A review on the characteristic of biomass and classification of bioenergy through direct combustion and gasification as an alternative power supply

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Abstract. Extinction of fossil fuel resources owing to excessive use has called up new solution-based resources called 'biomass' which is more affordable to deliver and utilize, bring less environmental damages such as greenhouse gas (GHG) emission, opened more employment opportunities in both rural or suburban areas due to the abundant availability of this resources throughout the world. About 44% of the energy required by the year 2030 and about 14% energy sourced from biomass in 2016 based on the World Bioenergy Association's data. Biomass can be sorted from various sources such as municipal solid waste (MSW), agricultural crops, crop residues, and forest residues. The clear cut of biomass characteristics in proximate analysis and ultimate analysis makes it possible to produce reliable energy resources. Biomass is multi-faceted fuel; thereof, it produces biofuel, which can be used in transportation and bioenergy to generate cleaner and affordable electricity throughout the world. In that sense, in this article, the characteristics and functionality of different thermochemical processes such as direct combustion and gasification have been discussed, and the reliability and new findings in various aspects in the bioenergy field. Furthermore, the advantages and disadvantages have been discussed to substantiate further the core objective of renewable energy in producing better, cheaper, and harmless to the surrounding environment. This study will give a brief understanding of the right way of using biomass and indirectly reduce the usage of fossil fuel, thus reserving a better world for the future generation.

1. Introduction

Anything that burns off will turn into ashes, but a fossil fuel burns off to produce energy. The basic rule of thumb behind non-renewable energy source-based vitality is more affordable to deliver and utilize than power from sustainable sources. However, the cost of unrefined oil has reached 141usd/barrel toward the beginning of July 2008 in contrast with the value during the '80s and '90s, whereby it is as low as 20usd/barrel. For example, as of late, petroleum products, oil, coal, and flammable gas have comprised a definitive energy source on the planet, whereby roughly about 80% of the overall energy utilization of more than 400 EJ every year as appears in Figure 1(Source: IEA
This world energy demand expending issue has compelled digging unconventional energy solutions to restore immense usage of conventional fuel.

Fig. 1 Global energy consumption from the year 1980 to the year 2050 (Adopted: IEA 2019)

The International Energy Outlook (2009) ventures that the world advertised energy utilization are required to increment by 44% by 2030 because of expanded interest from the under-developing nations such as India and China. Notwithstanding, it is foreseen that these wellsprings of energy will be drained inside the following 40 years to quite a while from now, and it takes almost a millennial to renew it. Also the environmental destruction such as "global warming, acid rain, and urban smog due to the discharges from conventional fossil fuel sources; therein the world attempts to diminish carbon outflows by 80% and move on the road in using an assortment of renewable energy sources (RES)", which are little destructive to the environment such as "solar, wind, biomass," and others in an imperishable manner [1]–[6].

1.1. World Energy

Renewable-based energy slanting since the late 1970s and U.S policymakers at both the government and state levels have established an assortment of incentives, guidelines, and programs to encourage cleaner, renewable energy agricultural-based sources. Based on the data projected by World Bioenergy Association in the year 2016, the trajectory of biomass energy is still in the most significant rate of about 14% in correlation with the total percentage of a sustainable power source, which is 18% from the general absolute world energy utilization appeared in Figure 2 [6].

Fig. 2 Different fuels contribution to total world energy consumption based on data from the World Bioenergy Association [6]
Despite the fact that there is an assortment of sustainable power sources accessible on the planet, energy derived from biomass is still making a benchmark due to little dependency on geographical location and climate variation, which are proven diversification factors of biomass can grow in heterogeneous conditions. The above facts have been conditioning with the 10% of global energy supply contribution are from biomass [7], [8] as well as it is liquidating millions of tons of vital carbon stocks amidst of a climate crisis which is already out of control and it is merely a belief that one day 80% of fossil fuel utilization will be supplanted by biomass globally.

Biomass ingests carbon dioxide (CO\textsubscript{2}) during the developing period and discharges it during ignition in kilns. In this manner, biomass aid the process of reusing of (CO\textsubscript{2}) from the atmosphere and does not contribute further to any of the greenhouse gaseous (GHG) such as CO\textsubscript{2}, methane (CH\textsubscript{4}), nitrogen dioxide (N\textsubscript{2}O), and biomass expends the same amount of CO\textsubscript{2} from the environment during the development period whereby it discharges during incineration which in scientific terms addressed as 'carbon neutral' [9].

1.2. Biomass vs fossil fuels

There will be pros and cons in utilizing every type of fuel in the world. Such a criterion is not ignorable in both biomass fuel and fossil fuels to produce prime energy source. Table 1 explains fossil fuels and biomass advantages and disadvantages in power generation [10]–[16].

| Fuel types | Advantages | Disadvantages |
|------------|------------|---------------|
| Biomass | Various categories of fuel; such as crops, municipal waste, sewage from animals, and forest residues | Most of the lignocellulosic material has a high amount of moisture, which needs to be evaporated before it ignites and indirectly reduces the efficiency of the boiler |
| | Can use together with coal to produce less toxic emission by specific ratios and recent studies collaborated with solar PV | Individual material prep needed such as densification (pelletization, briquette, agglomerating) |
| | Production cost is much cheaper compared to fossil fuels as the derivatives or biomass residues can be used again to produce biofuels (2nd generation biofuels) | Limited usage in power generation due to the cascade principle (reuse, recycling, bioenergy, and disposal), |
| Fossil fuels | High calorific value in comparison with biomass fuel and can produce much efficient energy by burning it. | Extinction of fossil fuel could cause an increase in price indirectly due to the demand more than production in the energy market |
| | Accessible to energy access with no geographical limitations | Excessive use of fossil could create grave environmental issues such as climate change due to CO\textsubscript{2} emission |

