hemicellulose in lignocellulosic waste, several pretreatment methods such as thermal (steam or hot water), chemical (acid, lime or ammonia addition) or combination of both methods can be used.

Anaerobic Digestion: Substrate Characteristics

- The composition of waste also determines the relative amounts of organic carbon and nitrogen present in the waste substrate (C/N ratio).
- A solid waste substrate with high C/N ratio is not suitable for bacterial growth due to deficiency of nitrogen. As a result the gas production rate and solids degradability will be low. On the other hand, if the C/N ratio is very low, the degradation process leads to ammonia accumulation which is toxic to the bacteria.
- A C/N ratio (based on biodegradable organic carbon and nitrogen) within the range of 25–30 is considered to be optimum for an anaerobic digester. To maintain the C/N level of the digester material at optimum levels, substrates with high C/N ratio can be codigested with nutrient-rich organic wastes (low C/N ratio) like animal manure or foodwaste.

Anaerobic Digestion: Substrate Characteristics

- The particle size has a significant role in anaerobic digestion of solid waste, especially during hydrolysis since a smaller particle size provides a greater area for enzymatic attack .
- The increase of the average particle size in anaerobic digestion of food waste was reported to decrease the maximum substrate utilization rate coefficient.
- *It has been* reported that by reducing the size to 2 mm, the potential methane production of sisal fiber waste will improve to more than 20 % and the total fiber degradation increased from 31% to 70% compared to the untreated fibers.

Anaerobic Digestion: Hydraulic Retention time

- The hydraulic retention time (HRT) is a measure to describe the average time that a certain substrate resides in a digester. In a digester with continuous mixing, the contents of the reactor have a relative uniform retention time. In this system, the minimum HRT is dictated by the growth rate of the slowest growing, essential microorganisms of the anaerobic bacterial community. If the HRT is shorter, the system will fail due to washout of the slowest growing microorganisms that are necessary for the anaerobic process.
- Shortening the HRT consequently reduces the size of the digester, resulting in capital cost savings. Furthermore, a shorter HRT yields a higher biogas production rate, but less efficient degradation of organic matter (as volatile solids or COD), associated with less process stability must be anticipated.

Anaerobic Digestion: Hydraulic Retention time

- The HRT of anaerobic digesters treating solid wastes varied from 3 to 55 days, depending on the type of waste, operational temperature, process stage(s) and configuration of the digesters.
- The HRT for dry anaerobic digestion ranges between 14 and 30 days and for wet anaerobic processes it can be as low as 3 days. Longer retention time of 50 – 100 days have been used for a digester treating solid waste from poultry slaughterhouse.
- However, at a shorter retention time (13 to 25 days), the process appeared to be inhibited, as indicated by the buildup of long chain fatty acids and a lower methane yield.

Anaerobic Digestion: organic loading rate (OLR)

- The organic loading rate (OLR) is defined as the amount of organic matter (expressed as volatile solids or COD of the feeding substrate) that must be treated by a certain volume of anaerobic digester in a certain period of time.
- The value of the OLR is mostly coupled with the HRT value. If the concentration of organic matter in the feedstock substrates is relatively constant, the shorter the HRT the higher value of OLR will be achieved. On the other hand, the value of the OLR will vary at the same HRT if there is a variation of organic matter concentration in the feeding substrate.

Anaerobic Digestion: organic loading rate (OLR)

- The potential danger of a rapid increase in the OLR would be that the hydrolysis and acidogenic bacteria would produce intermediary products rapidly.
- Since the multiplication time of methanogenic bacteria is slower, they would not be able to consume the fatty acids at the same rate.
- The accumulation of fatty acids will lead to a pH drop and hampering the activity methanogenic bacteria, causing a system failure.

Anaerobic Digestion: Mixing condition

- Mixing plays an important role in anaerobic digestion of solid waste.
- Mixing provides an adequate contact between the incoming fresh substrate and the viable bacterial population and also prevents the thermal stratification and the formation of a surface crust/scum buildup in an anaerobic reactor.
- Furthermore, mixing ensures that solids remain in suspension avoiding the formation of dead zones by sedimentation of sand or heavy solid particles.
- Mixing also enables the particle size reduction as digestion progresses and the release of produced biogas from the digester contents.
- Mechanical mixing systems generally use lows peed flat-blade turbines and are most suited for digesters with fixed covers.

Anaerobic Digestion: Biogas recirculation

- Biogas recirculation is a successful method of mixing the digester content and avoids the buildup of scum.
- Biogas mixing systems can be confined and unconfined.
  - In unconfined systems, the gas is collected at the top of the digestion tank, compressed and then released through a pattern of diffusers or a series of radially placed lances suspended from the digester cover.
  - In confined systems the gas is collected at the top, compressed and discharged through confined tubes and gas bubbles rise, creating an airlift effect.

Anaerobic Digestion: Inhibitory Substances

- Inhibition in anaerobic digestion process by the presence of toxic substances can occur to varying degrees, causing upset of biogas production and organic removal or even digester failure.
- These kinds of substances can be found as components of the feeding substrate (organic solid waste) or as byproducts of the metabolic activities of bacteria consortium in the digester.

