Energy Conversion Technologies (Biomass and Coal)

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Lecture 21

Biochemical conversion processes - Anaerobic Digestion in Landfills

Good morning everyone.

Welcome to this first lecture of the module 5. In this lecture, we will discuss about the biochemical conversion processes. In that we will discuss about anaerobic digestion in landfills, landfill gas and biogas, bioconversion into biogas, single two-stage anaerobic digestion system, wet and dry fermentation techniques and integrated centralized co-digestion plant concept.

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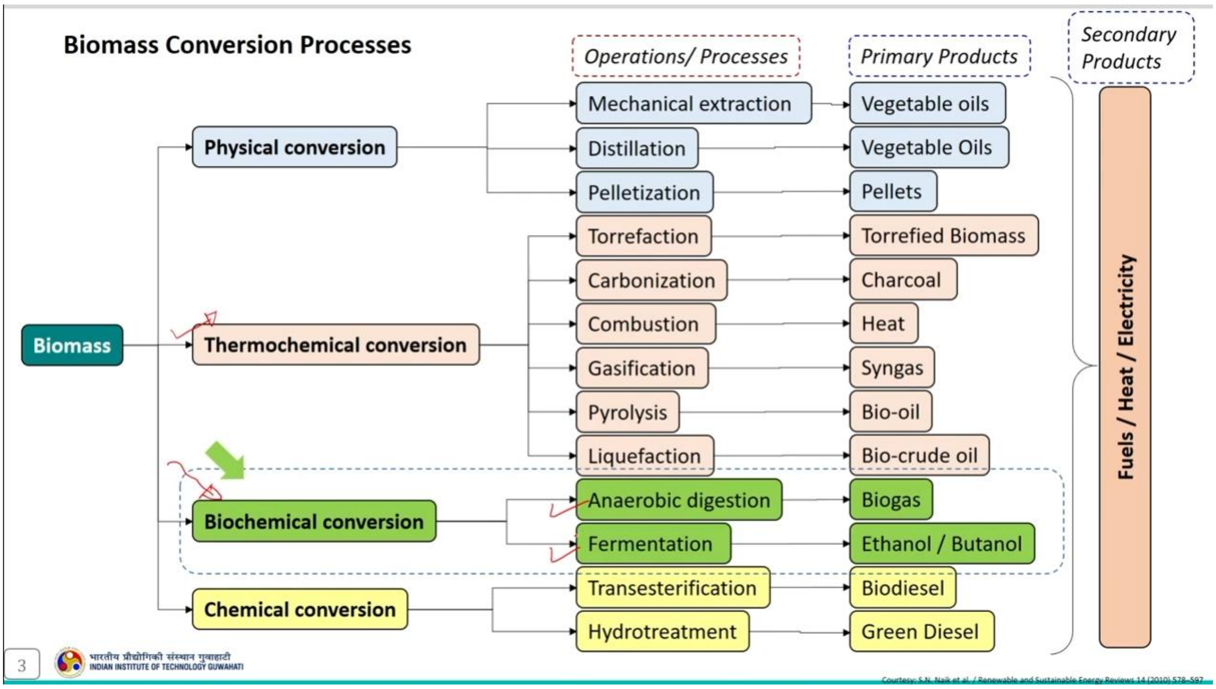

So, this chart here depicts the different biomass conversion processes. Among these different biomass conversion processes, we already discussed about the thermochemical conversion processes in previous module. However, in this module, the focus mostly would be on biochemical conversion processes that is anaerobic digestion and fermentation technique. Biochemical conversion includes technologies using microbial processes to convert biodegradable waste into liquid or gaseous fuel and other value added products. Two main pathways of biochemical conversion, first is anaerobic digestion and alcoholic fermentation. So, let us discuss about these two different pathways one by one.

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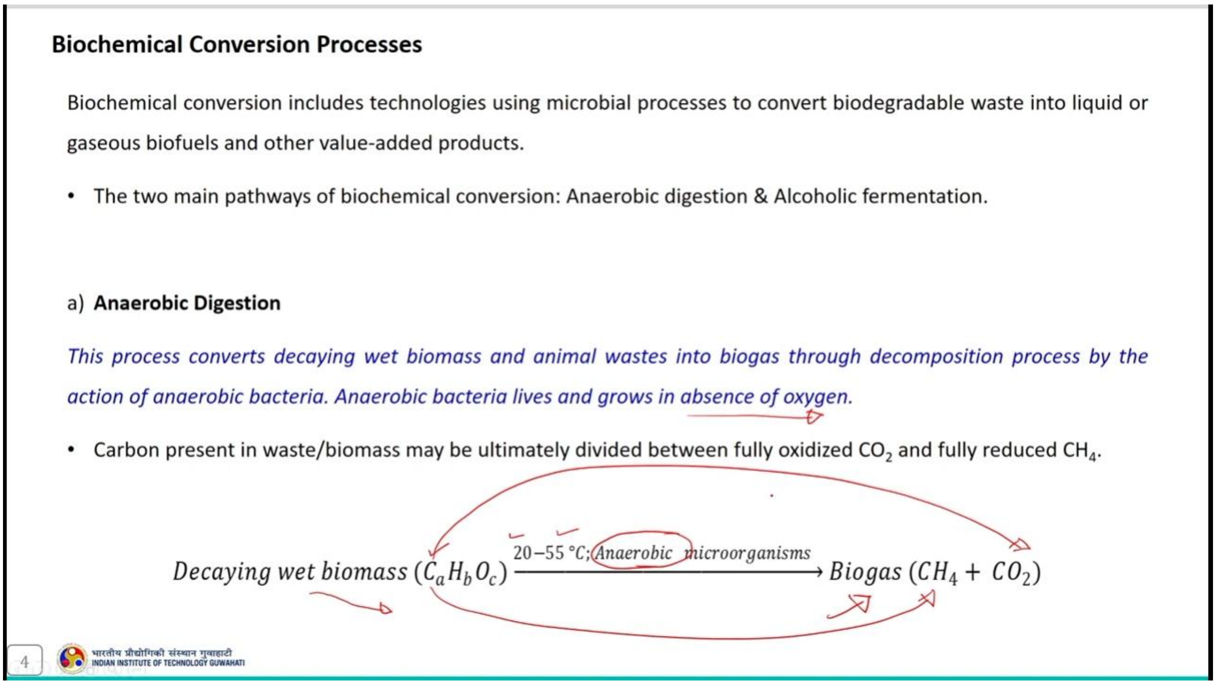

So, let us begin with the anaerobic digestion. In anaerobic digestion process, it converts the decaying wet biomass and animal waste into biogas. And it happens through the decomposition process by the action of anaerobic bacteria. In this anaerobic bacteria leaves and grows in absence of oxygen. And this process carried out at a temperature range of around 20 to 55 °C. Carbon present in waste or we can say bio-based feedstock or also the animal waste may be ultimately divided between fully oxidized carbon dioxide and fully reduced to form methane. So, these are the two ways how the methane and carbon dioxide production takes place in the anaerobic digestion process.

$$Decaying\ wet\ biomass\ (C_aH_bO_c) \xrightarrow{20-55\ °C;\ Anaerobic\ \ microorganisms} Biogas\ (CH_4 +\ CO_2)$$

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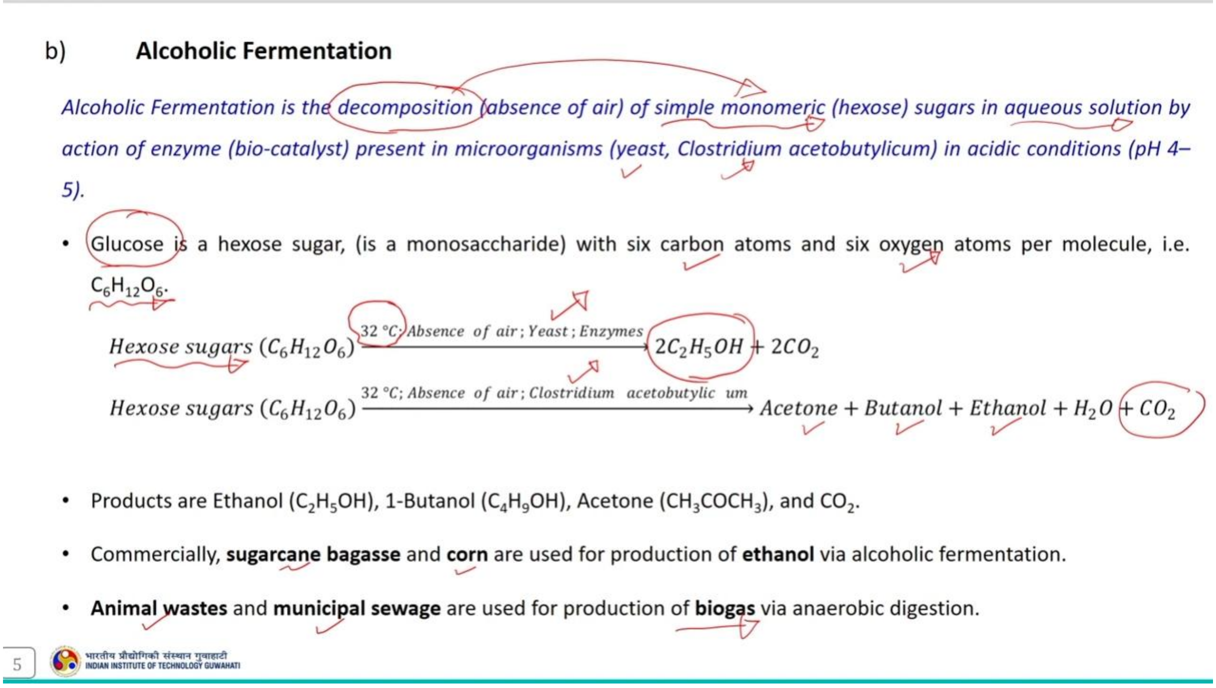

However, the alcoholic fermentation, it is a decomposition of the simple monomeric sugars. In case of anaerobic digestion, the wet biomass, decaying biomass or the animal waste directly is being used as a feed material for the anaerobic digestion process. However, in the alcoholic fermentation, the decomposition of the simple monomeric sugars in aqueous solution by the action of enzyme present in the microorganism and mostly the enzyme used are yeast or *clostridium acetobutylicum* in acidic condition where the pH is maintained between 4 to 5.

Mostly this alcoholic fermentation carried out at temperature of around 32-35 °C. And the hexose sugar in the glucose with 6 carbon atoms and 6 oxygen atoms per molecule that is $C_6H_{12}O_6$. It is termed as a hexose sugar is fermented to produce ethanol using yeast. While in case of clostridium it gives mixture of products that is acetone, butanol and ethanol.

$$Hexose\ sugars\ (C_6H_{12}O_6) \xrightarrow{32\ °C;\ Absence\ of\ air;\ Yeast;\ Enzymes} 2C_2H_5OH + 2CO_2$$

$$Hexose\ sugars\ (C_6H_{12}O_6) \xrightarrow{32\ °C;\ Absence\ of\ air;\ Clostridium\ acetobutylic\ um} Acetone + Butanol + Ethanol + H_2O + CO_2$$

Commercially, sugarcane, bagasse and corn are used for the production of the ethanol via alcoholic fermentation technique. And animal waste, municipal sewage, sludge or bio-based feedstocks are used for the production of biogas via anaerobic digestion process. And that is a small difference between these two processes.

Here the animal waste, the municipal sewage, sludge or the bio-based feedstock are directly being used as a charged material for the anaerobic digestion process. Whereas in case of the alcoholic fermentation process the monomeric sugars are used for the fermentation to take place and produce alcoholic mixture or single alcohol as a product.