2. Cycle of biomass

Biomass is a mix of both 'bio + mass' words that imply animal and plant origin, incorporating algae, trees, and crops. It demonstrates with the organic matter attained from plants which produced through photosynthesis. The conversion of the sunlight into organic matter by the plant through photosynthesis incorporates multi-faceted vegetations both above ground level and under terrestrial water vegetations as well as natural waste, and when it is being burned in kilns, the energy transformed from chemical energy into mechanical energy and finally to electrical power [17].
Agricultural crops, crop residue, and forestry products are the basic types of solid biomass [18], these biomass utilized (CO$_2$) from the atmosphere to assimilate carbon using energy from the daylight. Creatures that ate up the plants may, in this way, convert biomass into excrement, but the underlying absorption carries out by plants. The plant will be either decomposed by natural microorganisms or will be burned in incineration if it is not consumed by herbivorous yet in a case on the off chance that if it has naturally deteriorated than it discharges back the carbon in the form of (CO$_2$) or methane (CH$_4$) gas to the atmosphere, decided upon the conditions and processes involved. These processes will be continuous until the cycle gets interrupted on earth, known as the net carbon emission. Figure 3 illustrated the cycle of biomass energy, and equation (1) and equation (2) show the plant's conversion process through photosynthesis [19].

$$\text{Water} + \text{CO}_2 + \text{Sunlight} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + \text{O}_2 \quad (1)$$

$$6\text{H}_2\text{O} + 6\text{CO}_2 + \text{Radiant energy} \rightarrow \text{C}_6\text{H}_{12}\text{O} + 6\text{O}_2 \quad (2)$$

In an ordinary definition of energy outlook, biomass accumulated in general from living organisms such as plant resources and animals and wastes emerges from them. The usage of biomass as an energy purpose will diversify the energy supply and reduce fossil fuels' dependency due to the resource's bountifulness. According to Bhattacharyya, suburban cities in under-developed nations using 64% of firewood for cooking and other heating purposes and another 24% depending on the crop residues and dried cow dung due to its availability over the entire country [20]. This inefficiency and unsustainable biomass resources use cause severe side effects in the long run due to indoor air pollution exposure. It is also expected that biomass can be used to feed ruminant animals such as cows, chicken, and others, creating new job opportunities in suburban and urban cities in the world.

3. **Sources of biomass**

Globally biomass sources available from various categories, but the primary four sources which benefited the power industries are "agricultural crops, agricultural waste(crop residues), forest residues, and municipal solid waste" [21], [22]. Ahmann et al. have been divided further into three main classifications: solid in non-woody biomass and woody-biomass, liquid from processed waste, gas from processed fuel, as depicted in Table 2 below [23].
### Table 2. Sources of Biomass [25]

| Type of Biomass         | Processed waste (PW) | Processed fuels (PF) | Non-woody biomass (NWB) | Woody biomass (WB) |
|-------------------------|----------------------|----------------------|-------------------------|--------------------|
| Sawmill wastes          | Charcoal (wood & residues) | Energy crops (sugarcane) | Shrubs |
| Plant oil cake          | Briquette & densified biomass | Cereal straws | Trees |
| Waste from fruits       | Biogas               | Tobacco, cassava, cotton, stems & roots | Bushes (coffee & tea) |
| Nutshells and flesh     | Plant oil from palm, rape & sunflower | Grasses | Forest floor sweepings |
| Bagasse                 | Producer gas         | Banana               | Palms |
| Cereal husk             | Methanol & Ethanol   | Soft plant stems     | Bamboo |
| Industrial wood, bark & logs |                     | Water plants         |         |

### 3.1. Agricultural crop (energy crop)

A land without crops is just like a king without a crown. Natures have given a plethora of benevolence to humankind to convert lands into food. Science innovation has opened another passage of energy production through food crops. The farmland previously adopted for growing food crops has substituted to a land of energy crops production. Quispe et al. has performed a study on agriculture production and found that this agricultural crop variation is based on the type of soil, agronomic handling, climate conditions, and other parameters [24]. Several agricultural crops can be used in energy production, such as wheat, cotton, cassava, rice, palm fruits, and others; table 3 summarizes the six world major agricultural crops from 2018 and 2019 [25].

### Table 3. Listed summary of world major agricultural crop from the year 2018 to 2019[27].

| Year | World Total Million Metric Tons (MMT) | Foreign United States | China | India | Pakistan | South America | Selected Others |
|------|--------------------------------------|-----------------------|-------|-------|----------|---------------|-----------------|
|      | Wheat                                |                       |       |       |          |               |                 |
| 2018 | 763.1                                | 715.7                 | 47.3  | 134.3 | 98.5     | 26.7          | 18.5            | 21.0            |
| 2019 | 733.4                                | 682.2                 | 51.3  | 132.5 | 99.7     | 22.5          | 19.5            | 19.0            |
|      | Coarse grain                         |                       |       |       |          |               |                 |
| 2018 | 1357.3                               | 973                   | 384.3 | 266.6 | 47.0     | 6.2           | 39.3            | 13.0            |
| 2019 | 1373.6                               | 988.5                 | 385.1 | 263.8 | 42.3     | 6.8           | 50.4            | 13.5            |
|      | Rice                                 |                       |       |       |          |               |                 |
| 2018 | 495.1                                | 489.4                 | 5.7   | 148.9 | 112.9    | 7.5           | 0.9             | 0.5             |
| 2019 | 491.1                                | 484.2                 | 6.9   | 143.6 | 111.0    | 7.4           | 0.8             | 0.5             |