Anaerobic Digestion: Inhibitory Substances

- The main reason for these variations is the significant influence by microbiological mechanisms such as acclimation, antagonism, and synergism.
  - Acclimation is the ability of microorganism to rearrange their metabolic resources to overcome the metabolic block produced by the inhibitory or toxic substances when the concentrations of these substances are slowly increased within the environment.
  - Antagonism is defined as a reduction of the toxic effect of one substance by the presence of another.
  - Synergism is an increase in the toxic effect of one substance by the presence of another.
- Several substances with inhibitory/toxic potential to anaerobic digestion, such as ammonia, sulfide, light metal ions, heavy metals and organic substances, will be discussed shortly.

Anaerobic Digestion: Inhibitory Substances

- Ammonia is a hydrolysis product formed during anaerobic digestion of solid waste by degradation of nitrogenous matter in the form of proteins, phospholipids and nitrogenous lipids.
- The inhibition mechanisms of ammonia are presumably due to the change of intracellular pH, the increase of maintenance energy requirement to overcome the toxic conditions, and inhibition of specific enzyme reactions.
- *In a solution,* ammonium exists in the form of ammonium ion and free ammonia. Free ammonia is reported to have a more pronounced inhibition effect since it is freely membrane permeable and may diffuse passively into the cell, causing proton imbalance and/or potassium deficiency.

Anaerobic Digestion: Inhibitory Substances

Ammonia Toxicity

- 50 – 200 mg/L: beneficial
- 200 – 1,000 mg/L: no adverse effects
- 1,500 – 3,000 mg/L: inhibitory at pH 7.4 7.4- 7.6
- 3,000 mg/L: toxic

Anaerobic Digestion: Inhibitory Substances

- The formation of hydrogen sulfide in anaerobic digestion is the result of the reduction of oxidized sulfur compounds and of the dissimilation of sulfur containing amino acids such as cysteine by sulfate reducing bacteria. The reduction is performed by two major groups of SRB including incomplete oxidizers, which oxidize compounds such as lactate to acetate and CO2 and complete oxidizers (acetoclastic SRB), which completely convert acetate to CO2 and HCO3. Both groups utilize hydrogen for sulfate reduction.
- Inhibition caused by sulfate reduction can be differentiated into two stages. Primary inhibition is indicated by lower methane production due to competition of SRB and methanogenic bacteria to obtain common organic and inorganic substrates. Secondary inhibition results from the toxicity of sulfide to various anaerobic bacteria groups.

Anaerobic Digestion: Inhibitory Substances

- *The light metal ions including sodium, potassium, calcium, and* magnesium are commonly present in the digestate of anaerobic reactors. They may be produced by the degradation of organic matter in the feeding substrate or by chemicals addition for pH adjustment.
- Moderate concentrations of these ions are needed to stimulate microbial growth, however excessive amounts will slow down growth, and even higher concentrations can cause severe inhibition or toxicity.
- Salt toxicity is primarily associated with bacterial cells dehydration due to osmotic pressure.

Anaerobic Digestion: Inhibitory Substances

- Although the cations of salts in solution must always be associated with the anions, the toxic action of salts was found to be predominantly determined by the cation.
- The role of the anions was relatively minor and largely associated with their effect on properties such as the pH of the media.
- If compared on a molar concentration basis, monovalent cations, such as sodium and potassium, were less toxic than the divalent cations, such as calcium and magnesium

Anaerobic Digestion: Inhibitory Substances

- *Similar with light metal ions, the presence of heavy metals in trace* concentration will stimulate the growth of anaerobic digester's flora.
- However, unlike other toxic substances, heavy metals are not biodegradable and can accumulate to potentially toxic concentrations.
- Extensive studies (in 1969 by Swanwick and 2008 by Chen) on the performance of anaerobic reactors found that heavy metal toxicity is one of the major causes of anaerobic digester upset or failure.
- The toxic effect of heavy metals is attributed to their ability to inactivate a wide range of enzyme function and structures by binding of the metals with thiol (sulfhydryl) and other groups on protein molecules or by replacing naturally occurring metals in prosthetic groups of enzymes.
- *The toxicity of heavy metals in* anaerobic digestion depends upon the various chemical forms which the metals may assume under anaerobic conditions at the temperature and pH value in the digester. For instance, heavy metals in the precipitated form have little toxic effect on the biological system

Anaerobic Digestion: Inhibitory Substances

- *Many organic compounds were reported to have a inhibitory* potential to anaerobic digestion processes. The accumulation of hydrophobic organic pollutants in bacterial membranes causes the membrane to swell and leak, disrupting ion gradients and eventually causing the breaking of cellular membranes.
- *The toxicity concentration of* organic compounds ranges vary widely and is affected by many parameters, including toxicant concentration, biomass concentration, toxicant exposure time, cell age, feeding pattern, acclimation and temperature.
- Several important organic substances which are inhibitory to anaerobic digestion are: chlorophenols, halogenated aliphatic, nitrogensubstituted aromatic, longchain fatty acids and lignins/lignin related compounds.

Anaerobic Digestion: Minimizing the effect of inhibitory substances

- Several strategies to minimize the effect of inhibitory substances can be summarized as follows;
  - Removal of potential inhibitory/toxic substances from the feeding substrate.
  - Dilution of the feeding substrate in order to reduce the concentration of inhibitory substances below the threshold.
  - Addition of chemicals to precipitate or insolubilize the inhibitory substances.
  - Change of the chemical form of inhibitory substances through pH control.
  - Addition of material that is antagonistic to the inhibitory substances in order to counteract the inhibitory effect.