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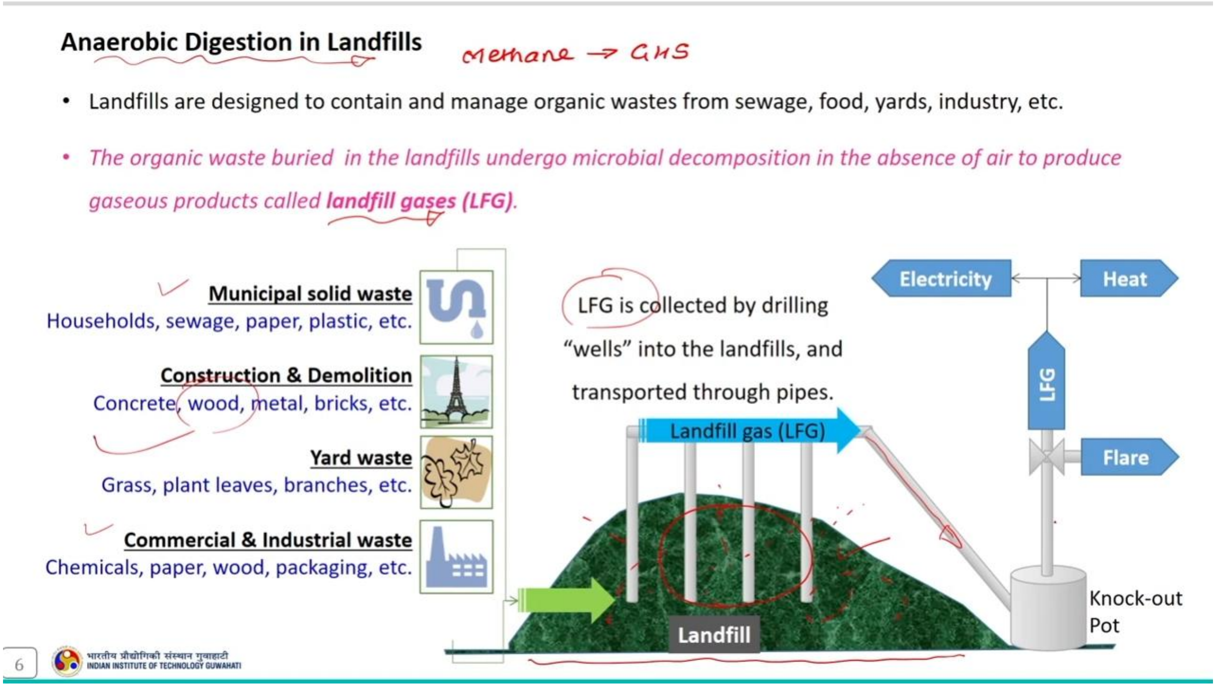

There is another important concept in the area of anaerobic digestion is anaerobic digestion in landfills. Anaerobic digestion is a powerful greenhouse gas with a substantial amount being derived from the unutilized methane production from the landfill sites. And its recovery therefore not only results in the stabilization of these landfill sites, but allowing faster reuse of the land and also serves to lessen the impact of atmospheric methane emission on the global warming.

Anaerobic digestion in landfill is brought about by the microbial decomposition of organic matter in the refuse. The organic waste which is buried in this landfill undergoes the microbial decomposition that is also in absence of air or oxygen to produce gaseous product called landfill gases. Since the oxygen is inaccessible to the organic material which is available in this landfill site so it provides a perfect environment for the anaerobic digestion process to occur. As a result it releases gas in the form of landfill gases. The organic waste in the landfill sites are mostly sourced from municipal solid waste, yard waste, the wood comes out from the construction and the demolition sector and the commercial and the industrial waste which undergoes the decomposition to produce the landfill gas. This landfill gas is collected by drilling wells into the landfills and transported through the pipes. The produced gas after certain cleaning treatment can be combusted to produce heat or can be used for the electricity generation or flared to reduce the emissions.

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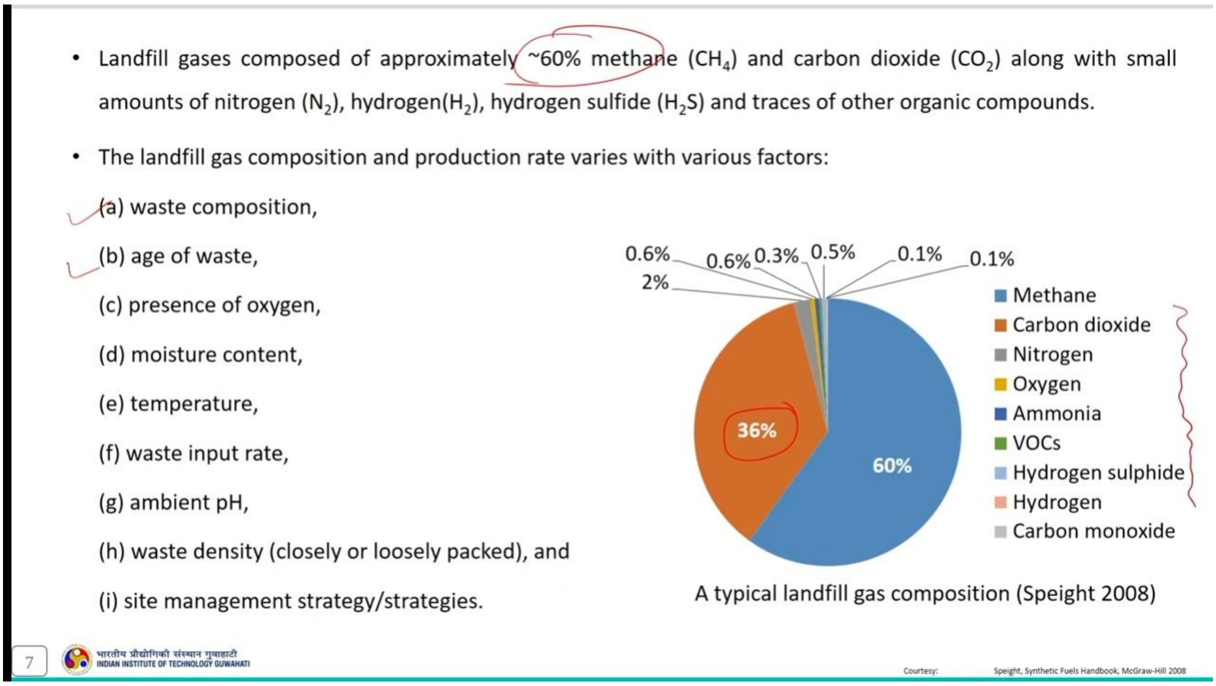

And this landfill gas mainly composed of approximately 60% methane and 36% around CO_2 with traces of other gases as listed here. The landfill gas composition and the production rate it varies with the several factors that is waste composition at the site, age of the waste, presence of oxygen and the moisture content, temperature as well as the waste input rate, ambient pH, the density of the waste as well as the site management strategies. All these factors are responsible for the gas composition as well as the production rate at the landfill site.

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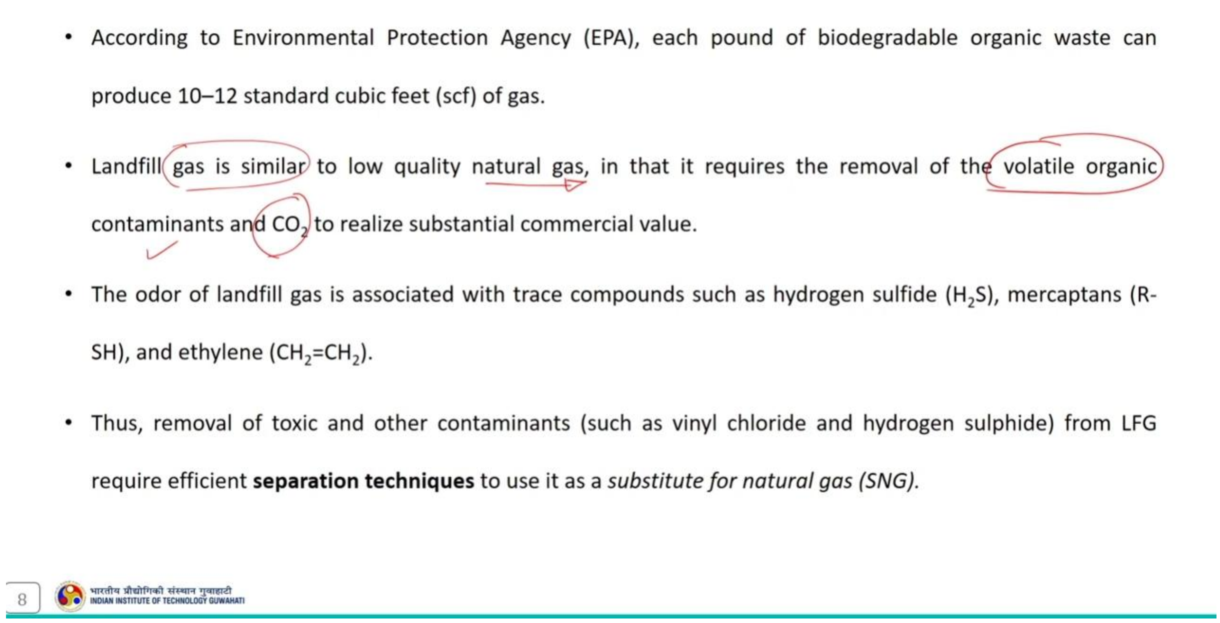

According to the environmental protection agency each pound of bio-degradable organic waste can produce about 10 to 12 standard cubic feet of gas. And this landfill gas is similar to the low quality natural gas and in that it requires the removal of only the volatile organic contaminants and the CO2 to realize the substantial commercial value of this landfill gas. The order of landfill gas is mainly associated with the trace of compounds that is mainly mercaptans, hydrogen sulphide and ethylene which need to be removed to make it an odorless gas. Apart from that the removal of toxic and the other contaminants from the landfill gas required efficient separation techniques to use this gas as a substitute for a natural gas.

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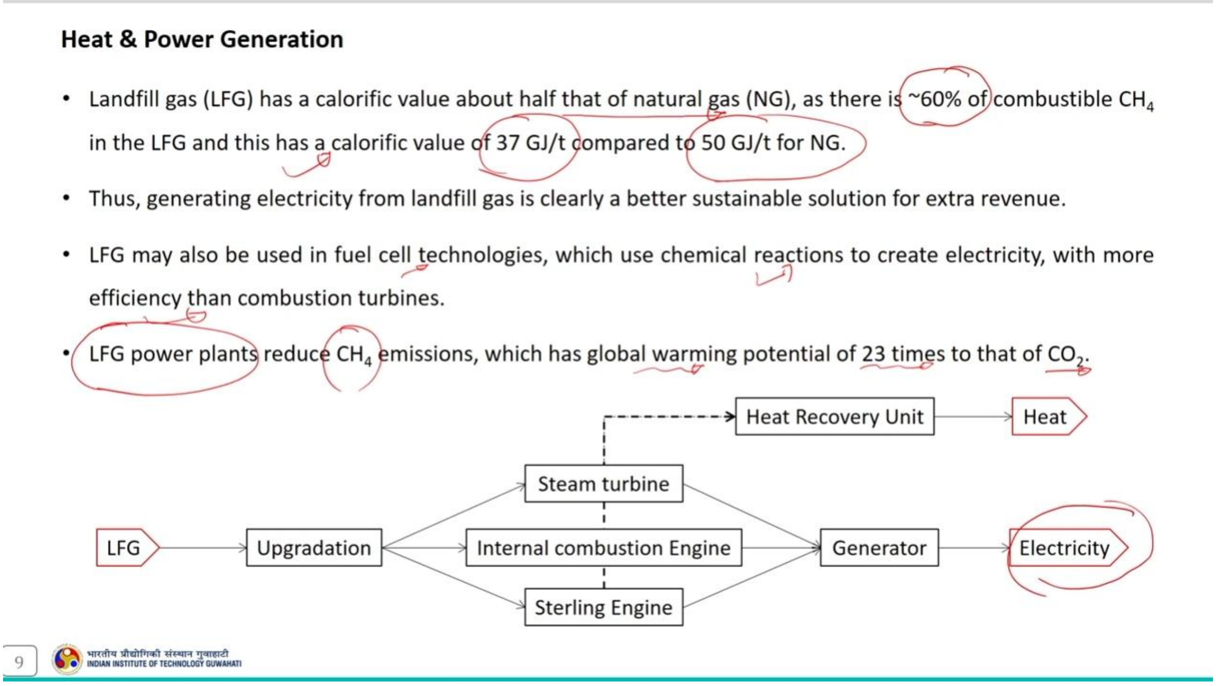

After the removal of toxic and the other contaminant from the landfill gas, the landfill gas can be used as a substitute for the natural gas because the landfill gas has a calorie value of about half that of the natural gas as there is 60 percent of the combustible methane present in the landfill gas. This has a calorie value of around 37 gigajoule per ton compared to that of the 50 gigajoule per ton for the natural gas. And thus this landfill gas can be used for the electricity generation and it is clearly a better sustainable solution for the extra revenue. Similarly this landfill gas may be used in fuel cells technology which uses chemical reactions to create the electricity with more efficiency than the combustion turbines and if required even the fuel cell stations can be installed near the landfill site. The landfill gas produced from the specific sites after purification may act as a fuel for the fuel cell to produce the electricity. Apart from that the landfill gas power plant reduces methane emissions which has a global warming potential of 23 times to that of the CO_2. And if you recollect we discussed this concept of global warming potential of different greenhouse gases in one of the lecture in the module 1.