### 3.2. Agricultural waste (crop residues)

Farmers produced an enormous amount of agricultural waste or crop residues from their farming activities, and it is begun directly from the beginning of the harvesting process on the farm. There are six categories from 39 residues from 26 crops explained by Hiloidhari et al. in Table 4 [26]. These horticultural wastages, which left untreated on the field, can cater to soil erosion and process a small number of nutrients back into the farm-fields without upsetting the soil fertility; again, some farmers from developing countries may openly burn it on the field causes loss of energy, which can be transformed to yield vital energy for consumers[27].
Table 4. shows six main categories of crop group with residues produced from the crops[28]

| Crop group | Crop               | Residue | RPR (MJ/kg) | (HHV) heating value, MJ/kg |
|------------|--------------------|---------|-------------|---------------------------|
| Cereal     | Rice              | Straw   | 1.5         | 15.54                     |
|            |                   | Husk    | 0.2         | 15.54                     |
| Wheat      | Shoot             | 1.5     | 17.15       |
| Maize      | Cob               | 0.3     | 17.39       |
| Bajra      | Shoot             | 2       | 16.67       |
| Barley     | Straw             | 1.3     | 18.16       |
| Small millet | Straw         | 1.2     | 18.16       |
| Ragi       | Straw             | 1.3     | 18.16       |
| Jowar      | Cob               | 0.5     | 17.39       |
|            | Husk              | 0.2     | 17.48       |
|            | Shoot             | 1.7     | 18.16       |
| Oilseeds   | Mustard and rapeseed | Shoot | 1.8 | 17 |
|            | Sesame            | Shoot   | 1.47       | 14.35                     |
|            | Niger             | Shoot   | 1          | 14.35                     |
|            | Linseed           | Shoot   | 3          | 13.9                      |
|            | Safflower         | Shoot   | 1.7       | 16.99                     |
|            | Soybean           | Shell   | 0.3       | 15.56                     |
|            | Groundnut         | Shoot   | 2         | 14.4                      |
|            |                   | Shoot   | 3         | 17.53                     |
| Sunflower  |                   |         |            |                           |
| Pulses     | Tur (arhar)       | Shoot   | 2.5       | 18.58                     |
|            | Lentil            | Shoot   | 1.8       | 14.65                     |
|            | Gaur              | Shoot   | 2         | 16.02                     |
|            | Gram              | Shoot   | 1.1       | 16.02                     |
| Sugarcane  | Sugarcane         | Bagasse | 0.33      | 20                        |
|            |                   | leaves  | 0.05      | 20                        |
| Horticultural | Banana         | Peel    | 3         | 17.4                      |
|            | Coconut           | Frond   | 4         | 10                        |
|            | Arecanut          | Husk    | 0.53      | 19.4                      |
|            |                   | Frond   | 3         | 18.1                      |
|            |                   | Husk    | 0.8       | 17.9                      |
| Others     | Cotton            | Shoot   | 3.8       | 17.4                      |
|            | Jute              | Shoot   | 3.8       | 17.4                      |
|            |                   | Husk    | 1.1       | 16.7                      |
|            |                   | Boll    | 1.1       | 19.7                      |
|            |                   | shell   | 2         | 18.3                      |
|            |                   | Shoot   |           |                           |
3.3. Forest residues
The definition of biomass in terms of forest biomass involves only the above-ground components of plants or trees, as due to the reason lies behind it are substantially counted on the total forest living trees and does not project too much on the logistical forest estimation [28]. This statement has been further added in the "Food and Agriculture Organization (FAO)" on the evaluation of forest resources estimation lies within a diameter equal to or greater than 10cm only [29]. Therefore, forest undergrowth and forest floor fine litter are disregarded under forest biomass material estimation.

A Forest residue generates woody biomass residues from timber logging. It is regarded that roughly a quarter of total global forest land covering almost 5B hectares is of wooded land globally according to world forest statistics by FAO. It is estimated that about 50% of these residues fall under developing nations. There are two types of residues within the category: direct residues (whole trees, branches, and leaves) and processed forest residues (sawdust and logs). The production of the forest residues depends upon the selection of tree species and local geographical conditions beforehand. The processed residues are further divided into primary and secondary forest resources [30].

3.4. Municipal solid waste
"Municipal Solid Waste (MSW)" discard has been a vital solicitude in most urban cities globally, and it has reached an alarming stage. Burke et al. [33] has performed a study on the global solid waste management (SWM) and expected that the rates of waste generation would be facing an alarming stage of escalation from 1.3 billion tonnes (MSW) annually to 2.2 billion tonnes by 2025, which is almost twofold in the next twenty years in low wage countries [31]. In addition, Burke et al. further added that globally, the cost of (SWM) would show a sturdy growth from today's annual of £165.56 billion to about £302.67 billion in the year 2025 [31].

MSW is a heterogeneous character of the waste in nature as it comprises households, including food waste, healthcare, and industrial waste, which are not segregated accordingly and are all disposed into the same landfill [32]. This MSW has to be segregated before undergoing a specific thermochemical or biochemical process to use it in the most sustainable ways formed by converting waste-to-energy.

MSW can lead to one of the most pernicious local pollutants if left unattended, which will cause serious public issues such as pollution of air, flooding, and public health deterioration such as respiratory diseases (asthma), diarrhoea, and dengue fever. Apart from that, MSW can produce a large amount of methane gas, causing short-term powerful GHG emissions in the surrounding atmosphere. Lately, several methods have been introduced to cater to the disposal of MSW around the world, such as follows:

1) Sorting ———> Recycling
2) Incineration (Combustion) ———> Heating/ Electricity/ Compost(fertilizer)
3) Anaerobic digestion ———> Bioenergy/ Compost/ Electricity
4) Landfilling ———> Bioenergy/ Compost

MSW can be collected and recycled into many useful end products or burn it in an incineration boiler to produce power or go through anaerobic digestion to produce bioenergy, compost, or electricity and landfilling to produce bioenergy or compost.