Types of AD reactors for solid waste

- Typically anaerobic reactors or processes of solid waste can be distinguished into several types, mostly according to the feeding mode (continuous mode: single stage, two stages and batch mode) and the moisture content of the substrate (wet or dry digestion).
- Furthermore with those basic types, the anaerobic reactors can be arranged according to the digestion process temperature (mesophilic or thermophilic) and the shape of the reactors (vertical or horizontal).

Large Scale Anaerobic Digestion

Small Scale Anaerobic Digestion

① Unit: PDAN. Anaerobic Digester

② Electronic Console

A typical Anaerobic Digester site

Plant Equipment:

1. Blending Tank
2. Industrial Sludge Holding Tank
3. Manure Hold Tank
4. Digester
5. Gas holder
6. Effluent Sludge Tank
7. CO-GEN Building
8. Office & Laboratory Bldg.

Main Operating Data:

Animal manure............................ 222 tons/day
Alternative biomass...................... 87 tons/day
Biogas production........................ 3,1 mill m³/year
Digester capacity (2 x 2500 m³).. 5000 m³
Process temperature.................. 53,5°C

Anaerobic Digestion: **Biogas**

- **Biogas** is the name given to the mixture of gases formed during the anaerobic digestion of organic wastes.
- Biogas consists of methane (c70%) and carbon dioxide (c30%).
- It can be used in stationary engines to generate electricity, but it is not suitable as a vehicle fuel
- After removing the carbon dioxide (and other trace gases using a variety of methods in a process known as upgrading) the remaining methane is known as Renewable Natural Gas or Biomethane.

Typical data on composition of biogas

Compound	Anaerobic Digestion biogas
Methane, CH_4	55-75 %
Carbon dioxide, CO_2	25-45 %
Carbon monoxide, CO	0-0.3 %
Nitrogen, CO_2	1-5 %
Oxygen, CO_2	Traces
Hydrogen, CO_2	0-3 %
Hydrogen sulphide, H_2S	0.1-0.5 %
Chlorine, Cl_2	-
Fluorine, F_2	-

Refining Bio-Gas into Biomethane

- The bio-gas produced in the methane digester is primarily methane and carbon dioxide, with traces of hydrogen sulfide, and other gasses.
- Bio-gas by itself can be used as-is for heating and for cooking. However, use of raw bio-gas in heating equipment and in internal combustion engines will cause early failures because of the corrosive nature of the hydrogen sulfide and water vapor.

Refining Bio-Gas into Biomethane

- Carbon dioxide in the bio-gas lowers the heating value of the gas. It should be noted that the bio-gas from the digestion of animal wastes does not have some of the contaminants of bio-gas from landfills or municipal waste water treatment plants and is therefore easier to clean up

Risks Associated with Bio-Gas

- While methane is a very promising energy resource, the non-methane components of bio-gas (hydrogen sulfide, carbon dioxide, and water vapor) tend to inhibit methane production and, with the exception of the water vapor, are harmful to humans and/ or the environment. For these reasons, the bio-gas produced should be properly “cleaned” using appropriate scrubbing and separation techniques.

Risks Associated with Bio-Gas

- In addition, the methane itself represents a serious danger, as it is odorless, colorless, and difficult to detect. Methane is also highly explosive if allowed to come into contact with atmospheric air at proportions of 6 to 15 percent methane. For these reasons, it is recommended that buildings be well ventilated; motors, wiring, and lights should be explosion-proof; flame arrestors should be used on gas lines; and alarms and gas detection devices should be used.

Anaerobic Digestion: Digester Failure

- Unbalanced microbiological growth
- Acid-formers out produce the methane-formers
- Over-production of acids

Process Failure Indicators

- VA concentration increases
- Alkalinity drops
- VA/ALK ratio increases
- pH falls
- Gas production rate drops,
- CO_2 Percent increases

Anaerobic Digestion: Digester Failure

Causes of Process Failure

- Hydraulic overload [Hydraulic residence time, HRT (in hours) or tau, is a measure of the average length of time that a soluble compound remains in a constructed bioreactor = Volume of aeration tank (m3)/inflow rate (m3/h)]
- Dilute feed sludge
- Excessive sludge production
- Grit and scum accumulation
- Alkalinity washout

Anaerobic Digestion: Digester Failure

- Organic overload
  - Increase in sludge production
  - Increase in sludge concentration
  - Change in sludge characteristics
  - Infrequent feeding
  - Too rapid startup

Anaerobic Digestion: Digester Failure

Toxic overload

- Heavy metals
- Detergents
- Chlorinated organics
- Oxygen
- Cations
- Sulfides

Anaerobic Digestion: Digester Solutions

- Adjust alkalinity
- Adjust feed schedule
- thicken feed sludge
- Industrial pretreatment
- Clean digester

Advantages of Anaerobic Digestion

- Wastewater pollutants are transformed into methane, carbon dioxide and smaller amount of bio-solids.
- The biomass growth is much lower compared to those in the aerobic processes.
- They are also much more compact than the aerobic bio-solids

Advantages of Anaerobic Digestion

- Anaerobic digestion reduces the emission of landfill gas into the atmosphere.
- Anaerobic digestion is a renewable energy source because the process produces a methane and carbon dioxide rich biogas suitable for energy production helping replace fossil fuels.
- The nutrient-rich solids left after digestion can be used as fertilizer.