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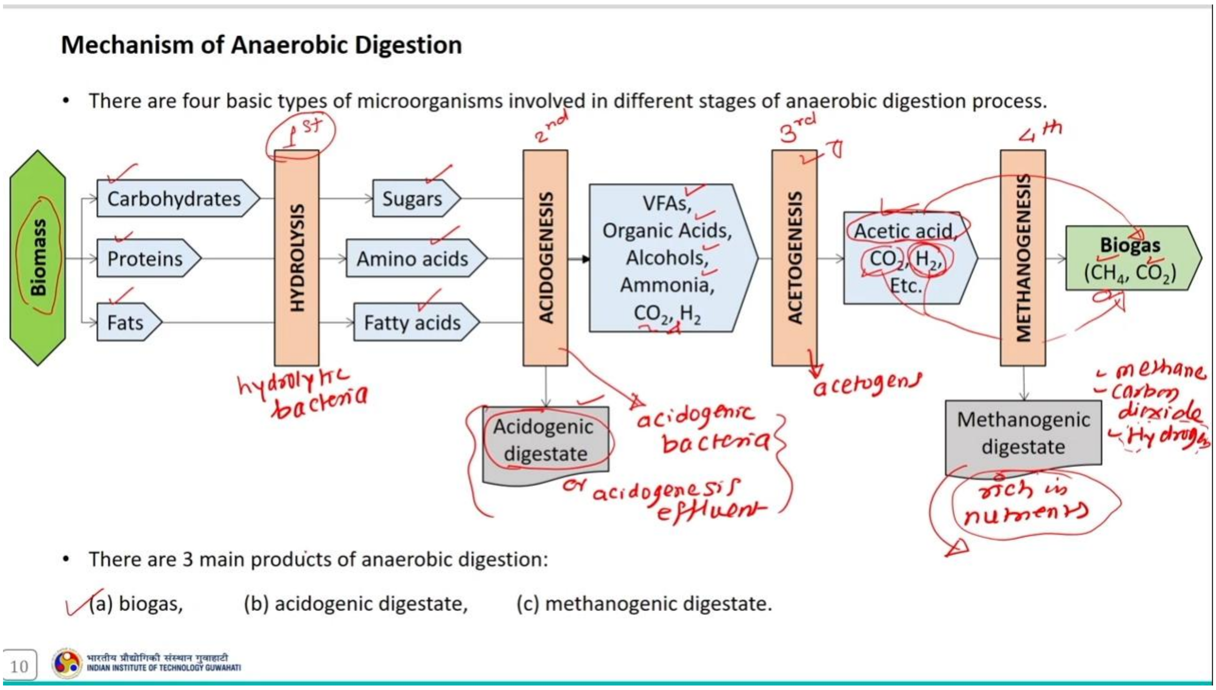

So, let us discuss about this mechanism of anaerobic digestion process. There are 4 different types of microorganisms are involved in the different stages of anaerobic digestion process. So let us discuss about this different stages of anaerobic digestion one by one. This schematic here, it represents the mechanism of anaerobic digestion process. At first the biomass that is carbohydrate, proteins and fats are hydrolyzed in stage 1. So here it is a stage 1 in which the hydrolytic bacteria first break down the carbohydrate, proteins and fats present in the biomass feedstock into sugars, amino acids and fatty acids. Acidogenesis is the second stage in the anaerobic digestion process where the complex organic matter is broken down into simpler compound by acidogenic bacteria. So here this process carried out in presence of acidogenic bacteria and these are also termed as an acid former. The products of the acidogenesis are primarily the volatile fatty acids, organic acids, alcohol, ammonia, carbon dioxide and hydrogen. And it also produces the liquid by-product known as acidogenic digested or acidogenesis effluent. This is also termed as acidogenesis effluent. This acidogenic digested is a stable organic material comprised largely of the lignin and chitin but also a variety of the mineral component in a matrix of the dead bacterial cell. And even some plastic may be present in its composition.

Acetogenesis is a biological process in anaerobic digestion and that occurs after the acidogenesis and before the methanogenesis step and this is called as a third stage in the anaerobic digestion process. And during this acetogenesis specific group of microorganism called acetogens convert the product of acidogenesis such as short chain fatty acids and alcohols into acetic acid, carbon dioxide, hydrogen and other short chain organic acids.

Followed by that is the methanogenesis stage that is termed as a fourth stage of the anaerobic digestion process and it is also the final stage of anaerobic digestion process. It is a biological process carried out by the group of microorganisms called methanogens. And in case of the methanogenic bacteria it finally produces methane from acetic acid, hydrogen and carbon dioxide and this stage occurs in two ways. Similarly the aceticlastic methanogens consume the acetic acid available in the slurry as their substrate to convert into methane and CO_2. Similarly the hydrogenotropic methanogens utilize the hydrogen and CO_2 as their substrate to produce methane and this is called as a reduction reaction where the carbon dioxide and hydrogen reduce to form methane, whereas in this case the acetic acid converts into the methane and carbon dioxide. This biogas, it is a mixture comprising mostly of methane, carbon dioxide but also contain some amount of hydrogen and occasionally trace levels of hydrogen sulphide. And this hydrogen in the biogas mostly comes from this particular stage the hydrogen which remains untouched here will come out as a product along with the biogas. But its percentage is relatively less compared to that of the methane and the carbon dioxide in its final composition.

This methanogenic digestate is a rich in nutrients and can be an excellent bio fertilizer. It also depends on the quality of the material being digested in the digester. In that case also this particular digested slurry also need certain pre-processing stage to remove the toxic contaminant as well as the other contaminant from this digested slurry before being used for the sustainable agriculture. The three main product of the anaerobic digestion process includes biogas, acidogenic digestate and the methanogenic digestate.

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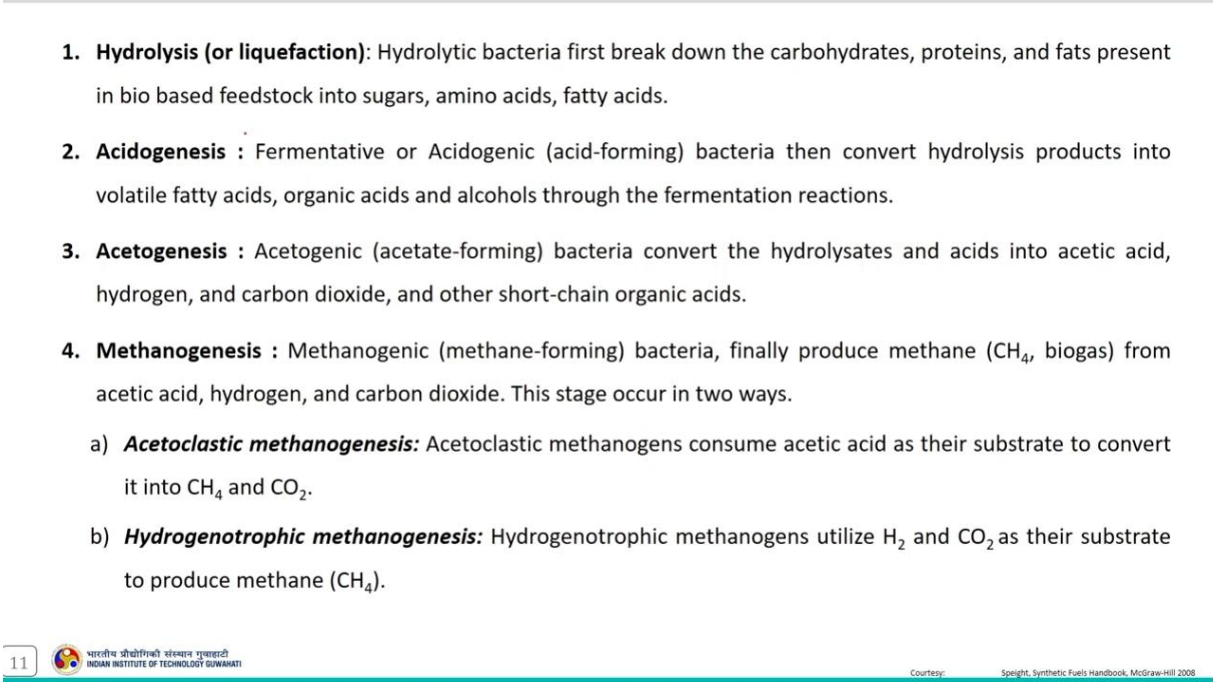

Although we discussed in brief about these stages which occurs in the anaerobic digestion process however for your convenience it has been reproduce here as a reading text.

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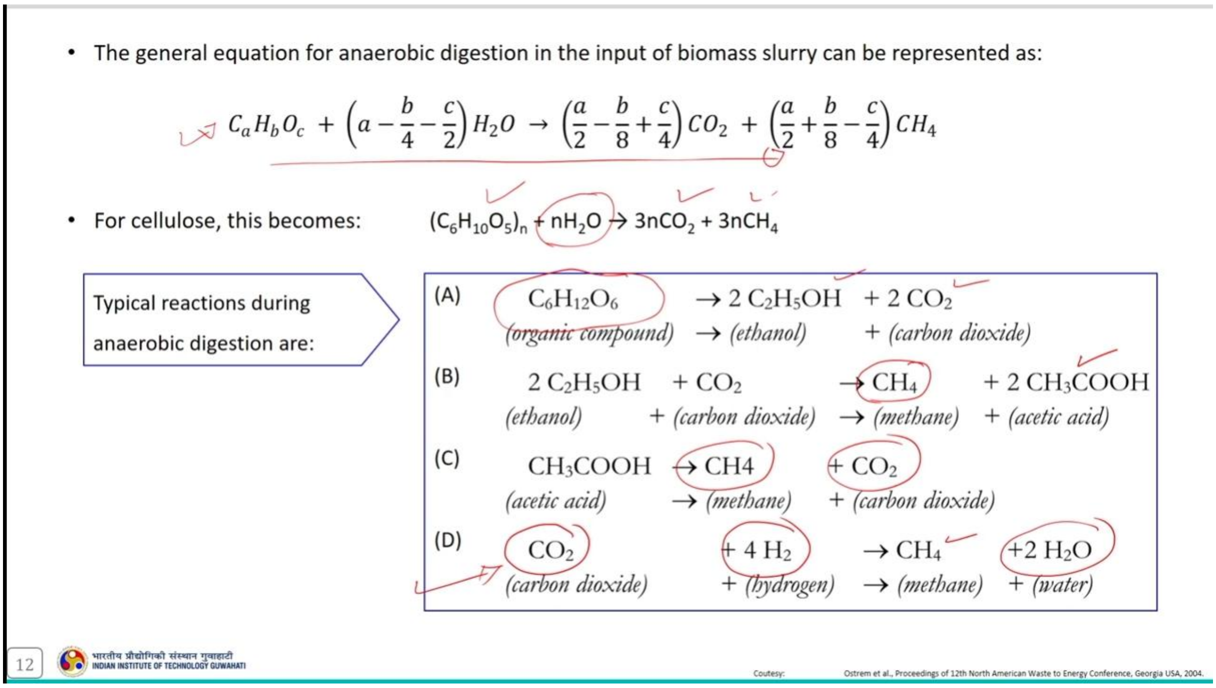

And this equation here it represent the general equation of the anaerobic digestion in the input of biomass slurry and it can be represented in this way.

$$C_aH_bO_c + \left(a - \frac{b}{4} - \frac{c}{2}\right)H_2O \rightarrow \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4}\right)CO_2 + \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4}\right)CH_4$$

Similarly for the cellulose this becomes like this, this is cellulose which undergoes the decomposition to produce methane and the CO_2 and typical reaction during the anaerobic digestion include decomposition of the organic fraction present in the feedstock material to produce ethanol and the CO_2. The produced ethanol and the carbon dioxide further converts into the methane and acidic acid. So produced acidic acid in this stage converts into the methane and carbon dioxide and in the last as we discussed earlier the carbon dioxide and hydrogen get reduced to form methane and water.

So this is the one of the important stage in the anaerobic digestion process where the hydrogen gets reduced to form the methane and as we discussed earlier some traces of hydrogen can be found in the composition of the biogas and that is mainly because if the reduction is not complete in that case some of the hydrogen may come out as it is along with the biogas. And this composition of the biogas it mainly depends on the quality of the material which is being digested in a digester.