4. Composition of biomass
Biomass can be dissected into a structural composition and chemical composition to understand further biomass availability and readiness for biochemical and thermochemical processes. It is a prerequisite in studying the biomass material before it can be transformed into biofuels, biogas, or rich compost to be used as fertilizers in agricultural industries.
4.1. Structural composition
In general, the biomass structural analysis is significant for procedures improvement in delivering different fuels and synthetic substances and investigating the ignition phenomenon. Apart from that, the structural analysis assumes a substantial job in the presumption of the "higher heating value (HHV)" as well. The structural composition has become one of the most talk-about criteria in biomass fuel for any type of energy generation. Among all these structural compounds such as lipids, protein, simple sugar, and starches, a varying amount of "cellulose, hemicellulose, and lignin" has become three core elements of biomass structural composition. The most inner part of cellulose (C₆H₁₀O₅) promotes a packing density that increases a biomass strength in biomass inner wall due to the nature of establishing "intra-molecular and inter-molecular hydrogen bond," where it is weight up to "500,000 units monomers" [33]. The primary cell walls structure of biomass made up of heteropolysaccharides such as hexoses and pentoses is a hemicellulose element that strengthens the whole unit [34]. Whereas lignin is a three-dimensional (3D) element build primarily by carbon-oxygen and carbon-carbon linkages[35]. The fraction of water and inorganic substances present in biomass too. "The compound of cellulose, hemicelluloses, and lignin are called lignocellulose, which comprises around half of the plant matter produced by photosynthesis and represents the most abundant renewable organic resource on earth." "Cellulose, hemicelluloses, and lignin are strongly intermeshed in lignocelluloses and are chemically bonded by non-covalent forces or covalent cross-linkages" as shown in Figure 4. "Cellulose is the largest component of lignocellulosic materials, followed by hemicellulose and lignin. Besides, cellulose and hemicellulose are macromolecules constructed from different sugars; lignin is an aromatic polymer synthesized from phenylpropanoid precursors," which were illustrated as structural composition shown in Table 5 [36].

![Fig. 4. shows the structural composition of lignocellulosic biomass feedstock](image)

| Feedstock sample | Lignin | Cellulose | Hemicelluloses |
|------------------|--------|-----------|---------------|
| Hazelnut         | 42.9   | 26.8      | 30.4          |
| Wheat Shell      | 18.6   | 28.8      | 39.4          |
| Olive husk       | 48.4   | 24.0      | 23.6          |
| Almond shell     | 20.4   | 50.7      | 28.9          |
| Walnut shell     | 52.3   | 25.6      | 22.7          |
| Sunflower shell  | 17.0   | 48.4      | 34.6          |

4.2. Chemical composition
A composition of chemicals substances and elementary elements present in each biomass determines its ability to produce a better fuel source in contrast with fossil fuel. An urgent need for substitution and employment of biodegradable material as an alternative fuel instead of conventional fuel for the age of power production is that biomass has high volatility contrary to traditional power sources. This
statement has been further proven from the biomass lower ignition temperature than fossil fuel sources such as coal. Despite that, biomass holds significantly fewer carbon and oxygen, which directly impacts being too high in polarity and lessens the molecules' heat content. This aspect will be discussed further in the upcoming section in the "proximate and ultimate analysis" of biomass materials.

4.2.1. Ultimate analysis
In viewing biomass fuel properties, the ultimate analysis is associated as a notable element. It assists with evaluating the percentage of each element such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N), chlorine (Cl), and sulphur (S) present in each sample of biomass and the effect of these components towards the combustion in boiler and environmental outlook. Moreover, it assists in the computational proportion of C, O, H heating value estimation of the biomass sample. Stummann et al. has performed a catalytic hydropyrolysis of biomass using a Como catalyst's deactivation and found biomass samples with a higher C and H percentage, notably proof of higher heating value [37]. "Biomass with higher nitrogen (N) and (S) will cause the production of toxic gaseous such as oxides of nitrogen (NOx) and sulphur oxides (SOx) during the combustion which is the paramount cause of acid rain and releases of particulate matter (PM)" [38]. The majority of biomass material contains sulphur of less than 0.2%, with only certain biomass fuels, go as high as 0.5%-0.7%[17].

4.2.2. Proximate analysis
In considering the combustion behaviours of biodegradable feedstock in the boiler, the percentage of "volatile matter, fixed carbon, and ash contents" is determined or evaluated through proximate analysis. On occasion, biomass containing high moisture content needs extra heat or energy before it can be ignited; thereof, this type of biomass material is better suited in producing biofuels. The low melting point of the dissolved ash contents in biomass fuels causes fouling and slagging issues in the boiler, and if left untreated, it might generate paramount combustion issues and deterioration of boiler equipment and worst comes the worst, cost of maintenance will be incurred with time. Nevertheless, the biomass material's high volatility will lead to numerous favourable circumstances with low ignition temperature and retained ignition for a more extended period. Also, the heating value of biomass material is determined by the "fixed carbon and volatile matter; an increase in any of this element will increase the heating value" of the feedstock too. Table 6 shows seven different types of biomass material with the proximate analysis[39].

| Biomass        | Moisture (%) | Volatile matter (%) | Ash (%) | Fixed carbon (%) | Gross calorific value Kcal/kg |
|---------------|--------------|---------------------|---------|------------------|------------------------------|
| Saw dust      | 13.8         | 72.9                | 0.6     | 12.7             | 4028                         |
| Groundnut shell | 10.1        | 68                  | 2.8     | 19.1             | 4008                         |
| Coconut husk  | 13.4         | 56.7                | 2.4     | 27.5             | 3800                         |
| Rice husk     | 7.2          | 61.8                | 16.4    | 14.6             | 3729                         |
| Sugarcane bagasse | 4.5      | 77.1                | 2.4     | 16               | 4547                         |
| Jatropha cake | 7.3          | 65.1                | 8.3     | 19.3             | 4725                         |

4.2.3. Higher heating value (HHV)
The total energy released by a kilogram of fuel when it is fully combusted expressed as (kJ/kg) shown in Eq.(3) below is referred to as high heating value (HHV) [40]. The produced HHV value is a function of chemical fuel elements. HHV can be exhibited in two methods as either HHV or lower heating value (LHV). The contrast between both terms is the water vapour, which does not add to the LHV calculation. From a broad perspective, not all biomass has the same amount of HHV, and this is
solely depending on the variation from one type of plant to another type of plants, such as sawdust and bamboo leaves, as shown in Table 6 [39]. Stolarski et al. evaluated biomass quality in terms of the heat content of a chosen woody biomass depending on the soil improvement practice and the surrounding climate and in which it is grown and other growing parameters [41].