Advantages of Anaerobic Digestion

- Almost any organic material can be processed with anaerobic digestion.
- This includes biodegradable waste materials such as waste paper, grass clippings, leftover food, sewage and animal waste.
- The exception to this is woody wastes that are largely unaffected by digestion as most anaerobes are unable to degrade lignin found in wood.

Advantages of Anaerobic Digestion

- Stabilization in the absence of oxygen
- Pathogen reduction
- Reduction in mass
- Production of methane

Disadvantages of Anaerobic Digestion

- Anaerobic Digestion (AD) produces certain emissions and effluents, to air, ground and water, which need treatment to avoid damage to human health and the environment.
- Water produced during process can be contaminated with nitrates and other chemicals – needs to be processed before release to the environment
- An expensive technology requiring grant to encourage development under current circumstances

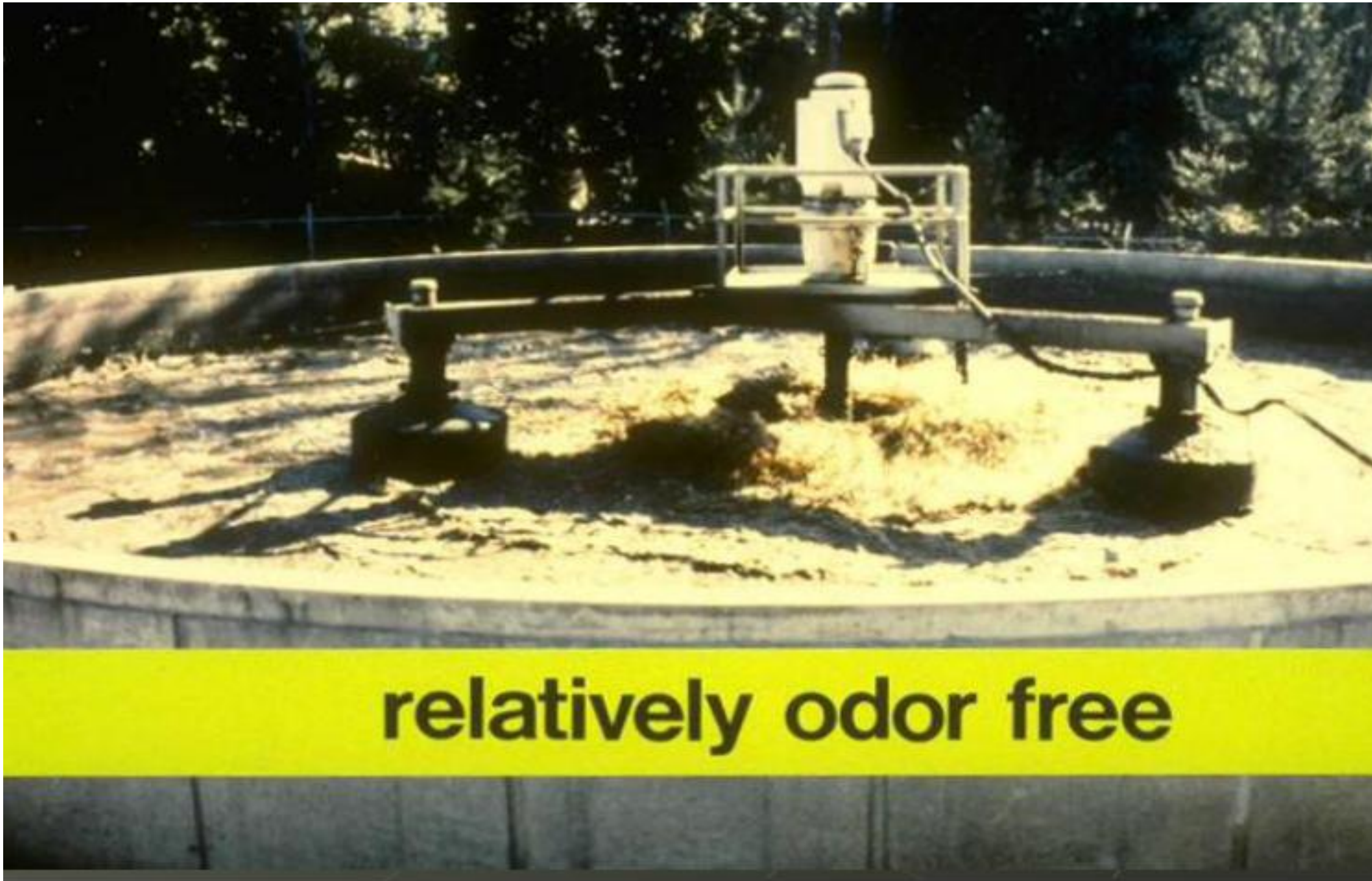
Disadvantages…

- Longer start-up time to develop necessary biomass inventory
- May require alkalinity and/or specific ion addition
- May require further treatment with an aerobic treatment process to meet discharge requirements
- Biological nitrogen and phosphorus removal is not possible
- Much more sensitive to the adverse effect of lower temperatures on reaction rates
- May need heating (often by utilisation of process gas) to achieve adequate reaction rates
- May be more less stable after 'toxic shock'(eg after upsets due to toxic substances in the feed)
- Increased potential for production of odours and corrosive gases.
- Hazards arise from explosion.