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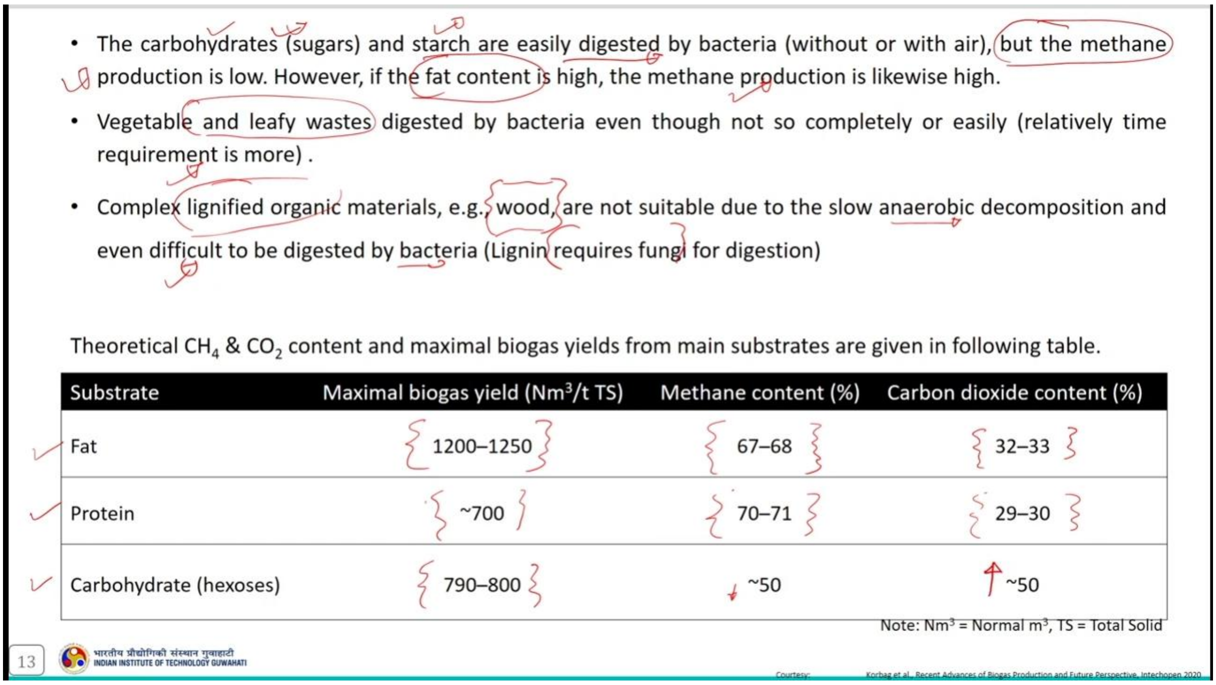

- The carbohydrates (sugars) and starch are easily digested by bacteria (without or with air), but the methane production is low. However, if the fat content is high, the methane production is likewise high.
- Vegetable and leafy wastes digested by bacteria even though not so completely or easily (relatively time requirement is more) .
- Complex lignified organic materials, e.g., wood, are not suitable due to the slow anaerobic decomposition and even difficult to be digested by bacteria (Lignin requires fungi for digestion)

Theoretical CH_4 & CO_2 content and maximal biogas yields from main substrates are given in following table.

Substrate	Maximal biogas yield (Nm^3/t TS)	Methane content (%)	Carbon dioxide content (%)
Fat	1200–1250	67–68	32–33
Protein	~700	70–71	29–30
Carbohydrate (hexoses)	790–800	~50	~50

Note: Nm^3 = Normal m^3, TS = Total Solid

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Courtesy: Korbag et al., Recent Advances of Biogas Production and Future Perspective, Intechopen 2020

For example, if the carbohydrates and starch are used as a feed material in the digester although we know these are easily digested by the bacteria but then the methane production would be less if the source material contain maximum amount of the carbohydrate and starch. However, if the fat contained in the feed material is relatively high then the methane production is also likewise high from such feed material. Vegetable and the leafy waste can be digested by bacteria even though not so completely or easily but it takes literally longer time for the digestion to complete.

Similarly the complex lignified organic materials example the wood is not suitable due to the slow anaerobic decomposition and even difficult to be digested by the bacteria because lignins require fungi for the digestion. Hence excess percentage of the woody material in the digester may result in the lower biogas production. Some theoretical methane and the carbon dioxide contained and the maximum gas yield from main substrates are given here in this tabular form that is fat, protein and carbohydrate. If the fat contained is relatively high as we discussed earlier then the biogas yield will be maximal even the methane contained in the biogas will be in the range of around like 67 to 68% and the carbon dioxide in this range. However, if the protein contained is high then the maximal biogas yield would be around this much and the methane contained varies in this range followed by the carbon dioxide contained.

However, if the carbohydrate contained is high then the maximal gas yield can reach up to this extent. However, the methane contained is marginally low in case of carbohydrate containing material and the carbon dioxide contained is significantly high compared to the other substrate.

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Properties of biogas:

Composition	50–75% CH_4, 25–50% CO_2, 0–10% N_2, 0–1% H_2, 0–3% H_2S, 0–2% O_2, etc.	
Calorific value	With 60–70% CH_4 (30–40% CO_2)	22–28 MJ/m^3 (650–750 Btu/ft^3)
	Without CO_2	34–35 MJ/m^3
Octane rating	With 30–40% CO_2	110
	Without CO_2	130
Ignition temperature		650 °C
Air to methane ratio for complete combustion (by volume)		10:1 approx.
Explosive limits (% biogas in air)(by volume)		5–10

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Courtesy: Speight, Synthetic Fuels Handbook, McGraw-Hill 2008

And this table here it depicts the properties of the biogas. The composition of the biogas includes the methane in the range of 50 to 75%, carbon dioxide in the range of 50 to 25% with traces of other gases and the calorie value of the biogas if it contains around 60 to 70% of the methane and the remaining is carbon dioxide then its calorie value range from 22 to 28 MJ/m^3. However, without CO_2 that is after removing the carbon dioxide from the biogas stream the purified biogas has a calorie value in the range of 34 to 35 MJ/m^3. Similarly, is the octane rating with CO_2 it is around 110 and without CO_2 it is around 130. Ignition temperature is around 650 degree Celsius and air to methane ratio for the complete combustion by volume is 10 is to 1 approximately and the explosive limit percentage biogas in air by volume is in the range of 5 to 10%. So this depicts the properties of the biogas.

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Comparison of biogas with other gaseous fuels

Fuels	Biogas (60% CH_4)	Natural Gas	LPG	CH_4	H_2	CO
HHV (MJ/m^3)	**24.22**	42.6	26.5	39.8	12.7	12.6
LHV (MJ/m^3)	**22.35**	37.3	24.4	35.8	10.8	12.6
HHV (MJ/kg)	**21.06**	55.0	49.3	55.5	141.7	10.2
LHV (MJ/kg)	**19.44**	48.0	45.5	50	120	10.2
Density (kg/m^3) @ 15 °C	**1.150**	0.777	0.537	0.716	0.090	1.240

- Typically, biogas required for cooking is about 0.227 m^3/person/day.
- Gas required for lighting a 100 CP (candle power) mantle lamp is 0.126 m^3/hour.
- A plant producing 2 m^3/day of biogas could replace a fuel equivalent of 28 kg of LPG (~2 standard cylinders) per month.

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Courtesy: Khan, Non Conventional Energy Resources, McGraw Hill, 2017

Similarly, if you try to compare the biogas with other gaseous fuel it can be seen that biogas has relatively lower calorific value compared to that of the other gases. However, the density of the biogas is relatively higher than that of the other gases and typically the biogas which is required for cooking is about 0.227 meter cube per person per day. And the gas required for the lighting a 100 CP lamp that is called as a candle power mantle lamp is 0.126 meter cube per hour. A plant which is producing around 2 meter cube per day of the biogas could replace a fuel which is equivalent to 28 kg of LPG that is substantially high and equals to around 2 standard cylinders per month. And these are the basic advantage of conversion of waste into the biogas because even the 2 meter cube per day of the biogas could replace a fuel equivalent to around 28 kg of LPG. So the waste which causes environmental load as well as the emission can be digested in a confined container to produce the biogas which after purification can suitably use for the application purpose.

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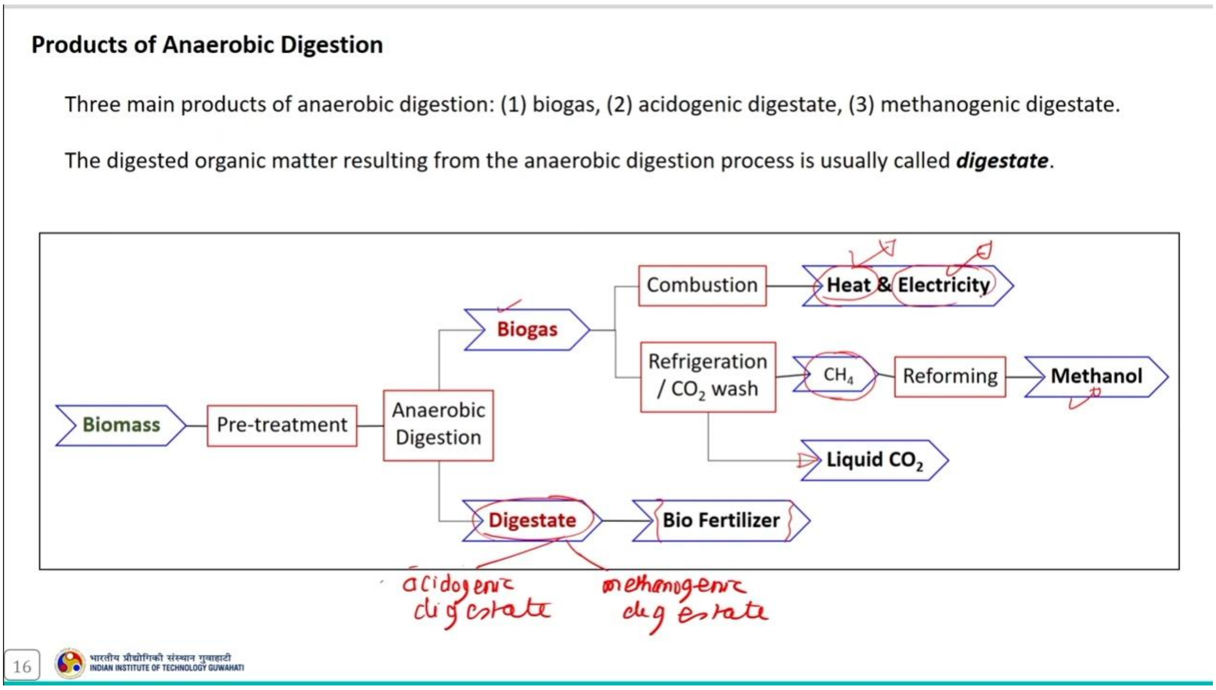

And this schematic here it represent the product of the anaerobic digestion process, 3 main product of the anaerobic digestion process includes the biogas and the digestate that is acidogenic digestate and the methanogenic digestate.

The digested organic matter resulting from this anaerobic digestion process that is at the end of the anaerobic digestion process is called as a digestate. And this digestate obtained at the end of the anaerobic digestion process can be used as a bio fertilizer but after certain pre-processing stage for example after removal of the toxic and other contaminants which are harmful that need to be removed from the digested before applying it as a sustainable bio fertilizer. And the biogas obtained from the anaerobic digestion process can directly use for the heating purpose that is in boiler, dryer, kiln even for the cooking purpose and even for the co-generation or the biogas can also be used for the generation of the electricity. The produced biogas can be separated into methane and the CO_2 so the separated CO_2 can be used to produce the liquid CO_2 and the purified methane can be converted into a synthetic fuel that is methanol. So the biogas obtained from the anaerobic digestion process has wide range of application it can be used for heating or it can be used for the electricity generation it can be diverted to produce a synthetic fuel that is methanol or the co2 which is separate out from the biogas can be converted into a liquid CO_2.

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Landfill Gas & Biogas

- Landfill gas and biogas are both forms of gas produced through the decomposition of organic matter. However, there are some key differences between the two process:

	Landfill gas	Biogas
Source of Production	Organic waste from food, yard, and paper, decomposes in a landfill in anaerobic conditions producing a mixture of gases called **landfill gas**.	**Biogas** is produced through a controlled anaerobic digestion of organic matter, such as agricultural waste, manure, sewage sludge, or energy crops.
Production Process	Landfill gas is captured and collected by installing gas collection systems, including pipes and wells. It is then typically treated and used as a source of energy or flared to reduce emissions.	Biogas is produced in an anaerobic digester, which is a sealed tank or system. It can be collected, purified, and used as a renewable energy source for electricity generation, heating, or vehicle fuel.
Composition & Impurities	Typically has a lower CH_4 content ~40-65%, with the remainder being mostly CO_2. It contain small amounts of N_2, O_2, H_2S, VOCs, H_2O, etc.	Biogas has higher quality compared to landfill gas. Typically, CH_4 = 70%+, with remainder being CO_2. It contain trace impurities depending on feed.
Environmental Impacts	Landfill gas accumulate inside buildings constructed on/close to a landfill site, which is a greenhouse gas contributing to climate change.	It has environmental benefits due to the controlled production and utilization.

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As we discussed about the landfill gas and the biogas both these gases are produced from the decomposition of the organic material. However there are some key differences between these two processes. So let us discuss about these key differences in these two processes that is landfill gas and biogas. So in case of landfill gas the source material includes the waste from food, yard and paper which decomposes in the landfill. So these are anaerobic conditions producing a mixture of gases and that is called as a landfill gas however in case of the biogas it is produced through a controlled anaerobic digestion process of organic matter such as agricultural waste, manure, sewage sludge or energy crops. And the production here is like in case of production and the processes the landfill gas is captured and collected by installing gas collection system including the pipes and the wells. Then it is typically treated and used as a source of energy or flared to reduce emission.