\[
\text{HHV (kJ/g)} = 1.1783 \text{H} + 0.3491 \text{C} - 0.0211 \text{A} - 0.0151 \text{N} - 0.1034 \text{O} + 0.1005 \text{S} \tag{3}
\]

5. Classification of biomass energy
The present innovation of energy from biomass derivatives is at the highest peak, carbon-neutral, yet the sum of CO\(_2\), which pre-existed for a significant number of years in the environment from the past fossil fuel activities, is as high as it is impossible to be absorbed back by soils and trees. Therefore, it is critical to diminish the worldwide CO\(_2\) outflows by energy age advancements that are carbon negative. This section gives an idea of changes in biomass into energy with a crucial remark to the bio-refinery idea. The ongoing advancements in the zone are likewise featured, and the pros and cons in each area are stipulated in upcoming sections.

Biomass energy is termed as 'Bio-energy,' and it is one of the infinite energy resources on our planet, and it has been used as a source of energy from the beginning of the human race. The energy derivatives from biomass and recent discoveries in technological advancement have extraordinary possibilities in resolving the energy crisis looked specifically by developing nations. Biomass advancement is an effective alternative method to discard open waste gathered in enormous amounts and ways every day from the urban and rural sectors. Bioenergy can be divided into two subsystems, which are biofuels and bio-power. In each of these bio-energy conversions, pre-treatment needed thermochemically or biochemically to produce biofuels, bio-products, or bio-power to a grid system. Figure 5 illustrated the biomass’s conversion process to produce end products such as biofuels, bio-products, and bio-power.

![Illustration of biomass conversion into end products such as biofuels, bioproducts, and biopower](image)

**Figure 5.** Illustration of biomass conversion into end products such as biofuels, bioproducts, and biopower

5.1. Biofuels
The biomass can be remoulded into "other forms of energy such as liquid biofuels, gases (syngas, hydrogen and others) and electricity accessible via the technologies and processes involved as in thermochemical or biochemical ways [42]. The conversion of biological matters such as corn, sugar cane, maize, and others, transformed into ethanol via fermentation, is called transportation biofuels, whereas soybean, canola, vegetable oil, or waste fats are biodiesel formed of a biofuel[43]. Bio-fuels can be divided further into four-generation groups, "such as first-generation (1G), second-generation (2G), third-generation (3G), and lastly, the fourth generation" [44]. Biomass composition and calorific values depend on the biomass nature and process involved[45].

This paper is not going in-depth on biofuel; instead, it focuses on bioenergy and its application. The accompanying segment gives a review of the diverse biomass transformation advances created to date.

5.2. Biopower
The biomass consumption to generate energy could vary from one to another in terms of the end product generated from each conversion, as depicted in Figure 6. It can be thermal energy generated
directly from biomass burning or the vent gases produced from the combustion. The generated heat from the processes, as mentioned earlier, is utilized to produce steam, which indirectly can be reutilized certainly as either process heat for specific material production industries or transformed into power denoted as "bio-power" by supplying it via a steam turbine. In particular, biomass conversion's key objective prior to its use is to improve the relatively low characteristic of the material as fuel, as fuel made up of biomass material is still exceptionally low in energy density. This problem can be catered easily by redesign to fit into the "high energy density fuel markets such as charcoal, liquid fuels, and gaseous fuels." This bio-fuel conversion will be the new advancement in bioconversion processes.

![Figure 6. Biopower Classification and conversion into energy](image)

In recent years, about half of all bio-power generation occurs within the forest products industry, where mills use their non-marketable waste biomass to provide power and heat for their operations. Table 7 forecasts the renewable energy growth comparison from the year 2017-2050[47]. Bio-power can be subclassified into two major conversions: thermochemical conversion and biochemical conversion[46]. Combustion, gasification, and pyrolysis are categorized as a primary energy source by thermochemical conversion. In contrast, anaerobic fermentation, aerobic fermentation, and enzymatic conversion are categorized under the secondary energy source, which chemically altered through biochemical conversion to produce thermal energy, electrical energy, and biofuels. In this article, only two thermochemical processes will be discussed, which are direct combustion and gasification.

Table 7. Breakdown of renewable energy growth from 2017–2050 [47]

| Renewable energy with units | 2017 (GW/yr) | 2018-2050 (GW/yr) | Final Consumption (2012-2050) (ppt/yr) |
|----------------------------|-------------|------------------|--------------------------------------|
| Wind (GW/yr)               | 53          | 154              | 0.33                                 |
| Solar PV (GW/yr)           | 99          | 210              | 0.21                                 |
| Solar Thermal million m²   | 30          | 283              | 0.10                                 |
| Bioenergy (GW/yr)          | 5           | 12               | 0.03                                 |
| Geothermal (GW/yr)         | 0.6         | 7                | 0.03                                 |
| Hydro (GW/yr)              | 25          | 17               | 0.05                                 |

5.2.1. Combustion

Combustion is the most straightforward route of the thermochemical reaction of a fuel with oxygen to generate CO₂, tar, water vapour, heat, alkaline ash particles and smoke as a by-product of the reaction[48] shown in equation (4) [49].

\[ C_xH_yO_z + aO_2 \rightarrow bH_2O + cCO_2 + dSO_2 + eN_mO_n + \text{Energy} \]  

(4)

During the primaeval age, the energy which has been employed in the agricultural products drying method or to generate heat or steam can be obtained through direct combustion, and it is unbelievable...
that roughly 90% of biodegradable material that has been used as energy derivatives are subjected through this combustion route globally[50]. Direct combustion very common in Central and South America used in agrarian process industries such as rice, coffee, sugar cane, and others[51]. In 1989, a biomass-based power plant was first introduced in the United States with a 6GW power supply[52].