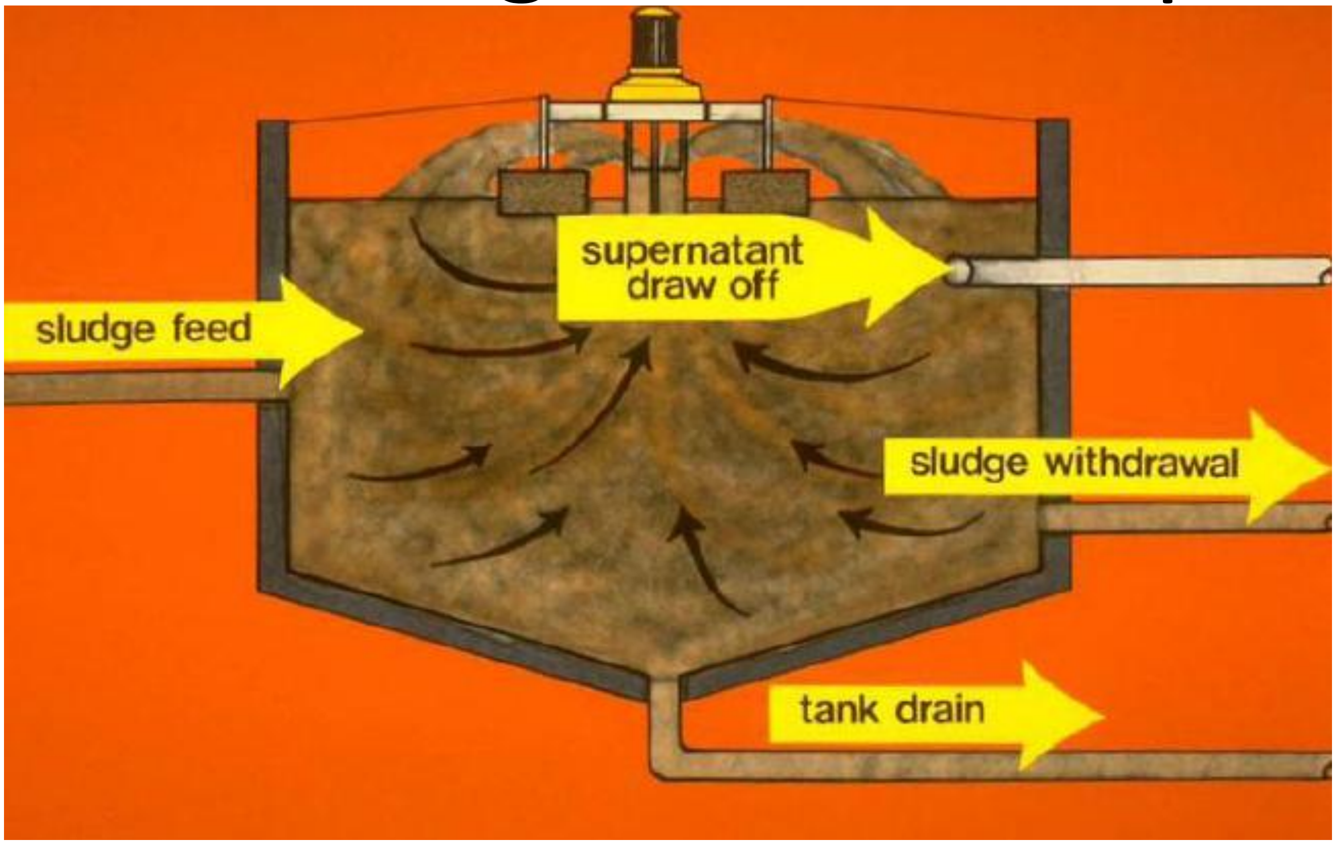
Aerobic Digestion

- The process uses organic matter, nutrients, and dissolved oxygen, and produces stable solids, carbon dioxide, and more organisms.
- The microorganisms which can only survive in aerobic conditions are known as aerobic organisms.
- This is the natural biological degradation and purification process in which bacteria that thrive in oxygen-rich environments break down and digest the waste.

Aerobic Digestion



Aerobic Digestion: Flow pattern



Supernatant: The liquid lying above a solid residue after crystallization, precipitation, centrifugation, or other process