However in case of the biogas it is produced in a anaerobic digester which is the airtight container that is termed as a digester. And it can be collected purified and used as a renewable energy source for electricity generation, for heating applications or may be used as a vehicle fuel. Composition and the impurities typically the landfill gas has a lower methane content in the range of 40 to 65% with remainder being the CO_2 and traces of other gases while the biogas has higher quality compared to that of the landfill gas. Typically it has around methane content 70% plus and remainder being CO_2 and traces of other gases.

The environmental impact of landfill gas as well as the biogas if you look at the environmental impact the landfill gas accumulates inside the building constructed on close to the landfill side as well which a greenhouse gas is contributing to the climate change. However, here in case of biogas it has environmental benefits due to the control production and utilization. Since the biogas production is carried out in a very controlled manner as well as this utilization also carried out in a very controlled manner. So it provides certain environmental benefits because of its control production as well as its contribution in the waste minimization.

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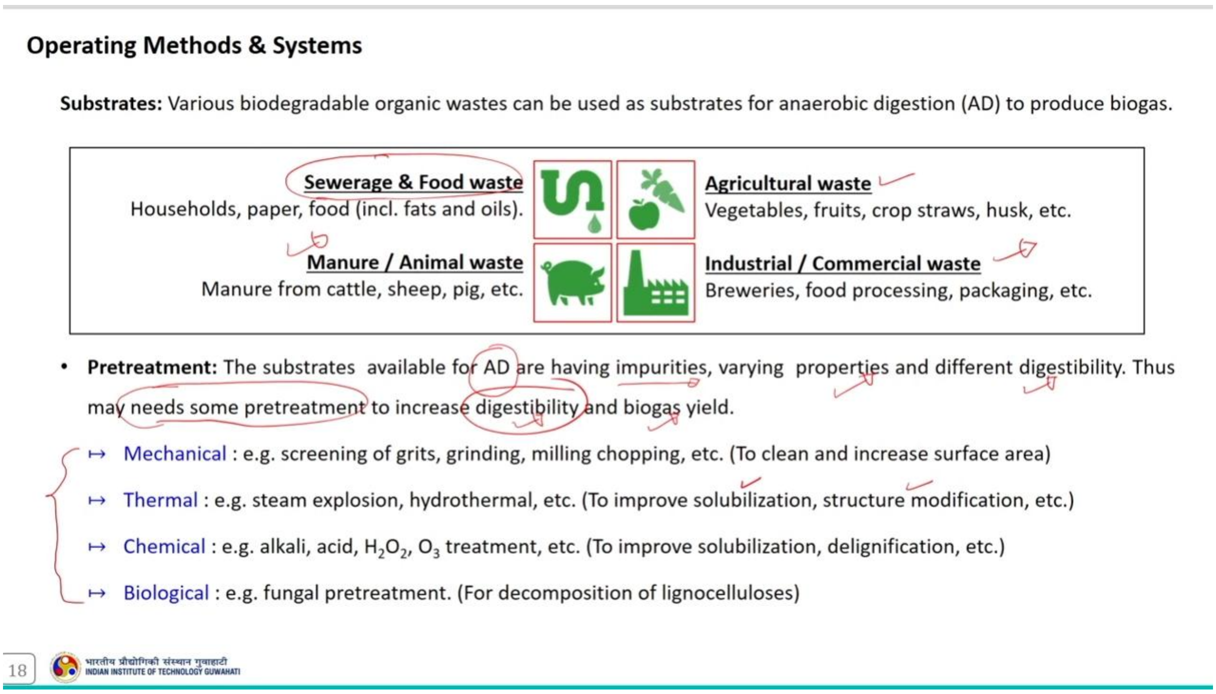

Operating methods and systems in the anaerobic digestion process as we know various biodegradable organic materials are used as a feed material in the anaerobic digestion process and these materials includes sewerage and the food waste, agricultural waste, manures and the industrial and commercial waste. Since the substrates available for the anaerobic digestion process are having impurities also having varying properties and different digestibility thus these feed material needs some pre-dement before being used in a anaerobic digestion process to increase the digestibility and increase the biogas yield. And these are some pre-treatment techniques which can be used to improve the solubilization, structural modification and digestibility of the feed material so that it can increase the biogas production. The material after pre-dement with improved structure and digestibility also with increased surface area can be digested using a digester.

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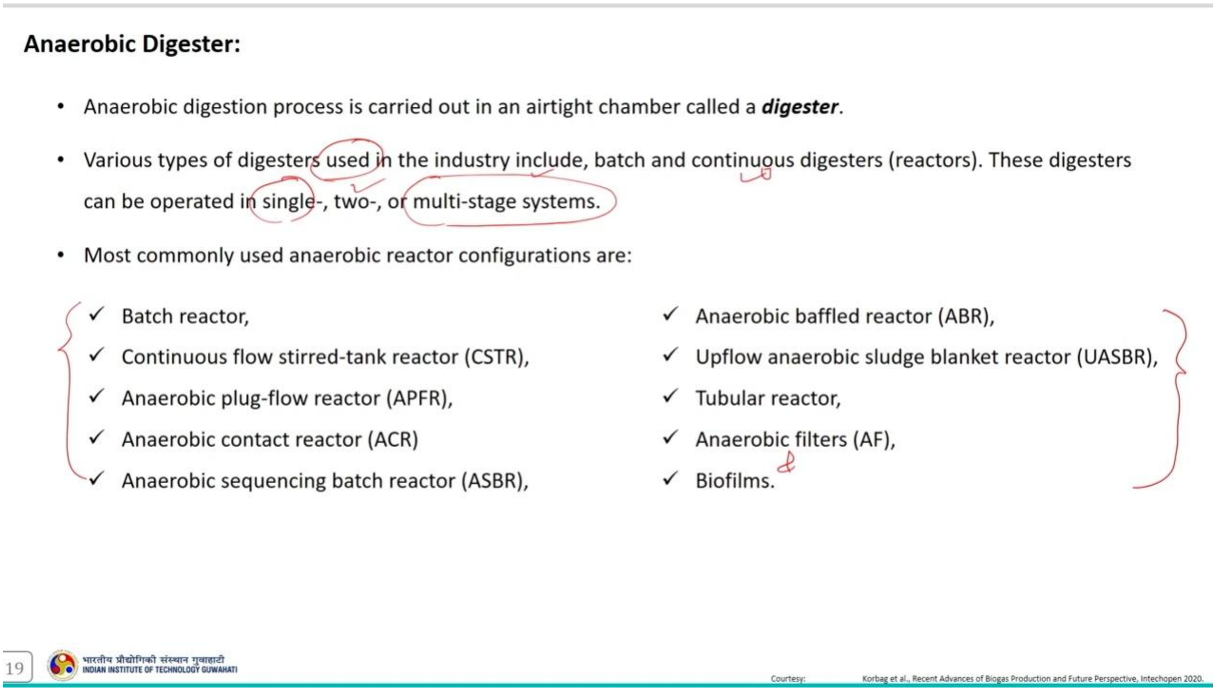

So let us discuss about the anaerobic digester. Anaerobic digestion process is carried out in an airtight container called a digester and in this case the various types of digester used in the industry include batch and the continuous digesters and these digesters can be operated even in a single two or multi-stage operational system. And the most commonly used anaerobic reactor configurations are listed here and biofilms is one of the recent concepts in anaerobic digestion process. So let us discuss about this anaerobic reactor configuration that is batch reactor and the continuous reactor.

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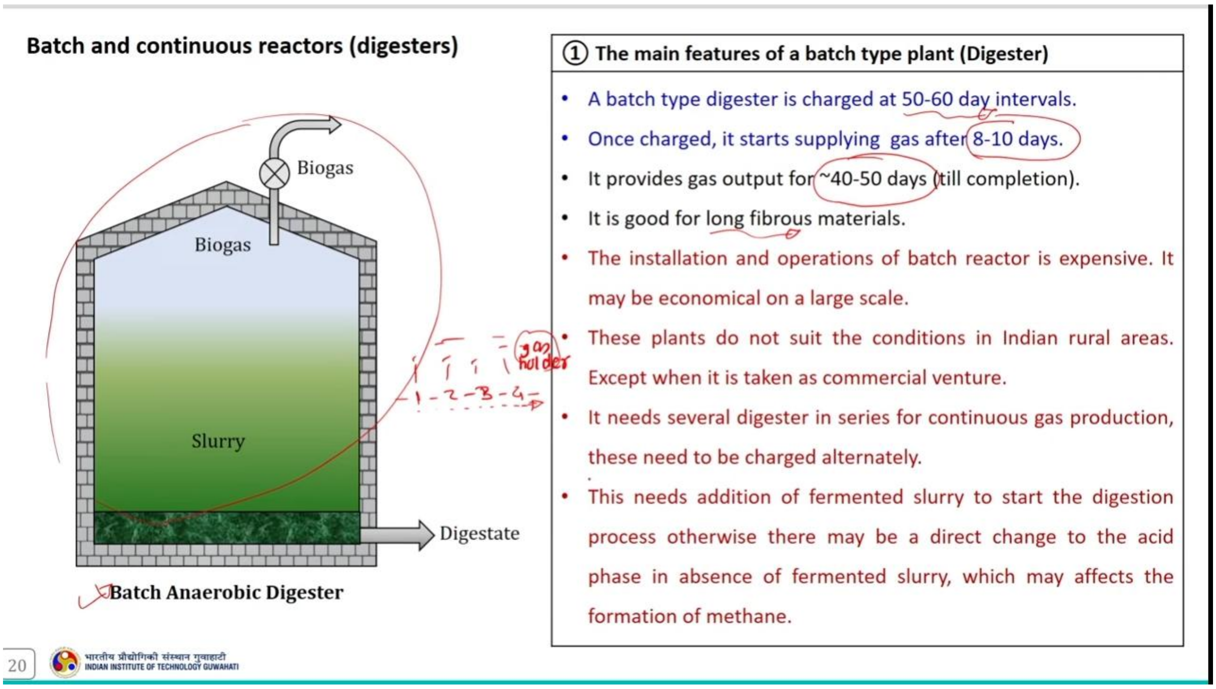

So to begin with let us first discuss the batch anaerobic digester. The schematic here it represent the batch anaerobic digester and the main features of batch type digester includes a batch type digester is charged 50 to 60 day intervals and once it is charged it starts supplying gas after 8 to 10 days and it provides a gas output for 50 to 40 days till the process of digestion is completed and it is good for long fibrous materials. But the installation and the operation of the batch reactor is expensive and it may be economical only on a large scale and this kind of plants do not suit condition in the rural areas except when it is taken as a commercial venture.

It needs several digester in series for continuous gas production and this need to be charged alternately that means the n number of batch digester can be arranged in a series and can be charged alternately so that the gas produced from each digester can be stored in a common gas holder and further be used for the heating and the electricity generation. Another limitation of the batch digestion process is this needs addition of the fermented slurry to start a digestion process otherwise there may be a direct change to the acid phase in absence of the fermented slurry which may affect the formation of the methane gas in the batch digestion process.

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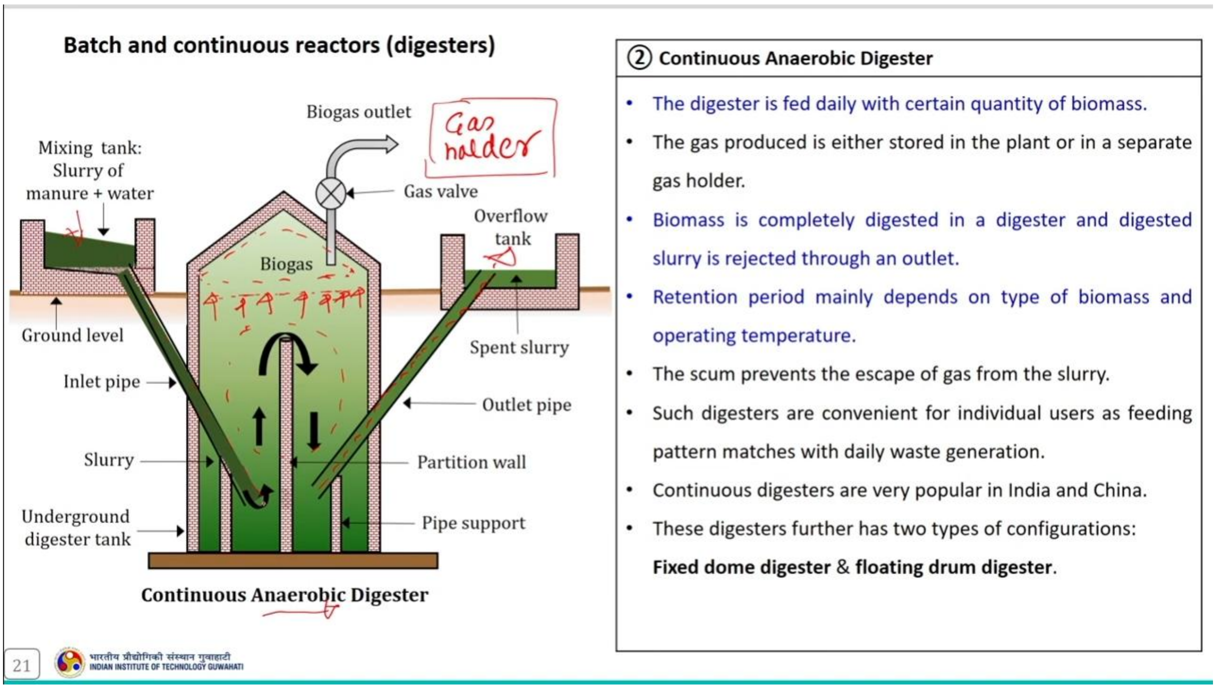

And this schematic here represents the continuous anaerobic digester and this digester is fed daily with certain quantity of biomass. The gas produced is either stored in a plant or in a separate gas holder. Biomass is completely digested in a digester and the digested slurry is rejected through the outlet. Retention time period here mainly depends on the type of biomass and the operating temperature in the digester. The scum formation on the top of the slurry prevents the escape of gas from slurry and such scum formation need to be avoided in the anaerobic digester. This kind of digesters is convenient for the individual users as the feeding pattern here matches with the daily waste generation. The continuous digesters are very popular in India and China and this digester further has two types of configuration that is fixed dome type digester and floating drum type digester.

