Energy Conversion Technologies (Biomass And Coal)
Prof. Vaibhav V. Goud
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Lecture 14
Energy from Bio-based Feedstock

Good morning everyone. Welcome to this first lecture under the module 3.

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Module	Module Name	Week	Lecture No	Title of the lecture
03	Energy from bio-based feedstock	3	1	*Energy from bio-based feedstock:* Availability of the feedstock, compositional analysis and properties of feedstock, preparation of fuel pellets using bio-additives

In this lecture, we will discuss about the energy from bio-based feedstock. In that we will discuss availability of the feedstock, composition analysis, and properties of feedstock; and preparation of fuel pellets using bio-additives. What is bio-based feedstock? Bio-based feedstock includes non-fossilized biodegradable organic material from plant, animal and microorganism. This includes varieties of material such as agricultural and the forestry by-products, residues and waste as well as organic components of industrial and municipal waste.

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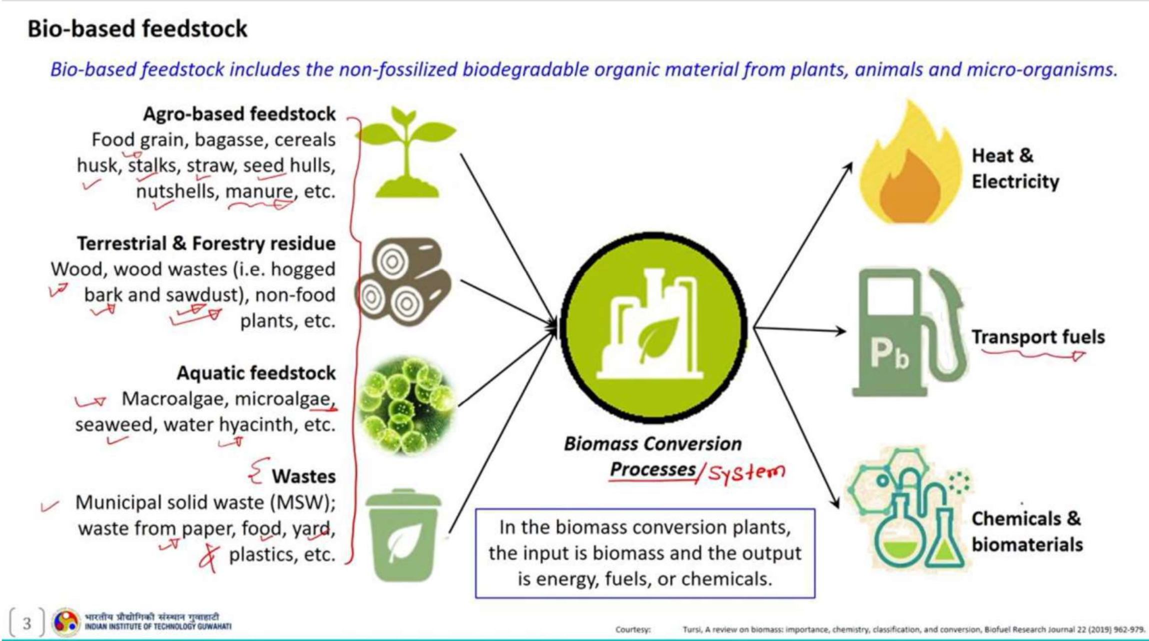

Agro-based feedstock includes the food grains. And food-grains here means the waste-grains that are not consumed or used for food-purpose. Also, it includes the agricultural residue referred to the various type of organic material left over from agricultural production after the crop or other agricultural products have been harvested. And this includes stalks, straw as well as seed hulls, husks, nutshells, and the manure from specific sources.

Terrestrial and the forestry residue includes the wood and wood waste. So here the wood waste refers to the organic materials, that are left over from the forest harvesting and the processing activities, that is mostly bark and sawdust which is by-product of the timber production, and the non-food plants. The aquatic feedstock here includes any plant material that has formed in water like macroalgae, microalgae, seaweed, water hyacinth, etc. And the waste here means the municipal solid waste, the waste from paper (mainly in the form of the cardboard), food, yard, and the plastic waste. These feedstock materials are transformed using suitable transformation process or system to produce either transport fuels, chemicals, or usable energy that is heat or electricity as a product. So, this is about the bio-based feedstock.

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Energy from bio-based feedstock

Bio-based feedstock can be converted into three main types of product: • electrical/heat energy, • transport fuel, • value added chemicals.

- Bio-based feedstock can be transformed into different forms of energy products by using various processes.
  1. Production of solid fuel for co-firing to generate thermal/heat and electrical energy.
  2. Production of transport fuels as an alternative to conventional fuels i.e. diesel or gasoline.
  3. Production of chemicals or biorefinery feedstock.
- Three main types of fuels could be produced from Bio-based feedstocks :
  1. Liquid fuels (ethanol, biodiesel, methanol, vegetable oil, and pyrolysis oil).
  2. Gaseous fuels (biogas: CH_4, CO_2; producer gas: CO, H_2, CH_4, CO_2, H_2; syngas: CO, H_2).
  3. Solid fuels (charcoal, torrefied biomass, biocoke, biochar).

For the sustainability of biomass conversion process, the feedstock must be economically viable and environmentally friendly.

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Courtesy: Non-conventional energy resources, by BH Khan, McGraw Hill Education, 2017. Biomass gasification, pyrolysis and torrefaction: Practical design and theory, by P Basu, Academic Press, 2013.

These bio-based feedstock materials can be transformed into different forms of energy products using various processes. (e.g.) to produce solid fuel for co-firing to generate thermal-energy or heat-energy and electrical-energy.

To produce transport fuel as an alternative to conventional fuel that is diesel and gasoline. It can also be used to produce chemicals and these chemicals can act as a feedstock material for biorefinery. Three main types of fuels which can be produced from this bio-based feedstock includes the liquid fuel that is mainly ethanol, biodiesel, methanol, vegetable oil and pyrolysis oil. The gaseous fuel includes the biogas and the main composition of the biogas here methane and the CO_2, producer gas consists of the following composition, and syngas. Solid fuels include the charcoal, torrefied biomass, bio-coke, and the biochar.

So, these three main types of products can be produced using these bio-based feedstock materials. However, for the sustainability of this biomass conversion processes, the feedstock must be economically viable and environment friendly. Therefore, suitable feedstock needs to be selected based on its availability, so that it can be used further in the energy conversion system.

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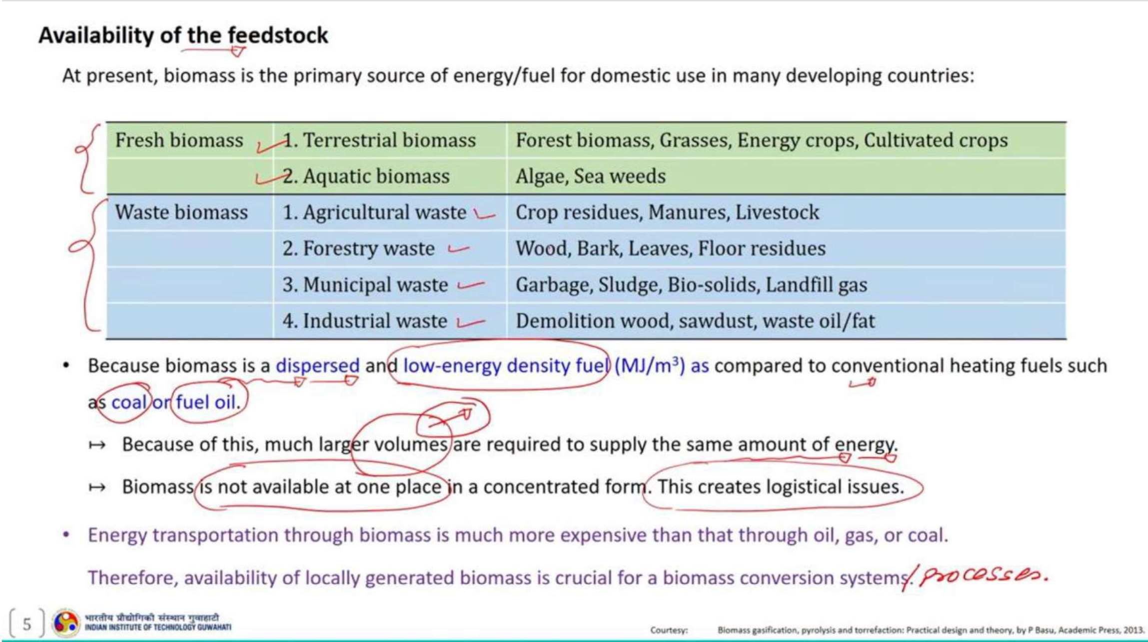