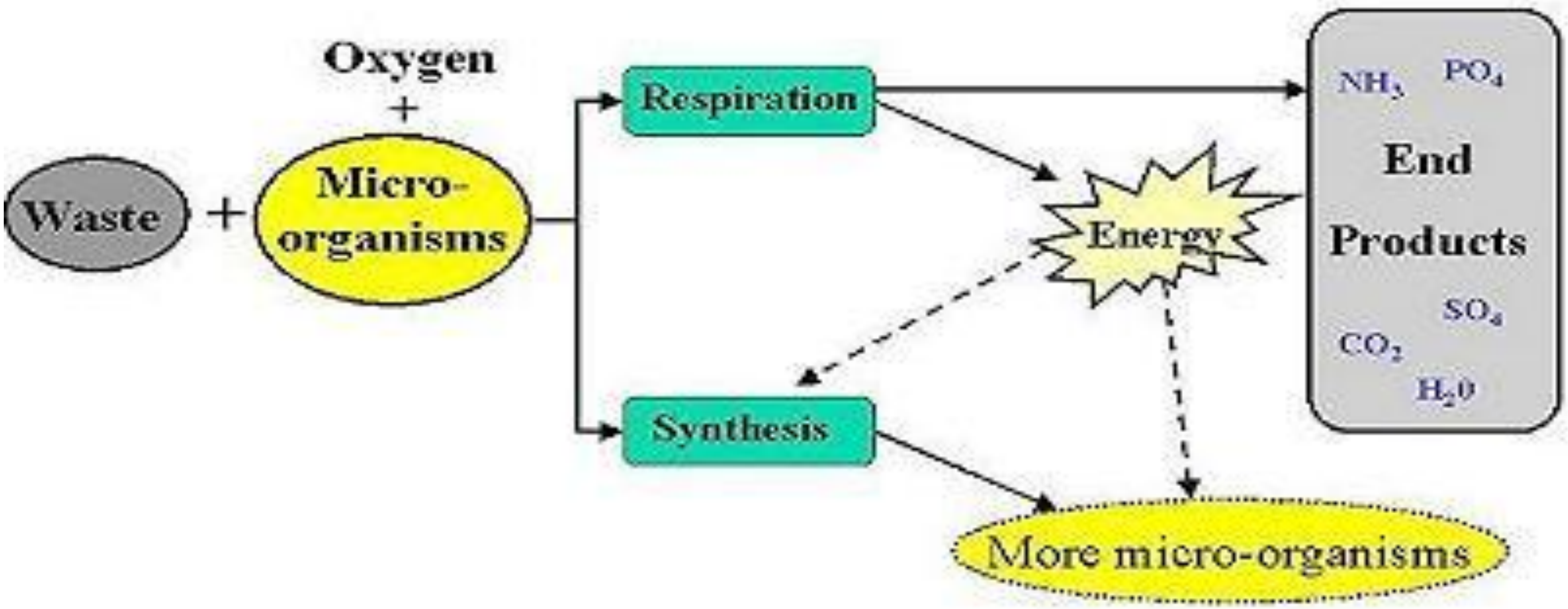
Aerobic Digestion

- In an aerobic system, such as composting, the microorganisms access free, gaseous oxygen directly from the surrounding atmosphere.
- The end products of an aerobic process are primarily carbon dioxide and water which are the stable, oxidised forms of carbon and hydrogen.
- Of all the biological treatment methods, aerobic digestion is the most widespread process that is used throughout the world.

Aerobic Digestion

- Under aerobic conditions, bacteria rapidly consume organic matter and convert it into carbon dioxide. Once there is a lack of organic matter, bacteria die and are used as food by other bacteria. This stage of the process is known as *endogenous respiration*. Solids reduction occurs in this phase. Because the aerobic digestion occurs much faster than anaerobic digestion, the capital costs of aerobic digestion are lower.
- However, the operating costs are characteristically much greater for aerobic digestion because of energy costs for aeration needed to add oxygen to the process.

Path of Aerobic Digestion



Aerobic Digestion: *Activated Sludge*

- In the activated sludge process, the dispersed-growth reactor is an aeration tank or basin containing a suspension of the wastewater and microorganisms, the mixed liquor.
- The contents of the aeration tank are mixed vigorously by aeration devices which also supply oxygen to the biological suspension .
- Aeration devices commonly used include submerged diffusers that release compressed air and mechanical surface aerators that introduce air by agitating the liquid surface.

Aerobic Digestion: *Activated Sludge*

- Following the aeration step, the microorganisms are separated from the liquid by sedimentation and the clarified liquid is secondary effluent.
- A portion of the biological sludge is recycled to the aeration basin to maintain a high mixed-liquor suspended solids (MLSS) level.
- The remainder is removed from the process and sent to sludge processing to maintain a relatively constant concentration of microorganisms in the system.

Advantages of Aerobic Digestion

- Aerobic bacteria are very efficient in breaking down waste products.
- Aerobic treatment usually yields better effluent quality that that obtained in anaerobic processes.
- The aerobic pathway also releases a substantial amount of energy.
- A portion is used by the microorganisms for synthesis and growth of new microorganisms.

Disadvantages of the Aerobic digestion

The major disadvantages of the aerobic digestion process are that :

(1) a high power cost is associated with supplying the required oxygen,

(2) a digested sludge is produced with poor mechanical dewatering characteristics,

(3) the process is affected significantly by temperature, location, and type of tank material and

(4) a useful by - product such as methane is not recovered

(5) More Sludge produced for disposal

Waste stabilisation ponds (WSPs)

- Waste stabilisation ponds (WSPs) are shallow man made basins into which wastewater flows through. After a retention time of many days, a well-treated effluent is discharged.
- They are a good alternative in countries where land and sunshine is plentiful.
- BOD, COD and SS removal efficiencies of 53%, 53% and 74% respectively and performances increased with an increase in temperature.
- WSPs can withstand shock loads without significant loss of efficiency in terms of BOD removal and bacterial pathogen removal, although nutrient removal by maturation ponds may be reduced.
- WSPs have been classified according to the availability of oxygen for the stabilization process as anaerobic, facultative and aerobic.
- There are three types of ponds; anaerobic ponds, facultative ponds and maturation/oxidation ponds.