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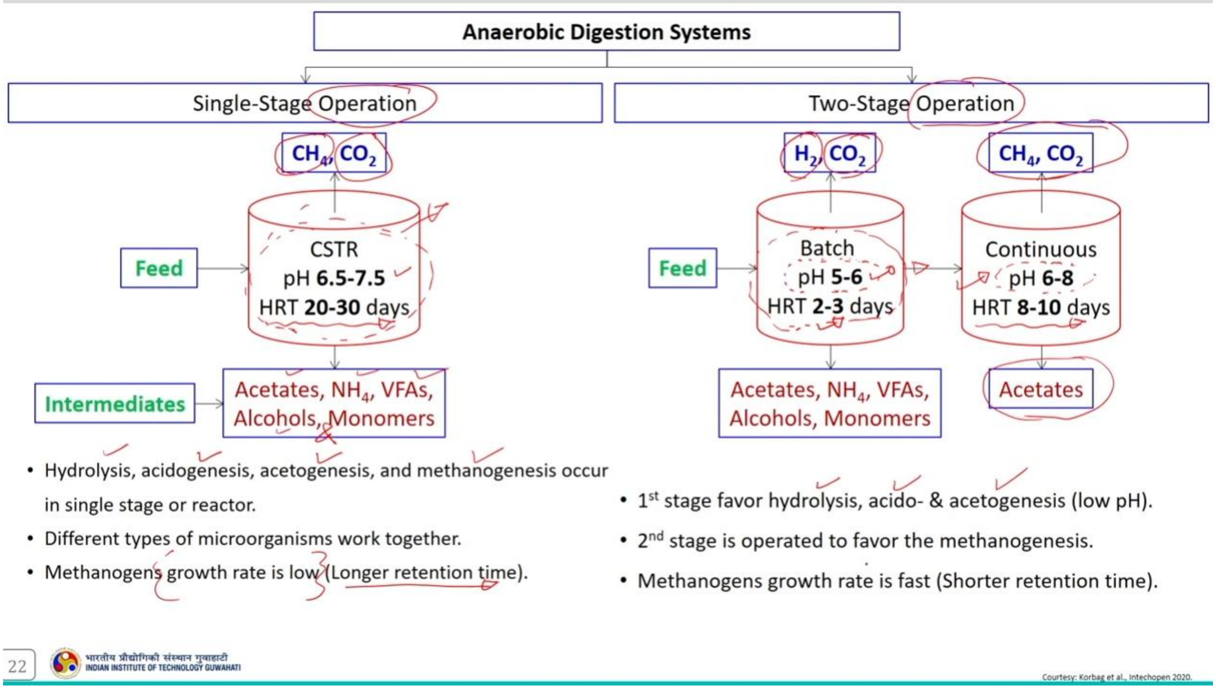

As discussed before anaerobic digestion system can be used as a single anaerobic digestion operation system or two stage system or multiple stage system. However, here we would be comparing the single stage and two stage anaerobic digestion system. So let us take a look at this schematic here - a single stage operation and two stage operation. In case of single stage operation, the feed is charged into the digester where the pH is maintained as 6.5 to 7.5 and HRD is around 20 to 30 days. Hydrolysis, acetogenesis, acetogenesis and methanogenesis stage occurs in a single stage or in a single reactor here and it produces methane and CO_2 as a gas along with the intermediate that is acetate, ammonia, volatile fatty acids, alcohol and monomers. Different types of microorganisms work together in a single stage operation system. However, the methanogens growth rate is relatively low in a single stage operation system and that is because of the longer retention time.

While in two stage operation the feed is charged to the first stage here where the pH is maintained around 5 to 6 and HRD is around 2 to 3 days. The first stage it favors the hydrolysis acetogenesis and acetogenesis where the pH is relatively low and that is what we can see here the pH is relatively low in this particular first stage operation that is between 5 to 6 and it mainly releases hydrogen and carbon dioxide as gas along with the intermediates as mentioned before. And the resulting mixture of first stage is charged to the second stage where it is operated to favor the methanogenesis and the pH in the second stage is around 6 to 8 and HRD of around 8 to 10 days which produces biogas along with the acetates.

Here the methanogens growth rate is fast and that is mainly because of the shorter retention time and that you can see the retention time in the single stage operation. And in the two stage operation and because of that here the methanogens growth is relatively fast.

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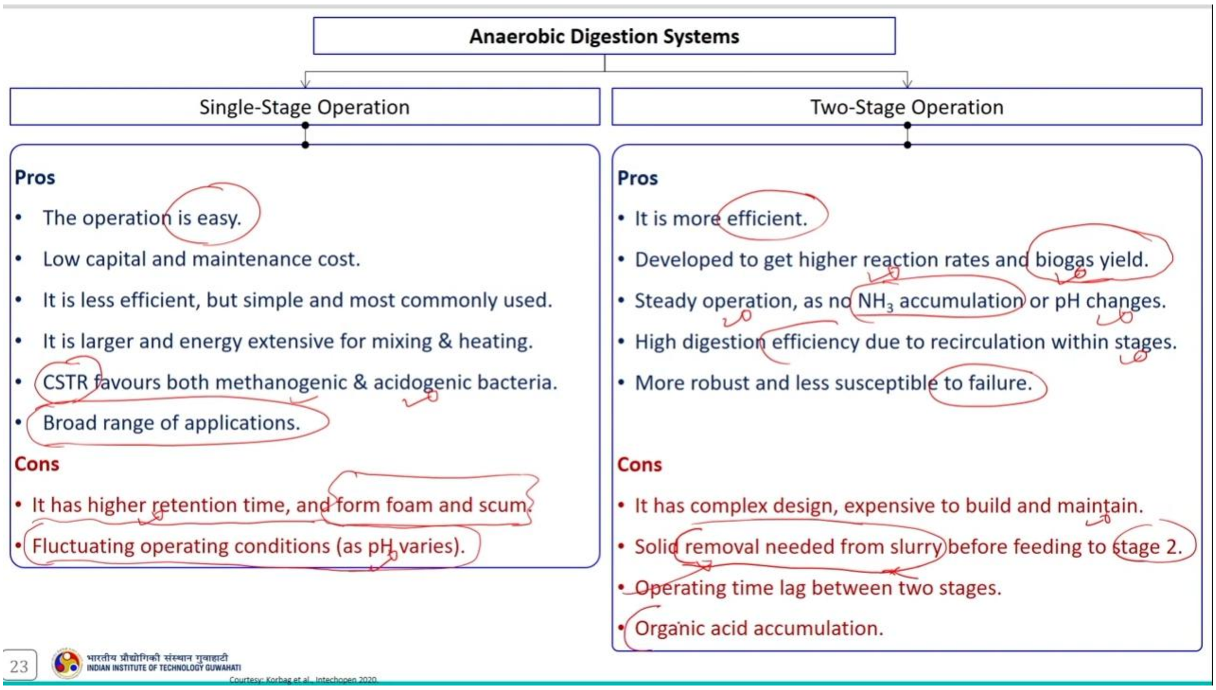

However this single stage operation and the two stage operation also has certain pros and cons. In single stage process the operation is easy, low capital and the maintenance cost. It is less efficient but simple and most commonly used process for the anaerobic digestion. It is larger and energy extensive for mixing and the heating. CSTR type digester favors both methanogenic and the estrogenic bacteria and broad range of applications are possible for this kind of operation but it has higher retention time as we already discussed before. And also form foam and the scum which prevent the escape of gas from the slurry. Because of the single stage operation fluctuating operating conditions can be observed in a single stage operation system and that is mainly because of the variation in the pH.

In case of two stage operation it is more efficient and basically it is developed to get higher reaction rate and the biogas yield that is the purpose of using the two stage operation so that we can achieve the higher reaction rates in the digester that is the first digester and then in the second digester because of the increased methanogenic rate it will result into higher biogas yield. Steady operation as no ammonia accumulation or the pH changes occur in the two stage operation. High digestion efficiency due to the recirculation within the stages is more robust and less susceptible to failure. However this particular operation it has a complex design expensive to build and also expensive to maintain the solid removal needed from the slurry of the first stage before charging into the second stage. And because of that there might be some operating time lag between these two stages and accumulation of the organic acid is another issue in the two stage operation.

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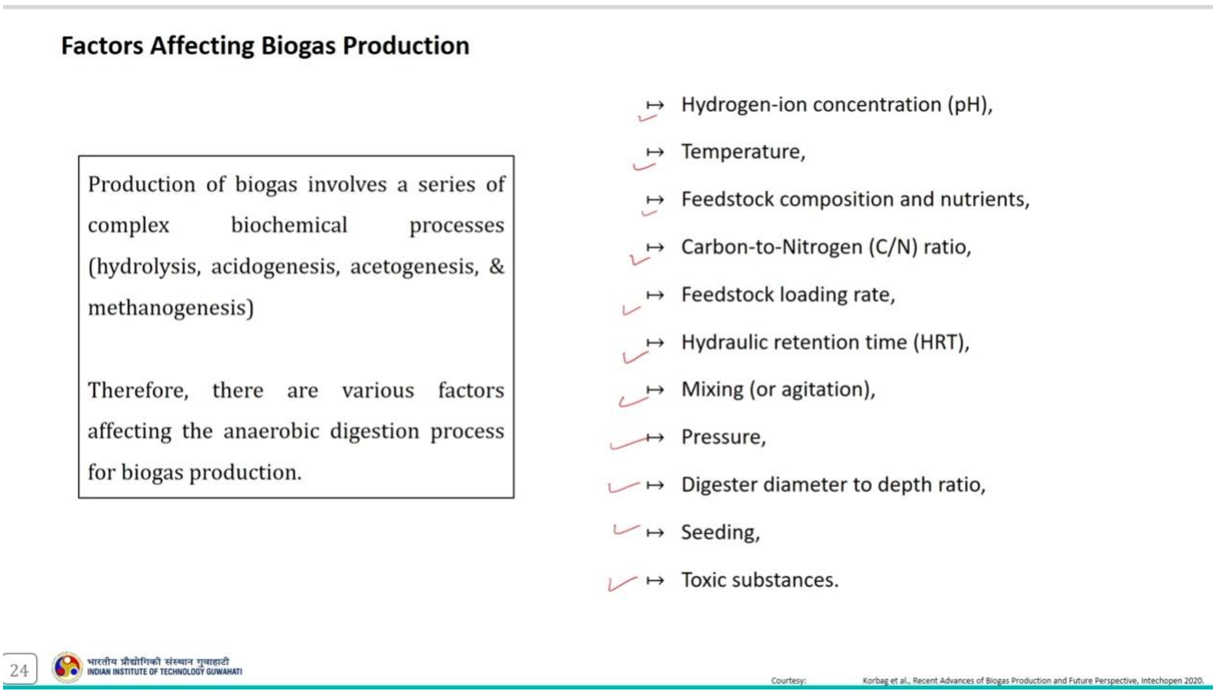

After learning about the anaerobic reactor configuration and anaerobic digestion system that is single step operation and two step operations, let us discuss about the factors affecting the biogas production process. The factors affecting the biogas production process are listed here that is hydrogen ion concentration temperature feedstock composition and nutrients carbon to nitrogen that is termed as C/N ratio feedstock loading rate hydraulic retention time mixing pressure digester diameter to depth ratio seeding and the toxic substances.

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Some of the key factors have been discussed here.

1 **Effect of Hydrogen-ion concentration (pH)**

- Hydrogen-ion concentration (pH) in the digesting material affects the biogas yield in anaerobic digestion process.
- pH of culture medium has an immediate effect on microbial growth, as the digestion is prevented by surplus acidity.
- Methanogens grow better under neutral and a bit alkaline environments and are sensitive to acidic conditions.
- In the stabilized anerobic digestion process, the optimum pH range of 6.5–7.5 is maintained, where optimal activity exhibited ~7 pH.