So, let us discuss about the availability of the feedstock material. At present, biomass is a primary energy source or fuel for domestic use in many developing countries. Primary biomass sources are categorized into two main types that is virgin biomass and waste biomass. Virgin biomass is available as it grows. But secondary or the waste biomass being a derived product is not available immediately. Moreover, the availability of the biomass is also influenced by its accessibility constraints, because biomass is a dispersed and possesses low energy density compared to that of the conventional heating fuels such as coal or fuel oil. Because of this, much larger volumes of biomass are required to supply the same amount of energy which can be made through limited source of conventional heating element that is coal.

Biomass is not available at one place in a concentrated form and this creates the logistical issues. Energy transportation through biomass is much more expensive than that through the oil, gas or coal. And therefore, the availability of the locally generated biomass is crucial for the biomass conversion process or system. So, the example of the fresh biomass is shown here that is terrestrial biomass and the aquatic biomass. Waste biomass as shown here being a derived product, these are not available immediately that is an agricultural waste, forestry waste, municipal waste, and the industrial waste. So, these are not available immediately whereas, these fresh biomass are readily available.

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Biomass classification

In general, based on its composition the biomass is classified into four groups:

	**1. Herbaceous biomass** Grasses (bamboo, cane, switchgrass, alfalfa, miscanthus, etc.); Straws (barley, bean, flax, corn, mint, oat, rice, sesame, sunflower, wheat, etc.); Other residues (fruit, shell, husk, hull, grain, seed, coir, stalk, cob, bagasse, fodder, pulp, etc.).
	**2. Woody biomass** Wood and wood waste including: stems, branches, foliage, bark, chips, lumps, sawdust, and others from various wood species.
	**3. Aquatic biomass** Marine or freshwater algae; Macroalgae (blue, green, blue-green, brown, red) and microalgae; Seaweed, water hyacinth, etc.
	**4. Wastes** Municipal waste, *Bio solids, sewage,* industrial waste (pulp, paper, food, plastics), various manures, etc.

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Courtesy: Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 22 (2019) 962-979.

These bio-based feedstock materials are classified into four groups that is herbaceous biomass, woody biomass, aquatic biomass, and waste biomass. Herbaceous biomass here includes grasses, straws and other residues. So, straw here basically originate from the agricultural residues. And grasses mainly include the bamboo, cane, switchgrass, miscanthus, etcetera.

The straws like wheat straw, rice straw, these are the agricultural residues. Other residues, in the form of fruit, shell, husk, hull, grains, seed, etc. are generally the waste generated during processing of the agricultural produce. Woody biomass includes the wood and the wood waste including stems, branches, bark, lumps, sawdust, and other material from various wood species. Aquatic biomass, as I mentioned earlier, includes any plant material that is formed in water like marine or fresh water algae, macroalgae and microalgae, seaweed, water hyacinth, etcetera. And the waste includes the municipal waste, bio-solids, sewage sludge, industrial waste, and various manures from specific sources. So, let us discuss about these bio-based fish stock materials one by one.

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1. Herbaceous biomass

"Herbaceous biomass originates from plants that have a non-woody stem and which die back at the end of the growing season." (European standard EN 14961-1).

Examples:

- Grasses (bamboo, cane, switchgrass, alfalfa, miscanthus, etc.);
- Straws (barley, bean, flax, corn, mint, oat, rice, sesame, sunflower, wheat, etc.);
- Other residues (fruit, shell, husk, hull, grain, seed, coir, stalk, cob, bagasse, fodder, pulp, etc.);
- *Energy Crops* also belongs to the herbaceous biomass: (poplars, willows, switchgrass, alfalfa, prairie bluestem, corn, and soybean, canola, and other oil plant).

higher nutrient content & lower lignin contents than wood.

Herbaceous Biomass. Herbaceous biomass originates from a plant that have a non-woody stem and which die back at the end of the growing season. And this herbaceous biomass includes most agricultural crops, and grasses including bamboo, and wheat straw.

In general, the herbaceous biomass will have the higher nutrient content and lower lignin content than the wood materials. Because of this heterogeneity in the class of biomass, herbaceous biomass is variable in composition. Because as you see here, there is a lot of heterogeneity involved in this class of biomass. And because of that we can observe a great variation in their composition. Energy crops also belongs to the herbaceous biomass that is poplars, willows, switchgrass, corn, soybean, canola, and other oil plants. So here the agricultural residues of the soybean and canola crop would be utilized for the energy application and not the seeds.

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- **Structural & compositional analysis** :
  - ↦ Mostly the herbaceous biomass are the rich source of carbohydrates (sugars) and starch.
  - ↦ Herbaceous biomass contain higher amounts of carbohydrates (70–90%) than lignin (10–30%).
  - ↦ In general, herbaceous biomass will have higher nutrient and lower lignin contents than the wood.
  - ↦ Cellulose, hemicellulose and lignin are the main constituents of the herbaceous biomass, thus also called as *lignocellulosic biomass*.

Biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Corn stover	38–40	24–26	7–19
Switchgrass	5–20	30–50	10–40
Rice straw	28–36	23–28	12–14
Corn cob	42–45	35–39	14–15
Barley straw	31–45	27–38	14–19
Sweet sorghum bagasse	34–45	18–27	14–21
Oat straw	31–37	27–38	16–19
Rye straw	33–35	27–30	16–19
Wheat straw	33–38	26–32	17–19
Sugarcane bagasse	42–48	19–25	20–42
Miscanthus	38–40	18–24	24–25
Rice husk	25–35	18–21	26–31

Structural and composition analysis of the herbaceous biomass indicates that herbaceous biomass are a rich source of carbohydrate and starch. This herbaceous biomass contains higher amount of carbohydrates that is cellulose and hemicellulose than lignin. If you see this particular table here, the lignin content in the herbaceous biomass is relatively low as compared to the carbohydrate content. And in general, the herbaceous biomass will have the higher nutrient and lower lignin content than the wood, as just we discussed one or two slides before. That the herbaceous biomass will have the higher nutrient and the lower lignin content. Cellulose hemicellulose and the lignin are the main constituents of the herbaceous biomass thus also called as a lignocellulosic biomass. So according to this table here, it appears that the herbaceous biomass contains higher amount of the carbohydrates than the lignin.