Anaerobic ponds

- These serve as a pre-treatment step for high BOD organic loading with high protein, fat and suspended solids content, they more or less function like open septic tanks.
- They are normally 2-5 m deep sometimes up to 9 m with long detention times of 20 – 50 days.
- Where temperatures are higher than 20 0C, they have shorter retention times of 1 – 5 days and can achieve 60% to 75% BOD removal. A consortium of microorganisms, mostly bacteria, is involved in the transformation of complex materials into simple molecules.

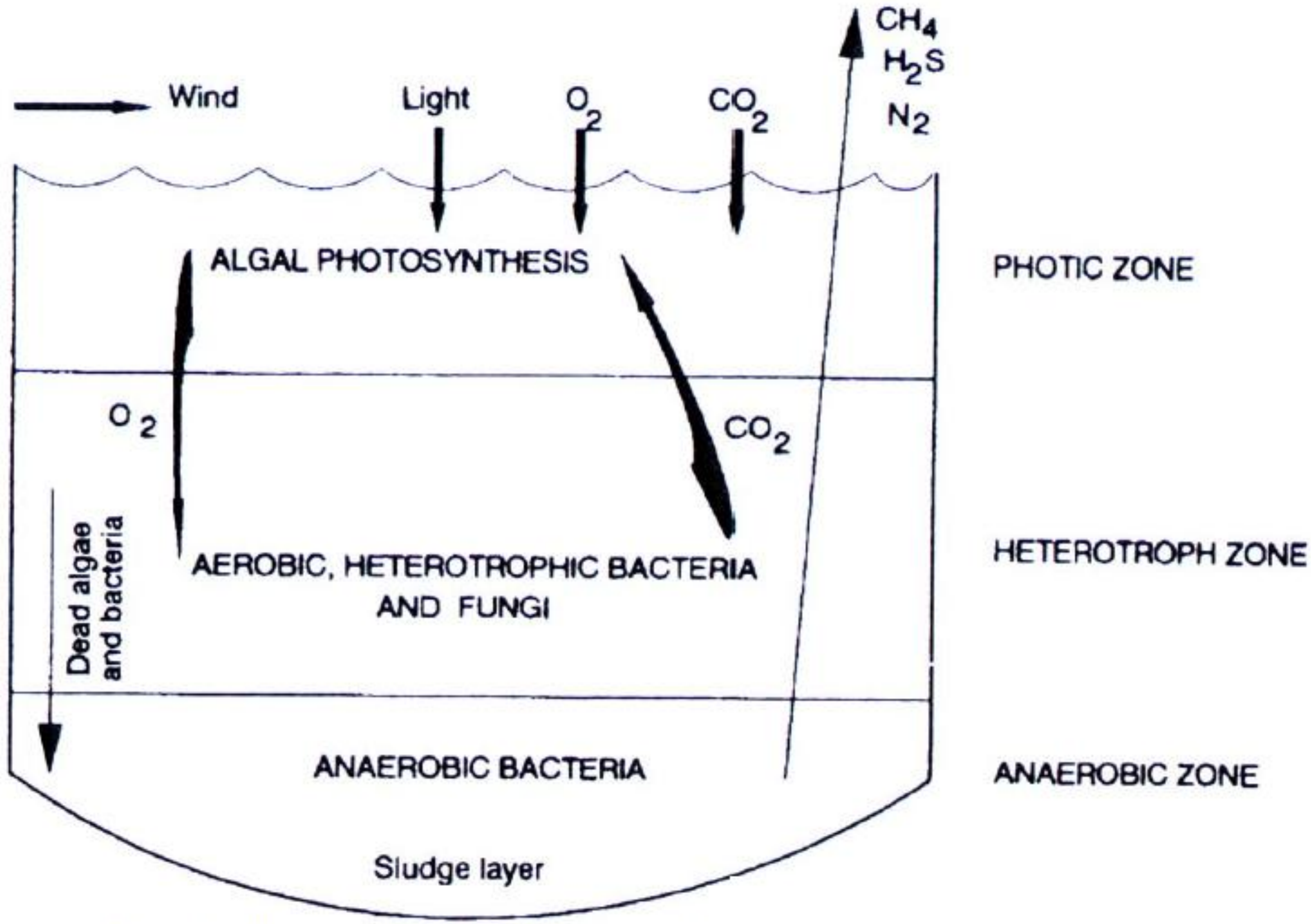
Anaerobic ponds

- Anaerobic biodegradation yields methane through methanogenesis, carbon dioxide (CO_2) and other gases such as hydrogen sulphide (H_2S).
- Anaerobic ponds require temperatures above 10 ^{o}C, and so work very well in warm climate

Facultative Ponds

- Facultative ponds can be primary or secondary. They are 1 – 3 m deep, designed for low BOD loading of 100 – 400 kg /ha/day and a retention time of 5 – 50 days.
- The biological wastewater treatment processes are carried out mainly by heterotrophic and autotrophic bacteria, algae and zooplankton, in a mixture of anaerobic, aerobic and facultative conditions.
- The biological activity in the facultative ponds can be classified into photic, heterotrophic and anaerobic zones

Facultative Ponds



Microbial activity in facultative ponds

Facultative Ponds

The Photic Zone

- This zone is aerobic, mainly dominated by algae, which are involved in nitrogen fixation, nutrient uptake through photosynthesis and therefore produce oxygen for the heterotrophic bacteria.
- Photosynthesis leads to an increase in pH, if alkalinity is low, and this favours phosphorus precipitation as calcium phosphate, and ammonium ion may be lost as ammonia.
- Good wind mixing ensures a more uniform distribution of BOD, DO, bacteria and algae and hence a better degree of waste stabilisation.