2 **Effect of Temperature**

- The temperature of slurry influences the biogas yield, as the activities of various types of anaerobic bacteria are temperature dependent (i.e. psychrophilic: <20 °C, mesophilic: 20–45 °C, and thermophilic: 45–80 °C).
- Anaerobic bacteria exhibit highest activity in the mesophilic and thermophilic range.
- The rate of decomposition and gas production becomes more rapid at high temperatures (optimum T = 35 °C).
- Exothermic reactions and mixing (impellers) may contribute to the heat generation/transfer in a digester.

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Courtesy: Korbag et al., Recent Advances of Biogas Production and Future Perspective, Intechopen 2020.

Among these several factors some key factors have been discussed here that is effect of hydrogen ion concentration that is pH. Hydrogen ion concentration that is pH of the digesting material affects the biogas yield in an anaerobic digestion process. For example the pH of culture medium has an immediate effect on microbial growth as the digestion is prevented by surplus acidity in a digesting material or we can call it as digester slurry. Methanogens grow better under the neutral and a bit alkaline environment and are sensitive to acidic conditions. In stabilized anaerobic digestion process the optimum pH range of 6.5 to 7.5 is maintained where the optimal activity exhibited at pH around 7. So this is one of the important factors in anaerobic digestion process that is pH. This pH in the optimal range of 6.5 to 7.5 needs to be maintained for the effective digestion of the material in the digester. So that it can result in efficient biogas yield.

Another factor is temperature. The temperature of the slurry influences the biogas yield as the activities of various types of bacteria are temperature dependent. That is if you see here for the psychrophilic it is in this range <20 °C. For the mesophilic the temperature is between 20 to 45 degree C and for thermophilic it is between 45 to 80 degree Celsius. Anaerobic bacteria exhibit the highest activity in the mesophilic and thermophilic range that is between 20 to 45 degree Celsius and 45 to 80 degree Celsius. Because the rate of decomposition and gas production it becomes more rapid at high temperature and the optimum temperature is considered as around 35 degree Celsius for the effective digestion of the material inside the digester. Since the anaerobic digestion process involves the exothermic reaction hence the exothermic reaction may contribute to the heat generation in the digester and the mixing effect may contribute to transfer of this heat in the digester. And because of that this temperature is considered as a very crucial factor in an anaerobic digestion process along with that the intermittent mixing is required to transfer the heat in a digester so that uniform temperature can be maintained in the digester.

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3 **Effect of Feedstock composition and nutrients**

- Biomass contain vital nutrients and carbon that promote the sustainable growth of the microbes.
- Therefore, the quality and quantity of the biogas yield is determined via nature of the feedstock used.
- The reactor selection also depends on the quantity and kind of solid contents of the feedstock. E.g. –
  - ↦ Plug-flow digesters are appropriate for animal dung having solid concentrations of 11–13%.
  - ↦ Complete-mix digester is appropriate for manure having 2–10 % solids.
  - ↦ Covered lagoon digester is used for liquid manure of less than 2% solids.

4 **Effect of Substrate particle size**

- Pre-treatment of biomass/substrate is necessary to be reduced to the digestible particle size.
- Smaller particles raise surface area for the microbial action of the methanogens.
- As a result the feedstock digestion rate increases and accelerates the rate of biogas production and vice versa.

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Another important factor is effect of feedstock composition and nutrients. The bio-based feedstock material used in the anaerobic digestion process contains vital nutrients and carbon that promotes the sustainable growth of microbes. Thus the quality and quantity of biogas yield is determined via the nature of the feedstock used during the digestion process. Apart from that the selection of the reactor also depends on the quantity and kind of solid contents of the feedstock. That means the solid content of the feedstock also plays a crucial role while selecting the reactor for the anaerobic digestion process.

For example here the plug flow digesters are appropriate for the animal manure having solid concentration of 11 to 13%. While complete-mix digester is appropriate for manure having the solid concentration in the range of 2 to 10%. And the covered lagoon digester is used for the liquid manure and in that the solid content is less than 2%. So this solid concentration is also one of the important factors in the anaerobic digestion process and based on that the proper reactor needs to be selected so that the effective digestion of the material would takes place in the digester which would result in the higher gas yield. Effect of substrate particle size, if the substrate available for the anaerobic digestion process are having impurities or having varying properties or we can say of different digestibility, then in that case some pre-processing or the pre-treatment is essential to improve the digestibility of the material as well as to increase the bio gas yield.

The higher surface area of smaller particles eventually helps for the microbial action of the methanogens. As a result the feedstock digestion rate increases and also accelerates the rate of bio gas production and vice versa. Because of that the feedstock which is used for the anaerobic digestion process need to have a sufficient digestibility so that it can help in increased digestion rate as well as to accelerate the rate of bio gas production during the operation.

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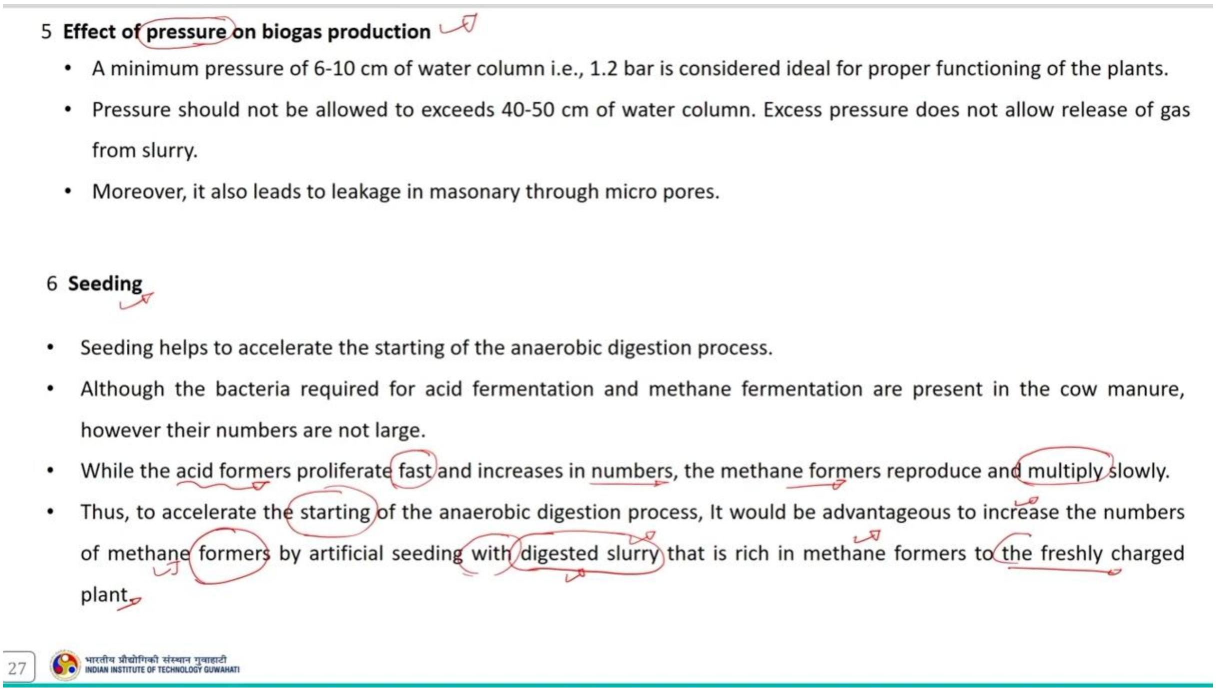

Similarly the pressure is also one of the crucial factors in bio gas production process. A minimum pressure of 6 to 10 centimeter of water column that is 1.2 bar is considered ideal for proper functioning of a bio gas plant. Pressure it should not be allowed to exceed 40 to 50 centimeter of the water column, because the excessive pressure does not allow the release of gas from the slurry. And this buildup pressure may lead to leakage through the micro pores in the machineries or we can say bio gas plant. A seeding is also another important factor in the anaerobic digestion process, because seeding helps to accelerate the starting of the anaerobic digestion process. Although the bacteria which are required for the acid formation and methane formations are available in manure however their numbers are not large.

Because if you see in this case here the acid formers proliferate fast and increases in numbers the methane formers reproduce and multiply slowly. And therefore to accelerate the starting of the anaerobic digestion process it would be advantageous to increase the number of methane formers by artificial seeding with digested slurry and that is rich in methane formers to the freshly charged plant. That means the digested slurry of the previous batch which has sufficient numbers of the methane formers bacteria can be added as a seeding material to the next batch that means the freshly charged batch in the anaerobic digester.

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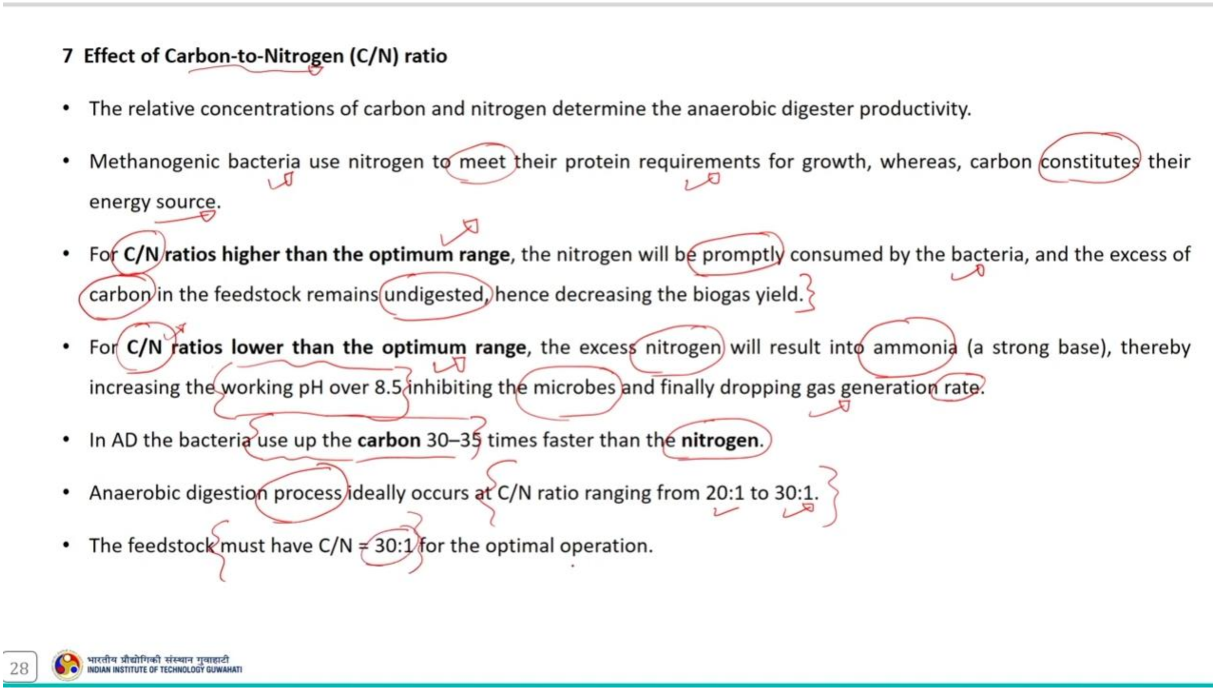

Another important factor is carbon to nitrogen ratio. The relative concentration of carbon and nitrogen determines the anaerobic digester's productivity because in the digester what happens is like the methanogenic bacteria they use nitrogen to meet their protein requirements for growth whereas the carbon it constitutes their energy source.

Say for example here if the c by n ratio is higher than the optimum range which is required for the anaerobic digestion process then the nitrogen will promptly consume by the bacteria while the excess carbon in the feedstock remains undigested and which eventually results in decreasing the biogas yield during the process. Another example is like suppose if the c by n ratio is lower than the optimum range. So in that case the excess nitrogen because if the c by n ratio is lower that means the nitrogen concentration is relatively high in the slurry and that will results in ammonia formation. And thereby increasing the working pH of the digester and it may go over 8.5 also and that may inhibit the microbes and may finally results in decreasing the gas generation rate. In anaerobic digestion process bacteria use of carbon 30 to 35 times faster than the nitrogen and hence the anaerobic digestion process ideally occurs at C/N ratio ranging from 20:1 to 30:1. So this is the ratio try to maintain in anaerobic digestion process. The feedstock must have the C/N ratio of 30:1 for the optimal operation and the effective gas yield.

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8 **Hydraulic retention time** (HRT)

- HRT is the time duration for which the substrates stay inside the anaerobic digester or the time that is available for the digestion.
- It is determined by the volume of a digester divided by the volume of slurry added per day.
- HRT strongly depends on the type of feed stock and temperature and it usually varies between 30 and 45 days and in some cases 60 days.
- In general, 30 days is typical retention time for non-stirring digesters, the digesters with high decomposition rates can be reduced to retention time of 10–20 days.