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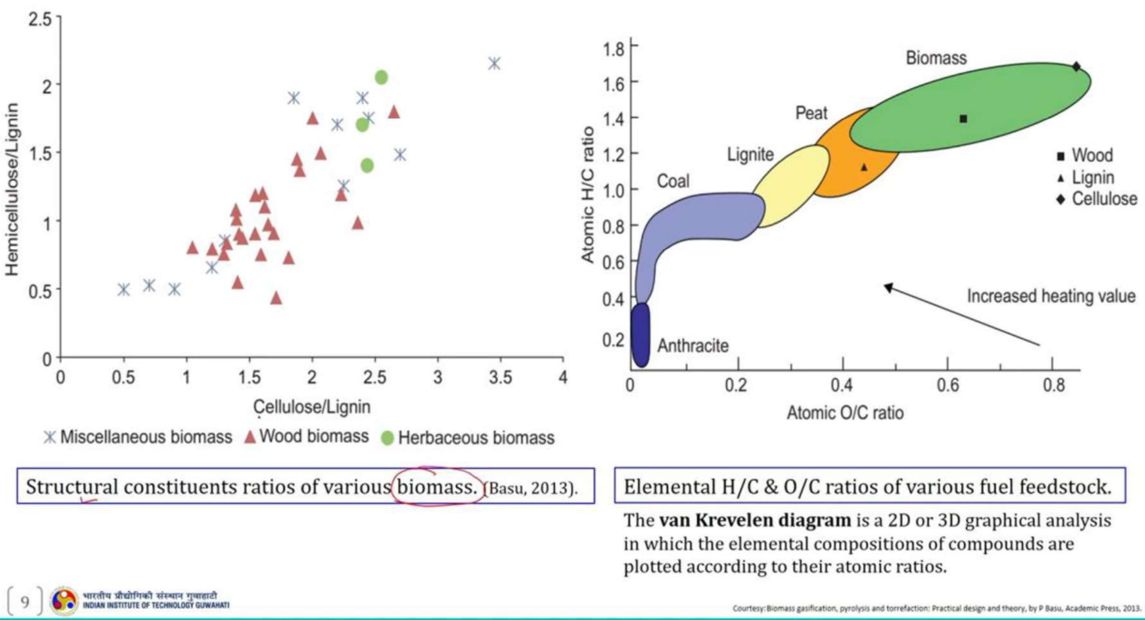

So, this particular schematic here, it compares the structural constituents' ratios of various biomass feedstock materials. From "cellulose to lignin ratio" and from "hemicellulose to lignin ratio" it appears that the herbaceous biomass contains higher amount of carbohydrate compared to miscellaneous biomass and the woody biomass. And that already we have discussed one slide back, that the herbaceous biomass are a rich source of the carbohydrate and starch. And that can be evident from this particular schematic here, that the herbaceous biomass has relatively higher "cellulose to lignin ratio" and also higher "hemicellulose to lignin ratio" compared to the miscellaneous biomass and the woody biomass. Similarly, this schematic here, it compares the H/C and the O/C ratios of various fuel feedstock. In that if you take a look at the biomass sample only, so here the cellulose shows relatively higher O/C and the H/C ratio compared to the woody material. And the lignin has relatively low O/C and H/C ratio compared to the cellulose and woody biomass.

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- Proximate analysis
  - ↦ The proximate content shows large variation depending on the specific type of biomass.
  - ↦ Herbaceous biomass typically has a **higher volatile matter** upto 87%, due to their lower density and higher carbohydrate content.
  - ↦ This higher **VM content** makes herbaceous biomass more suitable for fast pyrolysis or gasification processes, where the volatile components can be converted into bio-oil or syngas.
  - ↦ Some species of herbs shows higher **FC content** primarily due to the lignin, which is a complex polymer that contains a significant amount of carbon and contributes to the fixed carbon content.

Biomass group	Ultimate / Elemental analysis					Proximate analysis				HHV
	C (%)	O (%)	H (%)	S (%)	N (%)	VM (%)	FC (%)	M (%)	A (%)	MJ/kg
Herbaceous biomass	42-58	34-49	3-9	<1-1	<1-3	41-87	9-35	4-48	1-19	15-19
Woody biomass	49-57	32-45	5-10	<1-1	<1-1	30-80	6-25	5-63	1-8	16-22
Aquatic biomass	27-43	34-46	4-6	1-3	1-10	42-80	5-33	8-14	3-36	12-22
Municipal Wastes	57-61	21-25	7-8	1-2	6-12	43-62	12-13	3-9	23-34	10-20

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Courtesy: Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 22 (2019) 962-979.

Similarly, the proximate analysis of this herbaceous biomass, it shows a great variation and that is mainly because of the specific type of a biomass. Since this herbaceous biomass includes the biomass of different varieties, right from grasses to agriculture residues as well as to the energy crops so large variation is expected in this kind of a biomass material. Herbaceous biomass typically has a higher volatile matter content and the highest volatile matter content is around 87% in the herbaceous biomass. And that is mainly due to the lower density and the higher carbohydrate content in the biomass sample. And this volatile matter content makes the herbaceous biomass more suitable for the fast pyrolysis or the gasification processes, where the volatile matter content in the biomass can be converted into liquid fuel or gaseous fuel. Some species of the herbaceous biomass shows higher fixed carbon content and even the maximum limit here of fixed carbon content in the herbaceous biomass is around 35%. And this is primarily due to the lignin which is a complex polymer that contains a significant amount of the carbon. And that contributes to the fixed carbon content in the biomass sample.

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- Ultimate analysis
  - ↦ Herbaceous biomass shows high C and O content, 42–58% and 34–49%, respectively.
  - ↦ Lignin has lower H/C and O/C ratio, whereas cellulose has high H/C and O/C ratio.
  - ↦ Higher cellulose content and lower lignin content indicates higher H/C and O/C ratio.

Biomass group	Ultimate / Elemental analysis					Proximate analysis				HHV
	C (%)	O (%)	H (%)	S (%)	N (%)	VM (%)	FC (%)	M (%)	A (%)	MJ/kg
Herbaceous biomass	42-58	34-49	3-9	<1-1	<1-3	41-87	9-35	4-48	1-19	15-19
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Municipal Wastes	57-61	21-25	7-8	1-2	6-12	43-62	12-13	3-9	23-34	10-20

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Courtesy: Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 22 (2019) 962-979.

Similarly, the ultimate analysis of the herbaceous biomass, it shows high carbon and the oxygen content. And as we discussed few slides before, the lignin has lower H/C and the O/C ratio, whereas the cellulose has higher H/C and the O/C ratio. And since the herbaceous biomass has more carbohydrate content than the lignin, so this higher cellulose content and lower lignin content indicates higher H/C and the O/C ratio for the herbaceous biomass. So, the next classification is the woody biomass. Woody biomass here includes the non-herbaceous plant material which live for longer time and they stay on the ground with its stem.

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2. Woody biomass

Woody biomass includes non-herbaceous plants which are not seasonal, and they live for several years with their stems above the ground.

Examples: This category of biomass consists of materials such as stems, branches, bark, chips, lumps, sawdust, sawmill residues and others from various wood species including trees and woody shrubs.

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This woody biomass, it includes a non-herbaceous plant which are not seasonal and they live for several years with their stem above the ground. And this category of the biomass it mainly consists of the material such as the stems, branches, bark, lumps, sawdust, and the sawmill residues. And it also includes other sources of wood species including the trees and woody shrubs.

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Structural & compositional analysis

- Woody biomass includes different components, mainly cellulose, hemicellulose, & lignin.
- This type of biomass is also called as *lignocellulosic biomass* as a major part of biomass is lignocellulose. Lignocellulosic material is the non-starch, fibrous part of the plant materials.
- Carbohydrates are mainly cellulose or hemicellulose fibers, which impart strength to the plant structure, while the lignin holds the fibers together.
- As compared to the herbaceous biomass, in the woody biomass the **lignin** content is typically higher, whereas the **cellulose** content is slightly lower.

Biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Hardwood	20–25	45–50	20–25
Softwood	27–30	35–40	25–30
Willow	25	50	19
Larch	35	26	27

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Courtesy: Biomass gasification, pyrolysis and torrefaction: Practical design and theory, by P Basu, Academic Press, 2013.
Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 22 (2019) 962-979.