In the past, direct combustion using biomass as fuel has been viewed as a method to dispose of organic waste. The use of these low-cost fuels indirectly resulting in a low-efficiency boiler, which relatively has opened a new horizon towards the energy production technologies in today's power generation advancement. Besides that, the rising organic waste price and local factors such as taxes, fuel prices, and emission control standards (environmental legislation) have impacted the trading between investment and efficiency.

The interaction between fuel, energy, and environmental aspects can be considered the three fundamental combustion applications. The ignition of biomass fuel in the boiler causes combustible vapours' volatilization, which burns like flames. This unpredictable degradation resulted from the combustion comprises three divisions, such as the vaporous part of (CO, CO₂, and H₂), a condensable portion of (H₂O, aldehydes, ketones) and tar and alcohols part containing (furan, phenolic mixes, and sugar deposits). In excess air, the leftover material, which remains a carbon char, will consequently be burnt. The heat resulting from the combustion process can be used as a source for secondary conversion processes to produce electrical energy, which again depends on some other factors.

Few internal factors contribute to biomass material's combustion efficiency, such as moisture content, ash content, heat dissipation, and incomplete combustion. The content of biomass moisture differs from one type to another type of biomass; for example, agricultural residues have the lowest moisture content of 10-12% compared to wood residues and bagasse, which is as high as 50%. Therefore, it is proven that moisture content less than 50% will be the best prominent for combustion as the moisture content not only inhibit the combustion, but it can cause significant energy loss in the form of latent heat of steam, as well as rendering the material purification which indirectly reduces the net energy from the overall process. The presence of fixed carbon and volatile matter plays a vital role in combustion processes explained in the previous section. It is innocuous if biomass is fully combusted, leaving CO2 and water, but this would be an issue in incomplete combustion, which leaves fly ash, smoke, and other poisonous gases impeding the earth. Figure 7 illustrated biomass power plant combustion [53].

![Figure 7. Illustrated combustion system in a biomass power plant [53]](image)

Minimization of poisonous gas emission and convenience of their potential impacts are significant worries in the structure of ecological acceptance of biomass boiler systems. The biomass combustion system varies in the furnace's designation, which could be very efficient, typically recovering from 65% to 90% of its energy. "The net power cycle efficiency that can be achieved is about 23% to 25%" [50]. Diversification of a few internal factors explained in the previous paragraph, and the emission control requirements have considered the biomass combustion system explained in Table 8 [54].
Table 8. Biomass combustion types [54]

| Combustion types          | Advantages                                                                                       | Disadvantages                                                                                           |
|---------------------------|-------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Grate furnaces            | Economical in terms of operational cost                                                           | Non-homogenous combustion in fluidized furnaces                                                         |
|                           | Fair dust load in flue gas                                                                       | Unique designs need to mix with other fuels such as wood fuels and herbaceous fuel                      |
|                           | Can tolerate a wide variation in fuel quality (moisture, size of a particle)                    | The efficiency will drop in spare oxygen of 7-8 in volume%                                              |
| Underfeed stokers         | Low cost of investment                                                                            | Applicable for feedstock with lower ash content (woodchips and sawdust)                                 |
|                           | The straightforward system                                                                       | Only suitable for small scale with boiler capacity of < 6 MWh                                           |
|                           | with acceptable load control due to continuous fuel feeding                                       |                                                                                                          |
| Suspension burners        | Specific capacity is very high                                                                    | The moisture of feedstock should be within or <15%                                                     |
|                           |                                                                                                  | Drying of feedstock with size reduction needed to decrease discharges and unburnt residues             |
| Bubbling Fluidized Bed   | Moving parts excluded in the hot combustion chamber                                              | Uneconomical, boiler capacity of more than 20 MWh                                                       |
| Furnaces                  | Can be used for any type of biomass with a wide range of moisture content                         | Uneconomical                                                                                            |
|                           | Raises efficiency due to low excess oxygen up to 3-4% by volume of gas                           | Agglomeration of bed due to high alkaline feedstock (straw)                                             |
| Circulating Fluidized Bed| High turbulence causes high specific heat transfers                                               | Uneconomical, boiler capacity needs to be more than 30 MWth                                             |
| Furnaces                  | Can be used for any type of biomass with a wide range of moisture content                         | Agglomeration of bed due to high alkaline feedstock (straw)                                             |
|                           | Deficient excess oxygen (1-2 % by volume of gas) raises efficiency                                | Flue gas has high dust content                                                                          |

Sher et al. has performed a study on the combustion of biomass fuels in a 20 kWth fluidized bed combustor in oxygen medium and found that combustion medium alteration could lessen CO emission up to 80% and decrease in NOX emission too, which has been proven from her study of using 25% and 30% volume of pure oxygen with three different types of biomass feedstocks [55]. Sher et al. further investigate that even though a significant decrease in the toxic emission can be obtained from the study, an oxy-fuel mixture ratio of O2 and CO2 oxidant must be kept to 30 volume % due to a decrease in gas temperature from the overall operation [55]. Arranz et al. experimented on the pine wood pellets combustion behaviour and characterization through experimental and compared with other biomass pellets in South West Europe, resulting in another proven technology to reduce ashes production, NOX, and SO2 [56]. This palletization process's only drawback is that the processed pellets could be hydrophilic, which absorbed moisture and consequently swelled up, causing handling and storage constraints, explained by Koppejan et al. [57].
The addition of a certain percentage of biomass mix with coal can be co-fired in the coal-fired power plant is an added value of biomass combustion exclusive usage to power a steam turbine, which has been a promising method the nearest future[58]. Adding a biomass mixing fuel with coal would not only be a promising method in the combustion system but would instead causing disadvantageous too in boiler operation. This con can be catered with pre-treatment called torrefaction, which was studied by Eddings et al. [59] and Pahla et al. [60] from landfill food waste torrefaction to be used as in biomass co-firing and pulverized coal with raw Pinion Pine/Juniper wood as biomass in co-firing too, torrefied and pyrolyzed forms found that a percentage of biomass within 50-80% with remaining 5-10% of coal with insignificant changes in the handling equipment, however, if the percentage of coal is more than 10% or if both coal and biomass are burning separately in parallel co-firing then changes in burners, mills, and dryer are compulsory. Apart from that, biomass physical/"thermochemical and chemical properties are important tools in the application of biomass co-firing" [61]. Nevertheless, deposition of ash on the boiler tubes Pisa & Lazaroiu [62] and the characteristic of ash brings many complications later in the co-firing of biomass, which is proven by Zhou et al. [63] study on "biomass ashes effect on characteristics of sintering on high/low bituminous coal ash" melting point. Xing et al. [64],[41] evaluated pine ash and El Cerrejon coal properties in co-firing through an experiment and has identified that increase in biomass co-firing ratio will increase the rate of fly ash deposition and slag, which settle down on the convection surfaces. Table 9 below listed the advantages and disadvantages of biomass combustion [65]–[67].