Mainly the HRT is optimized to achieve a 70-80% complete digestion

SN	*Raw material*	*Required retention time (days)*
1.	Cow dung	50
2.	Poultry droppings	20
3.	Rice straw	33
4.	Sugar cane tops	43
5.	Water hyacinth	46

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Hydraulic retention time is commonly referred as HRT. So HRT is the time duration for which the substrates stay inside the anaerobic digester. Or we can term it as the time that is required or available for the digestion process to reach to the completion. And this HRT it is determined by the volume of digester divided by the volume of slurry added per day in the digester. So with the help of these two values we can easily find out the HRT for a specific digester. And this HRT it is strongly depends on the type of feedstock as well as the temperature and it usually varies between 30 to 45 days and in some cases also it goes up to 60 days. Because as mentioned earlier HRT is mainly depends on the type of the feedstock used for the anaerobic digestion process as well as the temperature maintained during the operation. In general the 30 days is a typical retention time for non-stirring digester. The digester with high decomposition rates can have a reduced retention time of even 10 to 20 days. Mainly the HRT it is optimized to achieve a 70 to 80 percent complete digestion during the operation.

Now if you look at this particular table here it shows the list of some feedstock which is used for the anaerobic digestion process that is cow manure, poultry droppings, rice straw, sugarcane tops and water hassles and these values here represent the HRT for this particular feedstock. If you look at the cow manure the HRT for the digestion that means around like close to 70 to 80 percent complete digestion of the cow manure the HRT required is around 50 days. Similarly for the poultry droppings it is 20 days. In case of rice straw it is 33 days, sugarcane 43 and water hassles around 46. If you look at this particular table here this HRT is basically the feedstock specific.

So this indicates the percentage of digestible material which is available in the feedstock during the anaerobic digestion process and based on that the HRT varies from feedstock to feedstock. Apart from that the temperature of the anaerobic digestion process also plays a role and because of that also there might be a variation in the HRT.

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The methanogens are sensitive to O_2, pH, temperature, nutrients, and other inhibitory substances:

- ↦ **pH** conditions should be mildly acidic (pH 6.6 -7.0) but not more acidic than pH 6.2.
- ↦ **Nutrients** (including nitrogen, phosphorus, and certain metal ions) are necessary in specific composition for maintaining a healthy methanogenic population.
- ↦ **Nitrogen** should be present at 10% by mass of dry input, and phosphorus at 2%.
- ↦ **Inhibitory Substances** (e.g., ammonia, hydrogen sulfide, heavy metals, and certain organic compounds). In certain concentrations they can be toxic to methanogens. They can inhibit their metabolic activity.
- ↦ **Temperature** conditions depends on the methanogen species.

A golden rule for successful digestion is to maintain constant conditions of temperature and suitable input material; consequently a suitable population of bacteria gets established to suit these conditions (pH).

Courtesy: Twidell, Renewable Energy Resources, Ed 3, Taylor & Francis, 2015.

Apart from these many factors the methanogens are also sensitive to oxygen, pH, temperature, nutrients and other inimetric substances which are present in the feedstock material. The pH should be maintained in the mildly acidic range that is pH 6.6 to 7.0 but should not be more acidic than 6.2. In case of nutrients the nutrients are necessary in a specific composition for maintaining a healthy methanogenic population in a digester. Similarly the nitrogen it should be presented around 10% but this is by mass of dry input and the phosphorus at around 2% in the digester. Inhibitory substances, that is like ammonia, hydrogen sulfide, heavy metals and certain organic compounds. So the presence of these compounds in certain concentration, they can be toxic to methanogens and they can inhibit their metabolic activity. Therefore the concentration of this component needs to be maintained below the allowable limit. The temperature as we discussed few slides back the temperature condition it depends on the methanogen species used during the anaerobic digestion process. All these are some key important parameters that affect the biogas production in a anaerobic digestion process.

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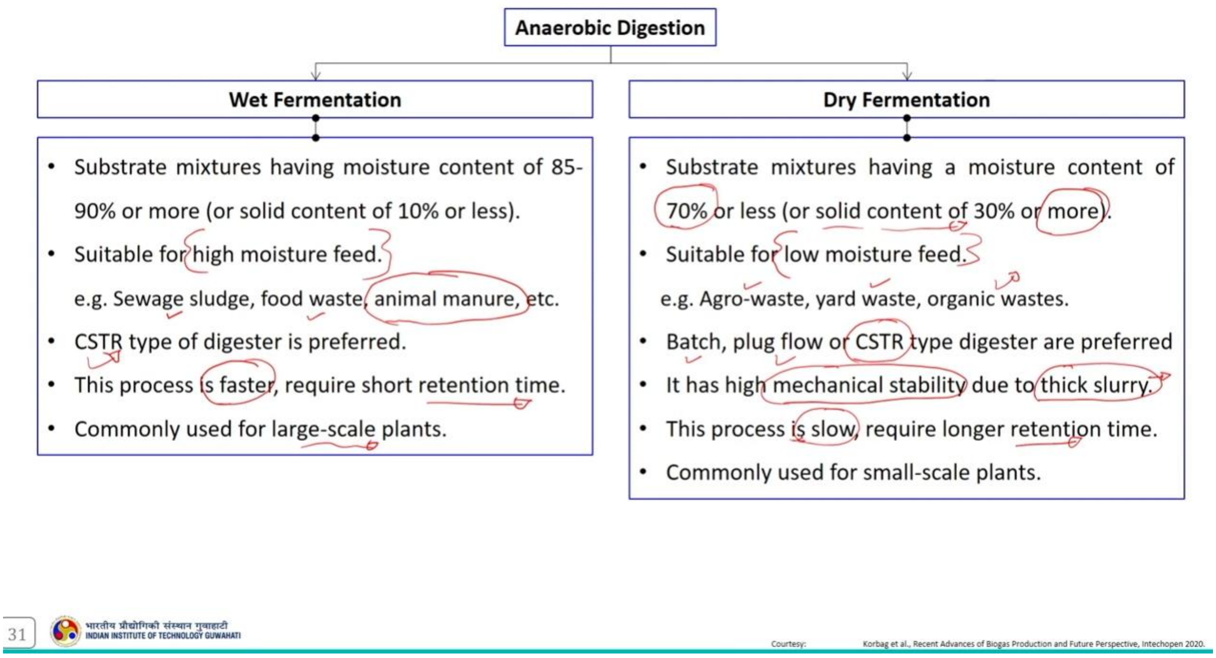

The anaerobic digestion process is also classified into two types that is wet fermentation and the dry fermentation technique. In case of wet fermentation the substrate mixture having moisture content of 85 to 90% or in other word the solid content of 10% or less is preferred in a wet fermentation process. The feedstock like sewage sludge, the food waste and animal manure are suitable for the wet fermentation process because all these material contains high moisture in its composition and the type of reactor which is preferred for the wet fermentation process is a CSTR. And this particular process is faster and it required relatively short retention time and this is commonly used for the large scale plants.

However, in case of dry fermentation process the substrate mixtures having moisture content of 70% or less or I would say solid content of 30% or more is preferred in a dry fermentation process and this particular process is suitable for low moisture feed example like the agro waste, yard waste and organic waste. However, the dry fermentation can be carried out in a batch plug flow or CSTR type digester. This particular process has high mechanical stability due to thick slurry since the moisture content is very less in this particular material as a result the digester slurry will be in the form of thick slurry in the dry fermentation process. This process is slow and required longer retention time and that is because as I mentioned just now the moisture content in the dry fermentation process is relatively less and because of that maintaining a uniform pH and temperature in the digester is difficult as a result the process efficiency is very less in case of the dry fermentation process and it required relatively a longer retention time. This is commonly used for the small scale plants.

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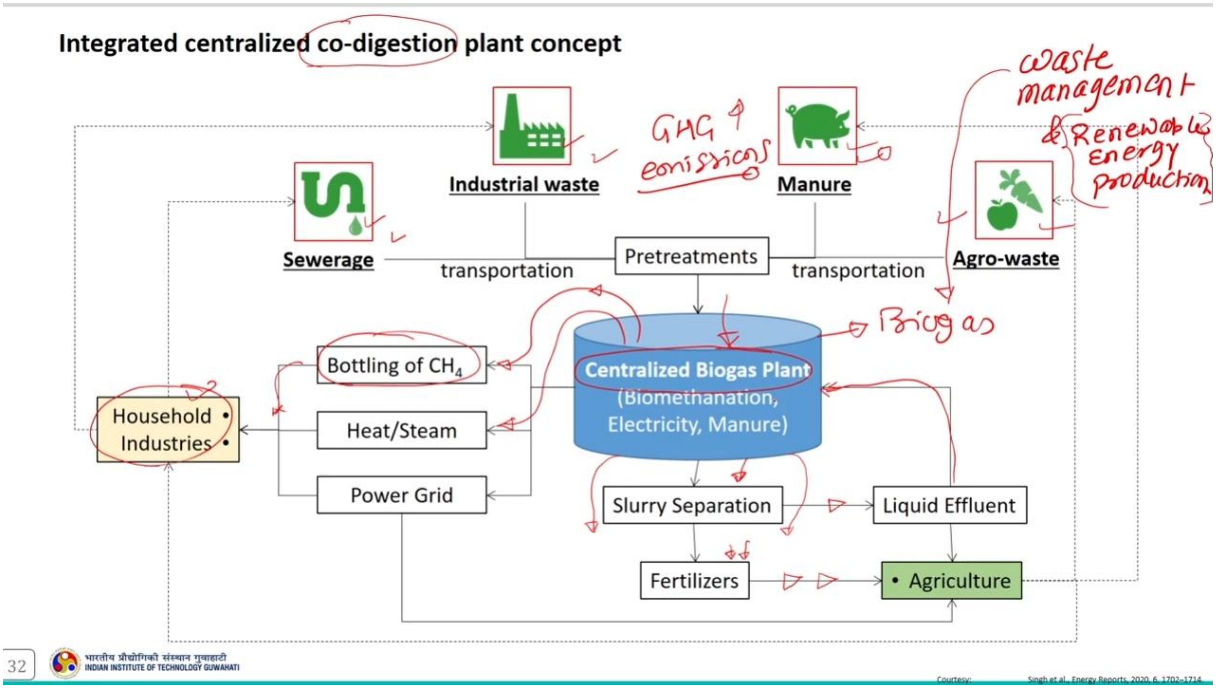

Another important concept which is used in the anaerobic digestion process is an integrated centralized co-digestion plant. The integrated centralized co-digestion plant approach it mainly refers to a system where the multiple waste streams are collected and preprocessed to convert into of sufficient digestibility and then process in a central facility for biogas production and this particular concept offers several advantages in the context of waste management and renewable energy production. For example like waste utilization and the environmental benefits, the utilization of the organic waste streams from municipalities, agriculture, industrial and other waste which can be processed in a centralized biogas plant to produce biogas as a product and this helps in minimizing the environmental load as well as the greenhouse gas emissions.

In case if these materials are not handled with proper waste management approach then these materials undergoes the natural decomposition process which eventually results into the environmental load as well as the emission of greenhouse gases. And as mentioned before this particular concept is more appropriate for the renewable energy production from the waste stream because the anaerobic digestion process it produces biogas as a product which can be combusted to produce heat or can be used for the generation of the electricity. Apart from that the purified and clean up gas can be used in the household industries using a proper approach. The resource recovery is another important point of centralized co-digestion plant. The digested obtained at the end of the digestion process is nutrient rich residue and it can be used as a bio fertilizer or soil amendment.

So here basically at the end of the anaerobic digestion process the digested slurry is allowed to separate out into a solid as well as the liquid effluent. The slurry which comes out here which has relatively a good amount of the solid content after certain processing can be used as a bio fertilizer in a sustainable agriculture. Apart from that the liquid effluent generated during the separation process can be recycled back to the centralized plant. And this is also a nutrient rich liquid effluent after certain processing it can also be used in a sustainable agriculture. Economic scale by processing these large quantities of waste the centralized plant can achieve higher process efficiency and lower cost that is capital operational and the maintenance cost in such kind of centralized plant would be less compared to that of the decentralized plant. Another important point of this integrated centralized co-digestion plant is collaborative partnership. The collaborative approach among municipalities, farmers and industries foster the partnership and share responsibilities for waste management and the renewable energy production. And this way this integrated centralized co-digestion plant concept would be effective in waste management as well as producing the renewable energy.

This gives details about the integrated centralized co-digestion plant approach however most of these points we already covered in the previous slide but for your convenience it has been reproduced here in the text form for the reading purpose. This covers our discussion on the anaerobic digestion process. So in the next lecture that is second lecture of module 5 in that we will discuss another biochemical conversion process that is alcoholic fermentation.

In that we will discuss about the comparison of biochemical and thermochemical routes, competitive production of alcohol, bioethanol from the edible sources and non-edible sources, energy description, distillation and the concept of combined biogas and bioethanol production.

Thank you.