Structural and the compositional analysis of the woody biomass indicates that the woody biomass includes different component mainly cellulose, hemicellulose and lignin in its composition. And this type of biomass is called as a "Lignocellulosic Biomass" as the major part of the biomass is lignocellulose. Lignocellulose material is the non-starch fibrous part of the plant materials. And if you see here the cellulose content in this particular type of biomass, it is relatively low compared to that of the lignin. Whereas, lignin content is relatively higher than that of the cellulose in this type of a biomass. Carbohydrates are mainly the cellulose and the hemicellulose fibres which impart strength to the plant structure, while the lignin holds these fibres together. As compared to the herbaceous biomass, in the woody biomass the lignin content is typically higher. Whereas the cellulose content is slightly lower in the woody biomass compared to that of the herbaceous biomass.

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- **Proximate analysis**
  - ↦ Proximate analysis shows large variations in the composition due to different biomass source.
  - ↦ Typically, the woody biomass tends to have a lower volatile matter content compared to herbaceous biomass, mainly because of its higher density and lignin content.
  - ↦ Thermochemical processing of woody biomass has been preferred over other biomass sources.
  - ↦ This makes it a potential raw material for slow pyrolysis or combustion processes for heat or power generation.

Biomass group	Ultimate / Elemental analysis					Proximate analysis				HHV
	C (%)	O (%)	H (%)	S (%)	N (%)	VM (%)	FC (%)	M (%)	A (%)	MJ/kg
Herbaceous biomass	42-58	34-49	3-9	<1-1	<1-3	41-87	9-35	4-48	1-19	15-19
Woody biomass	49-57	32-45	5-10	<1-1	<1-1	30-80	6-25	5-63	1-8	16-22
Aquatic biomass	27-43	34-46	4-6	1-3	1-10	42-80	5-33	8-14	3-36	12-22
Municipal Wastes	57-61	21-25	7-8	1-2	6-12	43-62	12-13	3-9	23-34	10-20

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Courtesy: Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 22 (2019) 962-979.

And even the proximate analysis of this biomass, it shows a large variation in composition. And that is mainly due to the large variation in the species of the woody biomass as well. And typically, this woody biomass it tends to have the lower volatile matter compared to the herbaceous biomass. Mainly it is because of its higher density and the lignin content. Because in case of the woody biomass the lignin content is relatively higher than that of the herbaceous biomass. And hence this kind of biomass are preferred for thermochemical conversion processing compared to the other biomass sources. And it also makes a potential raw material for the slow pyrolysis or combustion processes for heat and power generation. And if you look at this particular table here, the volatile matter content in this particular biomass is relatively low than that of the herbaceous biomass. The highest limit of the volatile matter content in this woody biomass is 80% and the lower limit is 30%. Even the ash content in the woody biomass is found to be relatively low compared to that of the herbaceous biomass.

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- **Ultimate analysis**
  - ↦ Woody biomass shows high C and O content, 49–57% and 32–45%, respectively.
  - ↦ Higher lignin content and lower cellulose content indicates comparatively lower H/C and O/C ratio than the Herbaceous biomass .

Biomass group	Ultimate / Elemental analysis					Proximate analysis				HHV
	C (%)	O (%)	H (%)	S (%)	N (%)	VM (%)	FC (%)	M (%)	A (%)	MJ/kg
Herbaceous biomass	42-58	34-49	3-9	<1-1	<1-3	41-87	9-35	4-48	1-19	15-19
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Courtesy: Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 22 (2019) 962-979.

And this ultimate analysis of the woody biomass it shows high carbon content and oxygen content, respectively. And this higher lignin content and lower cellulose content indicates that the woody biomass has relatively lower H/C and the O/C ratio than the herbaceous biomass. And this we already discussed few slides before. I will just take you to those particular slides, where we compared the H/C and the O/C ratio of the woody biomass and the cellulose. That is nothing but the biomass which has a relatively higher carbohydrate content. And compared to that the woody biomass has relatively lower O/C and H/C ratio. Because here the carbohydrate content is relatively less than the herbaceous biomass.

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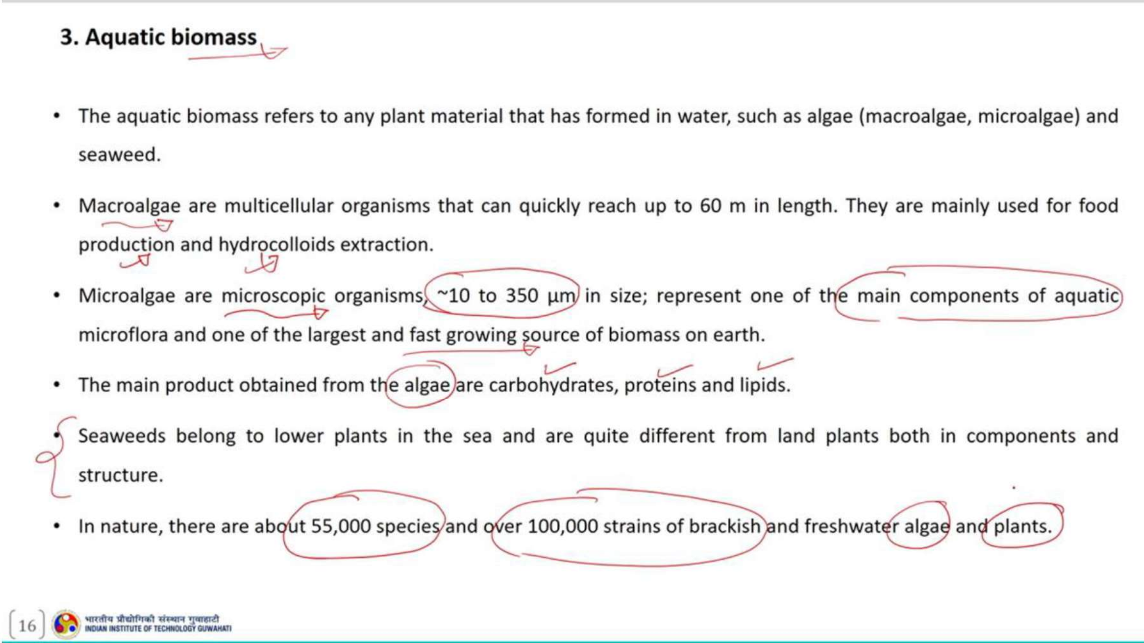

And the next classification is the aquatic biomass. The aquatic biomass refers to any plant material that has formed in water such as seaweed, microalgae, water hyacinth, etc. Macroalgae are multicellular organism that can quickly reach up to 60 meter in length. They are mainly used for food production and hydrocolloids extraction. Whereas microalgae are microscopic in nature and it ranges between 10 to 350 microns in size. It represents one of the main components of aquatic microflora, and one of the largest and fast-growing sources of the biomass on the earth. And the main product obtained from the algae are carbohydrates, proteins and lipids. Whereas seaweeds belong to the lower plants in the sea and are quite different from land plants both in the components and the structure. And in nature there are around 55,000 species and over 1 lakh strains of brackish and freshwater algae and the aquatic plants.

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Structural & Compositional analysis

- The composition of aquatic biomass varies depending on the growth conditions and nutrients.
- Aquatic biomass mainly consist of carbohydrates, proteins and lipids. Whereas the lignin content (<1 to 15%) is very low as compared to the lignocellulosic biomass.
- Seaweed contains higher amount of carbohydrates (upto 71-90%) than the proteins, lipids and lignin.
- Some species of macro- and microalgae are rich in protein (60-71%) and carbohydrates (33-64%), whereas few species of algae contains high amount of lipids (16-40%).