| Advantages | Disadvantages |
|------------|---------------|
| Waste wood material such as sawdust or wood chips is transformed into pellets that can be used as a source in biomass power plant to produce electricity | Agglomerating, fouling, slagging, and corrosion of the by-product ash produced in a very high-temperature boiler from the combustion in fixed-bed due to coalescence of the molten particles |
| Net carbon emission can be significantly reduced in comparison with fossil fuels, creating a clean development mechanism (CDM) in diminishing greenhouse gas (GHG) emissions | Harvesting the whole trees is not an effective way of providing low-carbon electricity production. |
| Co-firing such as (straw with coal) will be efficient in larger power plants whereby it produces less emission of CO₂, SOx, and NOx | Biomass fuel supply limited exceptionally economical biomass sources from waste wood products or agro-processing operations |

5.2.2. Gasification
Gasification is one of the oldest technologies in producing energy from biomass material and used in common in the early 1920s to power a car in Sweden by wood gasifier due to abundant wood biomass availability and lack of fossil fuel resources. Gasification has less carbon emission and NOx than combustion due to lower temperature range operation, which is the root cause of producing lower NOx. The design of wood gasifiers has been studied during World War Two from 1939 to 1945 to optimize and enhance their performance[68]. De Lasa et al. [69] has performed "catalytic steam gasification of biomass" and confirmed that this thermochemical process is well-known among other thermochemical conversions for the reasons of cost-effectiveness and efficiency in using lignocellulosic biomass conversion to bioenergy. Gasification is attained via incomplete combustion in a very high temperature in an oxygen-lean confined space, accompanying by gaseous release or syngas by-product, which primarily comprises CO, H₂, CH₄, CO₂, H₂O, and others are shown in equation (5) below. The produced syngas from the thermochemical reaction can be altered into liquid form via Fisher-Tropsch (FT) method or directly subjected to a combustion engine during the process of gasification [70], [71] as shown in Figure 8 [72].
Figure 8. illustrated the gasification system [72]

Biomass → H₂(g) + CH₄(g) + CO(g) + CO₂(g) + NH₃(g) + H₂S(g) + H₂O(l) + Tar(l) + C(s) + trace elements (5)

Factors such as the density of biomass fuel in distress and eradicated by introducing densification techniques such as palletization. In that sense, the pre-treatment method not only caters to moisture and bulk density of biomass feedstocks, but it has also reduced the transportation cost of the fuels. However, this technique has its imperfection, such as swelling of biomass pellets due to moisture absorption. Arranz et al. [56] has envisaged the problem of swelling through studies on the mineral oil coated wood pellet and have proven that coated mineral oil wood pellet retained its shape up to the 1800s submerged in water in comparison with untreated wood pellet. Moreover, this process has also shown that HHV's value increases significantly of the treated wood pellet by 0.9MJkg⁻¹ and bulk energy density by 1.4GJm⁻³ on average, which indirectly reduces the fuel's transportation cost Arranz et al. [56].

Apart from that, different biomass used in gasification needed different operating conditions yet still relied on the gasifier type used to get the desired by-product, especially the amount of tar in the gas product. Gasification comprises three stages: drying, pyrolysis, and partial oxidation, which overlap; thereof produces a combination of multiple reactions. Besides that, there are three different types of gasifying mediums, such as oxygen, air, steam, or CO₂, which gives different by-products from the reaction shown in Table 10 [73]–[76]. Parthasarathy & Narayanan [77] has studied different gasifying medium through the study of "hydrogen production from steam gasification of biomass" and has found that oxygen has the highest value of high calorific syngas. In contrast, in steam and air combination medium, it produces intermediates calorific value due to excessive H₂ production than air, which is proof that the gasifying medium plays an essential factor in the transformation of solid char and hydrocarbon into CO and H₂ Parthasarathy & Narayanan [77].

| Gasifying medium                  | Heating value MJ   | Effect                           |
|-----------------------------------|--------------------|----------------------------------|
| Air (Nitrogen)                    | 4 – 7              | Dilute syngas with the low calorific value |
| Air (Oxygen)                      | 28                 | High calorific syngas value      |
| Steam/steam & oxygen              | 10-18              | Syngas with intermediate calorific value |

Besides that, few other factors contribute to the end product production, such as gasifier pressure and temperature, residence time, the existence of a catalyst, and gasifier design. Based on the chemical reaction and temperature ranges, the gasification process is divided into primary, secondary, and tertiary reaction stages, shown in Table 11 [78]–[80]. Narváez et al. [81] have proven that an increase
in temperature will aid in the production of gaseous by-product in gasification where; this has been demonstrated in a recent study of bubbling fluidized bed gasification temperature changes from 700 °C to 850 °C with less tar formation of only 26% and economically expedient because of lower cost for gas cleaning. In general, the residence time has a significant effect on the tar composition rather than tar yield, which is proven by a slight increase with less than the 20s; it would increase the H2 and CO concentration and vice versa for CH4 and CO2 content from the overall gasification process.