Facultative Ponds

Heterotrophic activity

- Heterotrophic bacteria are the principal microbial agents for degradation of organic matter. The aerobic activity produces CO2 and micronutrients for algae growth and utilises O2 produced by algae by wind mixing, as electron acceptor. The anaerobic activity results in the production of gases such as methane (through methanogenesis), hydrogen sulphide, carbon dioxide and nitrogen (through denitrification).

The anaerobic zone

- The degradation in this zone is similar to that described earlier in this leacture (using controlled mesophilic and thermophilic conditions in industrial tanks).

Maturation/Tertially Ponds

- A series of maturation ponds receives effluent from facultative ponds, the size and number is governed by the bacteriological quality of the final effluent.
- These are 1 – 2 m deep and has a significant role in pathogen and nutrient removal but less significant in BOD removal.
- Oxygen is typically supplied by surface reaeration.

Pathogen and Parasite Removal in WSPs

- Bacterial die-off (pathogen removal) is dependent on long retention times, high pH and DO generated by algal photosynthesis, necessary for photo-oxidative damage, which in turn is promoted by high light intensity. Zooplankton predation is also important.
- The protozoan cysts and helminthes eggs are removed by sedimentation mainly in anaerobic and facultative ponds.

Nutrient Removal in WSPs

- The nutrient removal processes taking place in the ponds are purely biological processes, in which diversified groups of organisms are responsible i.e. bacteria, fungi and algae.
- The origin of these microorganisms could be from the air, soil, and animals living near the system and the wastewater itself.
- In waste stabilisation ponds, nitrogen removal is both assimilative (by algal uptake) and dissimilative (through nitrification and leading to denitrification and ammonification).

Factors affecting the Stabilisation Process, growth and activities in the WSPs

- Natural purification of wastewater by stabilisation ponds begins immediately after wastewater enters a pond. Settleable solids, suspended solids and colloidal particles either settles to the bottom of the pond by gravity or may be precipitated by action of soluble salts due to the rise in pH. Soluble materials are oxidised by bacteria. Settled organic matter is converted to inert residue and soluble substances diffuse into the bulk of the water above, where further decomposition is carried out by bacteria. Degradation of dead bacterial biomass with release of ammonia promotes algae growth.

Factors affecting the Stabilisation Process, growth and activities in the WSPs

- The stabilisation processes in WSPs is dependent on various factors. These include types of ponds (anaerobic, facultative or maturation).
- The type of ponds is generally determined by pond depth. In deeper ponds, light cannot penetrate the water because of the excessive water depth; algae photosynthesis is therefore inhibited, rendering the microbiological activity to be more heterotrophic than photosynthetic.
- Reduction of pathogenic organisms may be minimized as a result of inadequate exposure to direct sunlight. On the other hand maturation ponds are shallow (0.5 -1 m) and are good in destruction of faecal bacteria.

Factors affecting the Stabilisation Process, growth and activities in the WSPs

- Detention time is another important factor. Algae require sufficient time to grow and multiply through binary fission. Each pond cell (compartment) should provide a minimum retention time to avoid premature cell washout.
- Detention time will also influence the achievement of the desired level of coliform and organic matter removal.
- Sufficiently long detention times (dependent on type of pond) should be provided to allow parasites (faecal and helminths eggs) to die off and sink to the bottom and to allow sufficient nutrient removal and organic matter transformations.

Factors affecting the Stabilisation Process, growth and activities in the WSPs

- Temperature influences the organism yield coefficient, die-off rates, availability of nutrients and dominant species, all of which are influencing the organic matter decomposition.
- Temperature does not only influence the degradation of soluble matter in the supernatant, but also the settled sludge that is most often not considered during the design. At temperatures below 17 ^oC fermentation may be neglible, and above 23 ^oC it is so intense that sludge may float to the surface.
- Light intensity has a great influence on photosynthesis, which in turn can influence the stabilisation process. As the concentration of algae increases, light penetration decreases so that the phytoplankton becomes self-shading, and thereby restricting photosynthesis in the lower layers.

Wastewater Stabilisation Ponds in Ruai

- Birds at the sewage inlet

Wastewater Stabilisation Ponds in Ruai: Automated robot prepares to remove harmful solids from influent

Wastewater Stabilisation Ponds in Ruai: Gotcha! Trapped polythenes etc are being removed from the influent

Wastewater Stabilisation Ponds in Ruai:
Anaerobic pond (about 5 m deep!)

Wastewater Stabilisation Ponds in Ruai:
Facultative pond (1-2m deep)

Wastewater Stabilisation Ponds in Ruai: Excuse me... who is living in the sewage pond?

Wastewater Stabilisation Ponds in Ruai:

One of the maturation ponds

Wastewater Stabilisation Ponds in Ruai: Treated sewage about to be discharged! (Notice the green colour)

Wastewater Stabilisation Ponds in Ruai: Water from treatment being discharged to Nairobi River!