Biomass	Carbohydrate	Protein	Lipid	Lignin
Sargasuum spp. (Seaweed)	71–90	3–19	1–4	7–15
Ulva pertusa (seaweed)	76–87	2–5	1–2	1–2
Scenedesmus spp. (algae)	**21–52**	8–18	**16–40**	-
Spirogyra spp. (algae)	**33–64**	6–20	**11–21**	-
Chlorella vulgaris (algae)	12–17	**51–58**	**14–22**	-
Spirulina sp. (algae)	13–16	**60–71**	6–7	-
Blue-green algae (algae)	16–24	**55–63**	4–7	-

The structural and the composition analysis of the aquatic biomass indicates that the composition of the aquatic biomass varies depending on the growth condition and the nutrients which are used during its growth period. Aquatic biomass mainly consists of the carbohydrates, proteins, and lipids whereas the lignin contained in the aquatic biomass if you see here, it is relatively low compared to the lignocellulosic biomass. And seaweed contain higher amount of the carbohydrates than proteins and lipids, and even the lignin. And some species of macroalgae and microalgae are rich in protein and carbohydrate. Whereas few species of algae contain high amount of the lipid. It all depends on the growth-conditions and the nutrient used during their growth period. Because of that, if you could see here, there is a great variation in the composition of this aquatic biomass.

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Proximate analysis

- Proximate analysis shows great variation in the composition due to different aquatic (biomass) species.
- Aquatic biomass can be easily dried under sunlight, so the moisture content reduced to 8-14%.
- Aquatic biomass tends to have higher volatile matter content (up to 80%) and low ash content (up to 3%).
- These properties make it attractive for various applications, including biofuels production and biochemical processes.

Biomass group	Ultimate / Elemental analysis					Proximate analysis				HHV
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Municipal Wastes	57-61	21-25	7-8	1-2	6-12	43-62	12-13	3-9	23-34	10-20

Courtesy: Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 22 (2019) 962-979.

And similarly, the proximate analysis also shows here the large variation in the composition due to the different aquatic biomass species. Aquatic biomass can be easily dried under the sunlight so the moisture content can be reduced to around like 8 to 14% in the aquatic biomass. And this particular biomass tends to have higher volatile matter content and low ash content up to 3%. Whereas the highest limit of the ash content in this particular species is ~36%. And these properties of this biomass make it attractive for the various application including for the biofuel production and biochemical processes.

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- **Ultimate analysis**
  - ↦ Aquatic biomass shows moderate to high content of C and O, 27–43% and 34–46%, respectively.
  - ↦ Sulphur content is higher (1-3%) as compared to the lignocellulosic biomass.
  - ↦ Higher nitrogen content (1-10%) in aquatic biomass is due to the higher protein content.

Biomass group	Ultimate / Elemental analysis					Proximate analysis				HHV
	C (%)	O (%)	H (%)	S (%)	N (%)	VM (%)	FC (%)	M (%)	A (%)	MJ/kg
Herbaceous biomass	42-58	34-49	3-9	<1-1	<1-3	41-87	9-35	4-48	1-19	15-19
Woody biomass	49-57	32-45	5-10	<1-1	<1-1	30-80	6-25	5-63	1-8	16-22
Aquatic biomass	27-43	34-46	4-6	1-3	1-10	42-80	5-33	8-14	3-36	12-22
Municipal Wastes	57-61	21-25	7-8	1-2	6-12	43-62	12-13	3-9	23-34	10-20

Courtesy: Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 22 (2019) 962-979.

Ultimate analysis of this aquatic biomass shows moderate to high content of carbon and the oxygen in its composition. Whereas the sulphur content is slightly higher in this type of biomass compared to the lignocellulosic biomass. And that is mainly depends on the media composition which is used during its growth period. If the media composition contains relatively higher concentration of sulphur in its composition then these particular aquatic species or the cells of these aquatic species will uptake the sulphur and accumulate it during their growth period and which eventually reflects in its composition. Similarly, the higher nitrogen content in the aquatic biomass is mainly referred due to the higher protein contents in its composition.

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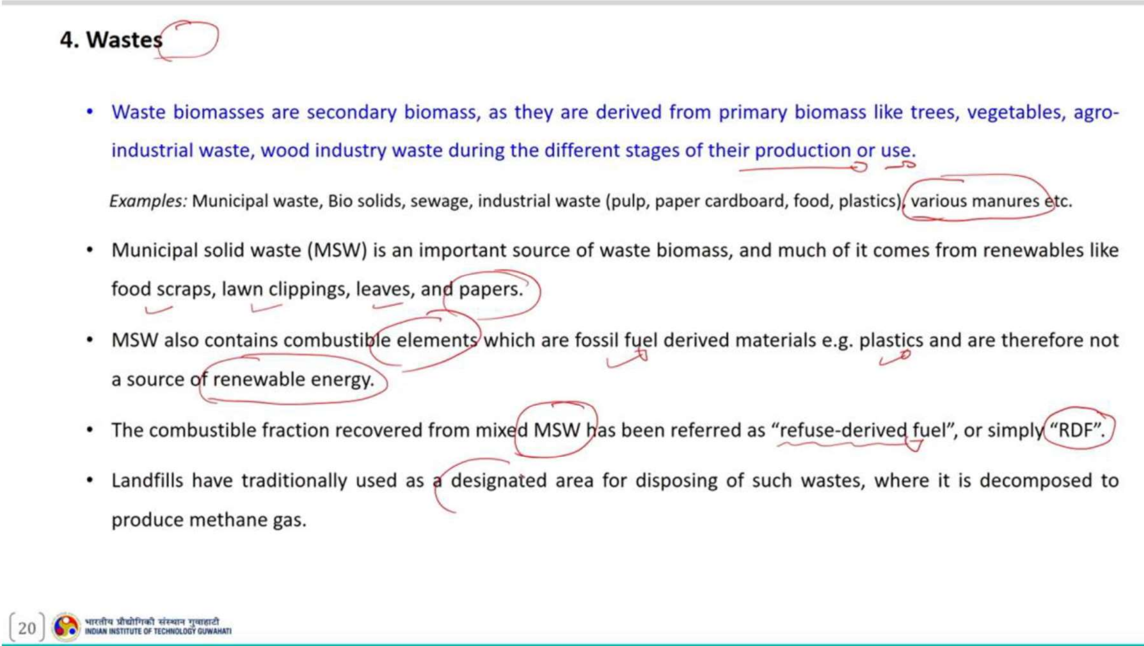

The waste biomass is secondary biomass as they are derived from the primary biomass source like trees, vegetables, agro-industrial waste, wood industry waste during the different stages of their production or use. And the example includes the municipal waste, bio-solids, sewage, industrial waste, and various manures but from the specific sources. However municipal solid waste is an important source of the waste biomass and much of it come from the renewables like food scraps, lawn clippings, leaves, and papers. MSW also contains the combustible element which are fossil fuel derived material, example the plastics and are therefore not a source of renewable energy. And this combustible fraction which is required from the mix municipal solid waste has been referred as a refuse derived fuel or simply termed as RDF. Even the landfills have been traditionally used as a designated area or site for disposing of such waste where it is decomposed to produce methane gas.

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- Composition of MSW varies as it is a mixture of various waste materials.
- Proximate analysis of MSW show higher content of **volatiles** (43-62%) and **ash** (23-34%) than other biomass materials.
- Ultimate analysis of MSW show higher content of **C** (57-61%) & lower content of **O** (21-25%) as compared to other biomass materials. Also, the **N** content is much higher in MSW (6-12%).