| Reaction stages | Temperature °C | By-product | Characteristic of by-product |
|-----------------|----------------|------------|-----------------------------|
| Primary         | < 500          | Oxygen vapour, liquid, H2O, and CO2 | Monomer with a low molecular weight |
| Secondary       | 700 - 850      | H2, water vapour, CO, CO2, gaseous ole-fins, phenols and aromatics from primary vapour and liquid by-product | Tar from this stage contains mixed oxygenates, alkylphenols, phenolic ethers, heterocyclic ethers, and polynuclear aromatic hydrocarbon |
| Tertiary        | 850 - 1000     | H2, CO, and CO2 are formed along with water vapour, polynuclear liquid tar, and polynuclear aromatic | |

The sum of biomass to be prepared is an additional consideration; for instance, "fixed bed systems are reasonable for marginal capacities while fluidized and entrained bed systems are befitting for medium-sized and large-scale capacities, respectively." Even though there are few varieties of gasifier[82] in the market such as fluidized bed, fixed bed, and spouted bed[83]–[85]which well suited the gasification system but these technology application does not contribute any values in the gasifier system due to limited operational condition that need to be met to run the system such as high temperature and pressure. Hence, Garcia et al. [86], Choudhary et al. [86], and Sharma et al. [87] have studied the essence of gasification is to operate in the lower range of temperature, which grows the realization of practical catalyst application such as oxides, hydroxides, nickel throughout the process and therein lays the suitability of converting a lower calorific value of lignocellulosic material into rich H2 gas, decrease liquid and tar yield and to eradicate problems such as agglomeration, sintering, erosion, decomposition, and corrosion. Corella et al. have reported that about 1.3% wt tars formation decrement can be seen from the initial amount of 6.5 with calcined dolomite addition in gasification[87]. Rapagnà et al. have experimented by adding olivine as a catalyst could be a more practical alternative due to its attrition resistance potential compared to dolomite, making it more tar reduction of up to 90% [88]. Apart from that, Ni-based catalyst addition, not favourable in the gasification process due to its fast deactivation of the catalyst, which can be catered by temperature levitating to a certain degree. Moreover, the formation of tar from the process cause limitation in the gasification system too in blockages of filter, which can be in the form of ceramic or metallic and fuel lines[89].

The gasification system choices are "biomass feed-stock characters function such as particle size or density, moisture, inorganic content (ash), and toxicity." Also, "supercritical water gasification (SCWG) can be used in higher moisture content" biomass material. It is proven feasible in one of the studies conducted by Tock et al. [90] where banana peel can be processed via gasification to produce 80.52MW in the absence of drying process, which could be costly and the yield of H2 will be higher compared to CO and less tar formation; thereof corrosion and gas treatment complication can be circumvented too. Apart from that, plant size is another matter of concern, especially in biogas volume and gasification designation cost production. Mann has found that in hydrogen production through
gasification, a small plant (30tons/day) is vital to produce (21,594 m³/day), which can be feed for 500 automobiles [91]. Besides that, a giant plant needs higher costs, and biomass prices directly contribute to the hydrogen market price. Density and particle size engaged a substantial part or aspect in the gasification system by sustaining heat transfer rate, less tar, and high gas yield. Kumabe et al. have found that during co-gasification in Mulia Coal, the particle size reduction ranges from (0.5 - 1.0mm) has a significant amount of sulphur reduction compared to the particle's initial size (106µm) [92]. The production of methanol through gasification might not be economically feasible due to the gaseous separation process complication using special equipment[93]. In fact, this could be the cause of methane production via steam changing familiar than through the gasification process. "Every gasification system has its pros and cons and, therefore, feedstock with a character appropriate for a gasifier should be employed to ensure high-quality syngas, cost-effective and efficient operation, and minimum environmental impact," which has been listed in Table 12 below [83]–[85].

### Table 12. Listed advantages and disadvantages of gasification bed [83]–[85]

| Advantages | Disadvantages |
|------------|---------------|
| More variation in gasifier design such as fluidized bed, fixed bed, and spouted bed | Gasification needs a catalyst for the process |
| Gasification can provide both power and heat and useable syngas which can be transformed into chemicals | The obtained syngas needs to be cleaned and treated before the desired product |
| Lower NOₓ, CO, and particulate emissions | low calorific value (LCV) of gas produced |

### 6. Conclusions

Expecting a fruit on the next day of planting a seed is against the natural nature's cell turnover capability. The same thing goes for implementing biomass as one of the energy supplies depends on the acceptance of humankind and the reliability of the source with negligible environmental damages. After all, humankind only starts to view supplementary sources after seeking goodness from various points of view, such as comprehensive energy security, fluctuation of fossil fuel price, environmental legislation and subsidies from government agencies, new job opportunities, and others.

The production of bioenergy still a most controversial topic in the world due to uncertainty of how reliable this technology could be and, at the same time, replacing current fossil fuel usage for electricity or biofuel productions. Even though the expanding usage of raw material has been implemented with its thermochemical properties, it produces other drawbacks such as slagging and fouling in the direct combustion system and temperature, pressure, and catalyst constraints in the gasification system. Again, this implementation will lead to scholars' paradox in finding ways by introducing co-firing solutions with fossil fuel to reduce the problem mentioned above; thereof, it causes price decrement. Moreover, a binding agent such as algae of 20% has been proven durable with a negligible reduction of the feedstock's original energy content and alters fuel's physical properties to reduce transportation costs. In contrast, both government and non-government agencies have introduced policies and subsidies throughout the world to reduce the import dependency of fuels, promote a cleaner environment, create new employment in rural areas, create additional income for farmers, and sustain health benefits. Thus, the decision-making process has landed on our palms now to decide whether to pick it or to drop it.

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