Biomass	**Cellulose (%)**	**Hemicellulose (%)**	**lignin (%)**
Municipal solid waste (MSW)	33–49	9–16	10–14
Newspaper waste	40–55	25–40	18–30

Biomass group	Ultimate / Elemental analysis					Proximate analysis				HHV
	C (%)	O (%)	H (%)	S (%)	N (%)	VM (%)	FC (%)	M (%)	A (%)	MJ/kg
Herbaceous biomass	42-58	34-49	3-9	<1-1	<1-3	41-87	9-35	4-48	1-19	15-19
Woody biomass	49-57	32-45	5-10	<1-1	<1-1	30-80	6-25	5-63	1-8	16-22
Aquatic biomass	27-43	34-46	4-6	1-3	1-10	42-80	5-33	8-14	3-36	12-22
Municipal Wastes	57-61	21-25	7-8	1-2	6-12	43-62	12-13	3-9	23-34	10-20

Courtesy: Tursi, A review on biomass: importance, chemistry, classification, and conversion, Biofuel Research Journal 22 (2019) 962-979.

And this composition analysis of the MSW also varies because it is a mixture of the various waste materials. So, as I mentioned just before, it is a heterogeneous material, which consist of cardboard material, papers, the food waste as well as the residual waste of the different fractions. So, as a result we can expect a great variation in its composition. And even the proximate analysis of the municipal solid waste, it shows higher content of volatile matter and ash than the other biomass material. Similarly, the ultimate analysis shows here the high content of carbon, however relatively lower content of the oxygen in its composition as compared to the other biomass materials. And also, the nitrogen content is much higher in the municipal solid waste, and the maximum limit also it goes up to 12% in the municipal solid waste. Now if we compare the composition analysis of the municipal solid waste with that of the newspaper, so the municipal solid waste has the cellulose and the hemicellulose contained in the range of this much.

Whereas the lignin content is relatively less in the municipal solid waste. However, if you compare it with the newspaper, then the carbohydrate content in the newspaper is relatively higher and even the lignin content is relatively higher in the newspaper waste. So, which shows the heterogeneity of this particular mix fraction of waste material. As a result, we can expect huge variation in the composition of the municipal solid waste.

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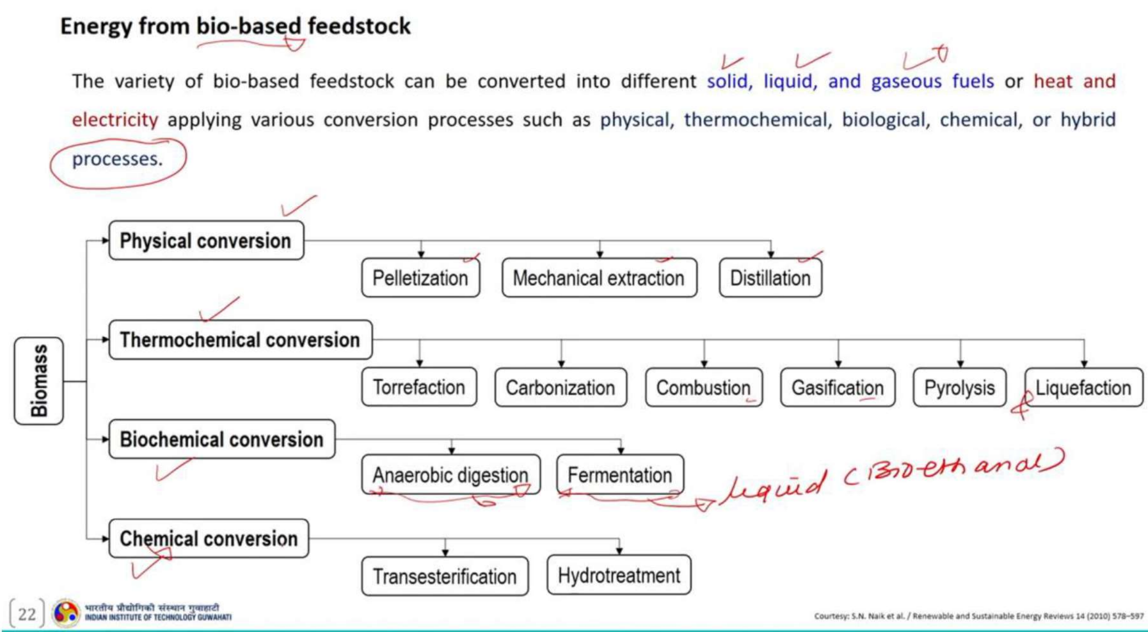

So, these different varieties of the bio-based feedstock material can be converted into either solid, liquid, and gaseous fuel as a product, applying various conversion processes such as physical conversion, thermo-chemical conversion, bio-chemical conversion and chemical conversion or even the hybrid conversion processes. So, the physical conversion here includes palletization, mechanical extraction and the distillation. And in this particular process the material is just transformed from one form to the another without undergoing any chemical reformation. While the thermo-chemical conversion processes include torrefaction, carbonization, combustion, gasification, pyrolysis, and the liquefaction process. And the bio-chemical conversion includes the anaerobic digestion and the fermentation processes which are very popular and widely used at a commercial scale for the production of gaseous product and liquid bioethanol as a product. And the chemical conversion processes include the transesterification and the hydro-treatment. So in this module as well as in the next module, we will be mostly discussing in detail about this conversion technologies.

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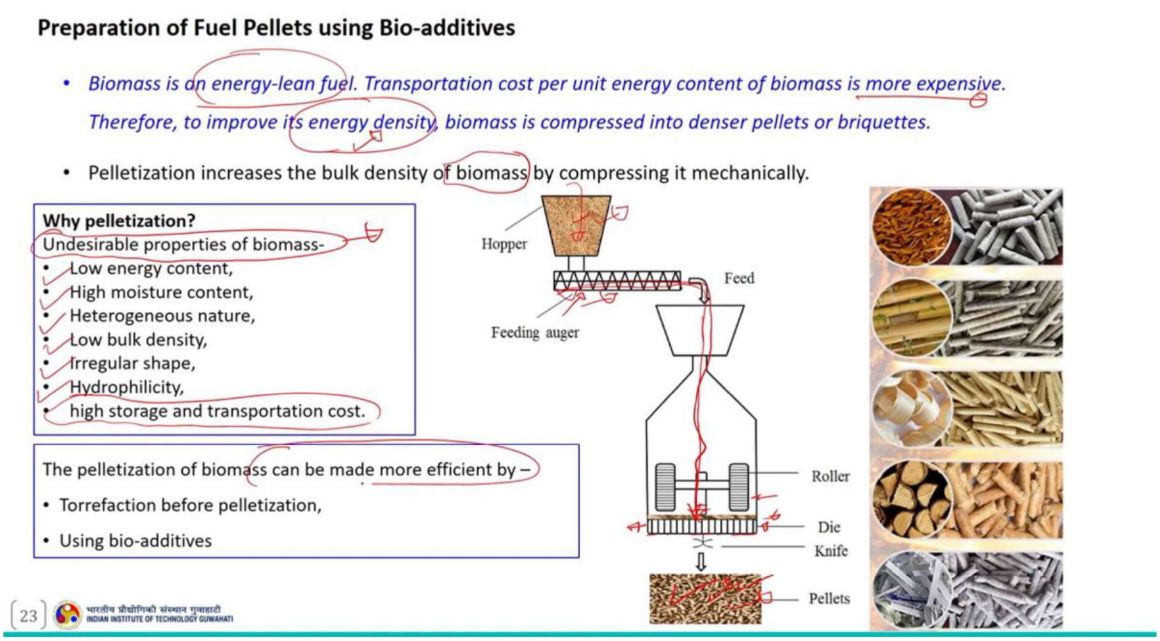

So, let us first discuss about the physical process that is a palletization. Since we know that the biomass is a energy lean fuel the transportation cost per unit energy content of the biomass is more expensive. And therefore, to improve its energy density, biomass is compressed into a denser pellet or the briquettes of this particular form, so that it improves its energy density. The palletization process basically it increases the bulk density of the biomass by compressing it mechanically.

Why palletization? Because it converts the undesirable properties of the biomass to the desirable properties. Because, if you look at the undesirable properties of the biomass, it has low energy content, high moisture content, heterogeneous in nature, as we discussed just now, low bulk density, irregular in shape, hydrophobicity, and requires high storage and the transportation cost. And once this material is converted into a pellet, ultimately it increases its energy density. Because the pelletization process reduce the moisture content to 7 to 10% than its original moisture content of around like even 40%. And even the pellets produced from this raw biomass sources shows high energy content.

This particular schematic here it represents the pelletization process. This is a hopper and then it feed this particular raw material into this particular pelletization chamber. And where the raw forms of the biomass convert into this kind of pellets. The pelletization of the biomass can also be made more efficient by torrefaction of the biomass before pelletization or by using the bio additives. So, let us discuss about this torrefaction and the bio additives process.

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Torrefaction-pelletization:

- Biomass is torrefied, cooled, grinded to required size and then subjected to densification under higher T & P.
- *Torrefaction is a process of production of carbon-rich solid fuels from biomass, by removing only the early volatilized low energy dense compounds & chemically bound moistures in a temperature range of 200 - 300 °C.*
- It increases the energy density of wood from 10.5–20.7 MJ/kg (by mass) or from 5.8–16.6 GJ/m³ (by volume)
- Through the pelletization and torrefaction could make transportation and handling of biomass competitive with that of coal.
- The net volumetric energy density can be calculated from HHV and pellet's bulk density (BD).

$$\text{Net volumetric energy density } (GJ/m^3) = HHV\,(MJ/kg) \times BD\,(kg/m^3) \times 10^{-3}$$

Biomass	Moisture (%)	Bulk density (kg/m³)	Heating value HHV (MJ/kg)	Net Volumetric Energy density (GJ/m³)
Fresh wood	35	550	10.5	5.8
Pellet of wood	8.5	575	15.9	9.2
Pellet of torrefied wood	3	800	20.7	16.6

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Courtesy: Biomass gasification, pyrolysis and torrefaction: Practical design and theory, by P Basu, Academic Press, 2013.

So, in case of the torrefaction the biomass is first torrefied then cooled and grinded to required size and then subjected to the densification under high temperature and pressure. And the torrefaction basically it is a process of production of the carbon rich solid fuels from biomass by removing only the early volatilized, low energy dense compounds, and chemically bound moisture in a treatment range of around 200 to 300 degree Celsius. And it increases the energy density of the wood from say 10.5 to 20.7 MJ/kg by mass and from 5.8 to 16.6 GJ per meter cube that is by volume. So that is what is the advantage of this torrefaction followed by the pelletization process, where it increases the energy density of the raw wood sample. And through this pelletization and the torrefaction that could make transportation and handling of biomass competitive to the conventional material that is coal. And the net volumetric energy density, it can be calculated from its HHV and the bulk density. And this is basically the conversion factor, because here we are converting the value from mega joule to giga joule. So, if you just compare the fresh wood, the pellet wood, and the pellet of the torrefied wood, we can see there is a significant decrease in the moisture content, whereas significant increase in the bulk density, even the heating value increase significantly from 10.5 to 20, i.e. almost like double. And also, the net volumetric energy density almost increases three times in case of the pellet of torrefied wood sample.

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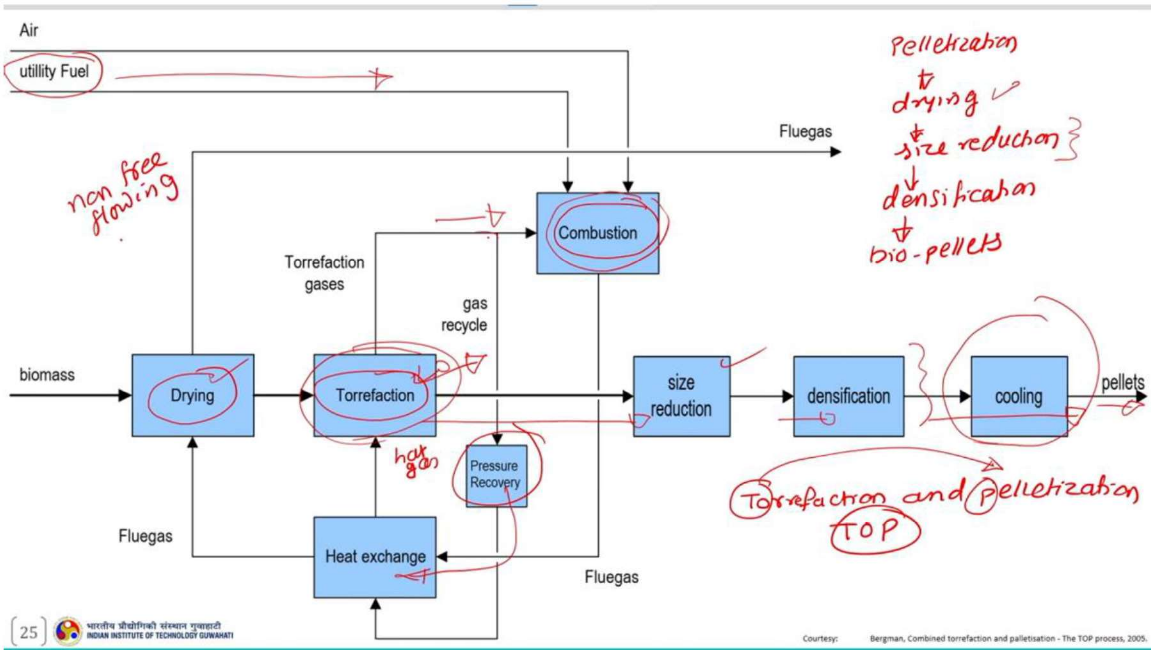

And this particular schematic here it represents the pelletization and the torrefaction process. Because a biomass pelletization process typically consist of drying and size reduction prior to the densification process and then densification. After densification these hot bio-pellets are cooled. Sometimes the steam conditioning is also used for the biomass, because it also enhances the densification process through the softening of this fiber. Since the biomass contains lot of fiber, so if the steam conditioning is given to such kind of raw material then because of that fibers get soften and it helps in the pelletization process. And the torrefaction, typically it consists of a pre-drying of the biomass then torrefaction and followed by size reduction and then densification and then hot densified pellets are cooled to obtain the torrefied pellets. So, if you compare both these processes, you can see, there is a great similarity exist between the basic structure of these processes. Because it also requires drying, normal pelletization process also require the drying operation. Then in case of torrefaction the intermediate operation comes as a torrefaction process, here the material undergoes the torrefaction process, and after torrefaction again it goes for the size reduction, as it has gone for the size-reduction in the normal pelletization process as well, followed by densification and the cooling operation.

So there is a great similarity which exist between these two processes. And that is why the **TO**rrefaction and **P**elletization also known as TOP process. It combines the torrefaction and pelletization as shown in this particular schematic. So, this schematic here it represents the conceptual process structure of the torrefaction. The process layout here is based on the direct heating of biomass during torrefaction by means of the hot gas that is recycled in this particular loop. The hot gas it consists of the torrefaction gas and this particular gas is recycling in this particular loop to provide the required energy during this torrefaction process.

The hot gas which is consist of the torrefaction gas itself is re-pressurized using this pressure recovery system and heated using this heat exchanger after each cycle. The necessary heat for torrefaction and the pre-drying is produced by the combustion of the liberated torrefaction gas in this particular combustion chamber. And possibly a utility fuel is used, when the energy content of this torrefaction gas is insufficient to thermally balance the torrefaction process. So, the heat balance which is observed in each recovery cycle can be balanced using this combustion process here with the use of utility fuel. This process concept is considered the most promising for torrefaction of the biomass. As it optimizes towards the heat integration and is considered as suitable for non-free flowing biomass and waste sample.

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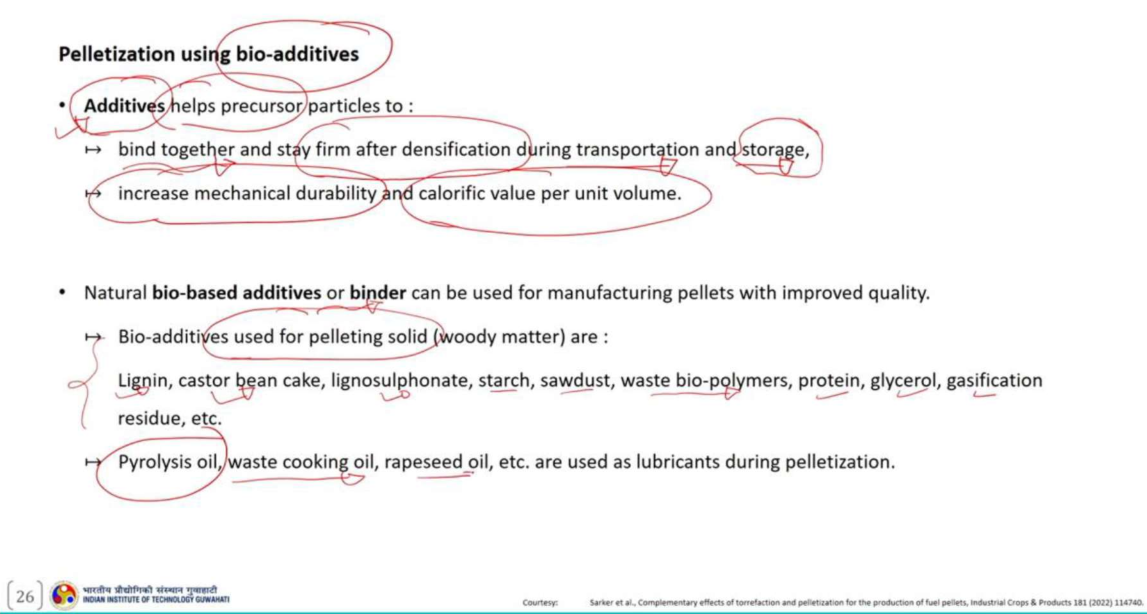

And the pelletization using the bio additives here, this additive basically it helps as a precursor particle to bind together and stay firm after the densification operation during the transportation and storage so that it can maintain their physical integrity. Also, the additives help to increase mechanical durability and the calorific value per unit volume. And that is the advantage of utilizing the additives during the pelletization process. And the natural bio additives or the binder that can be used for the manufacturing of the pellets with the improved quality includes the bio additives used for pelletizing wood sample, that is lignin is a natural bio additive or you can say the binder, the castor bean cakes, lignosulphonate, starchy material, sawdust, waste biopolymers, proteins, glycerol, and gasification residues are used as the bio-additives for pelletizing the solid wood matter.

Apart from that the pyrolysis oil, the waste cooking oil, and rapeseed oil are used as lubricants during this pelletization operation.

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- **Durability** refers to the ability of biomass or other feedstock to withstand mechanical forces and retain its physical integrity as a pellet.
- Durability is calculated as:

$$\text{Durability (\%)} = \frac{\text{mass of the pellet retained intact after dropping}}{\text{initial mass of pellet}} \times 100$$

Biomass	Bulk density (kg/m³)	Heating value HHV (MJ/kg)	Net Energy density (GJ/m³)	Durability (%)
Oat Hull (OH)	-	17.0	-	-
Canola Hull (CH)	-	17.8	-	-
Mustard Meal (MM)(bio-additive)	-	24.7	-	-
Torrefied pellet of OH+MM 3:1	512	23.0	11.78	77.9
Torrefied pellet of CH+MM 3:1	788	24.4	19.23	99.8

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Courtesy: Sarker et al., Complementary effects of torrefaction and pelletization for the production of fuel pellets, Industrial Crops & Products 181 (2022) 114740.

And if you just calculate the durability, so durability here refers to the ability of the biomass or other feedstock to withstand the mechanical forces and retain its physical integrity as pellet. With the help of this simple equation, we can calculate the durability of the prepared sample. Now, if you compare the pellets prepared using the bio additives, it shows significant increase in its bulk density as well as the heating value, and even the net energy density of pellets prepared using the bio additives is significantly higher. And the durability found to be much higher in case of pellets produced using the bio additives.

So, this particular sample represents the terrified pellet of oat-hull with this bio-additive in the ratio of 3:1. And this particular sample shows the pellet prepared from the terrified canola hull with bio additive in the similar ratio. And if you compare these two pellets, the pellets prepared from the canola hull shows significant improvement in its properties compared to that of the pellets prepared from the oat hull. Even the durability of the canola hull pellet is significantly higher compared to that of the previous sample.

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Technical specification for biomass pellets (Central Electricity Authority, India, 2018)

S.N.	Technical data	Unit	Guaranteed value range
1	Base material	-	Agro residue/ crop residue
2	Diameter	mm	Not more than 25 mm
3	Length	mm	Not more than 50 mm
4	Bulk density	kg/m^3	Not less than 600 kg/m^3
5	Fines% (length <3 mm)(ARB)*	wt%	Fines ≤ 5%
6	Gross calorific value (ARB)	MJ/kg	Non-torrefied pellets: 14.6 ± 0.5 Torrefied pellets: 18.8 ± 0.5
7	Moisture (ARB)	wt%	Not more than 9%
8	Ash (ARB)	wt%	Not more than 20%
9	Hardgrove Grindability Index (HGI)#	-	50 or more
10	Particle size distribution$ (After crushing and pulverizing)	wt%	Passing proportion from 2 mm mesh size sieve: ≥ 75% Passing proportion from 3 mm mesh size sieve: =100%

Note: ARB: As Received Basis,
*Assessment of Fines shall be as per durability test of pellets;
#Applicable for torrefied pellets.
$Applicable for non- torrefied pellets.

And this particular slide it represents the technical specification for the biomass pellets and this is obtained from this particular reference. Now, if you see the biomass material which is used for the pelletization process which includes the agro-residue and the crop residue. The diameter here is considered as not more than 25 mm for the pelletization and the length should not be more than 50 mm. The bulk density not less than 600 kg per meter cube. Fines in the sense of is like as-received basis it is in this particular range. The gross calorific value for the non-torrefied pellet it is 14.6 MJ/kg, whereas for the torrefied pellet it is around 18.8 MJ/kg. And the moisture content it should not be more than 9%. And that is what I mentioned few slides back, pelletization reduces moisture to even 7-9%. than the original moisture content in the raw biomass sample, which is around close to 30% or even 40%.

Ash on as received basis not more than even 20%. And this particular parameter which is called as a hard groove grindability index. It should be in this particular range. But the particle size distribution, it should pass proportion from 2 mm mesh size sieves and passing proportion from 3 mm mesh size sieves. And this particular information we obtain from this specific source. So, if you just go back to the previous table, so the pellets which are prepared using the oat-hull has literally lower bulk-density compared to that of the pellets which are prepared from the canola hull. And this particular bulk density is as per the standard specification limit of this particular table as well, which is not less than 600 kg/m^3.

Whereas the pellet prepared from oat hull has the bulk density of 512, which is less than the prescribed limit. Therefore, the specific suitable biomass source needs to be selected with the proper bio additive to achieve the prescribed standard limits of the fuel pellets, which can be further used in energy applications. With this we will end our lecture here. In the next lecture we will discuss about the thermochemical processes, that is carbonization and torrefaction.

Thank you.