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## **Torrefaction of Agricultural Residues**

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### **ABSTRACT:**

*Biomass torrefaction is a pre-treatment method carried out at 200-300°C in controlled atmospheric conditions. The occurring decomposition reactions at this temperature level cause the biomass to become completely dried and to lose its tenacious and fibrous structure. Therewith the grindability of the subjected biomass is improved significantly. In addition, torrefaction increases the calorific value and the biomass, its hygroscopic nature can be destructed to yield a hydrophobic material. Depending on the applied torrefaction conditions, torrefied biomass is coloured brown to dark-brown and approaches the properties of coal. The process makes the logistics of transporting and storing bulky biomass more efficient. This opens the prospects of using existing coal pulverizers and of considerably lowering costs of co-firing biomass to generate electricity. With coal prices at all time highs, torrefaction technology might arrive just in time to make biomass even more attractive to energy industries looking into co-firing.*

**Key words:** *Torrefaction, pre-treatment of biomass, mild pyrolysis, Agro waste utilization.*

### **INTRODUCTION**

The torrefaction of biomass is a thermo-chemical decomposition process in which hemicellulose degradation is the dominant reaction, with the cellulose and lignin fractions largely unaffected. The primary product is a solid material that retains 75–95% of the original energy content. Properties of the torrefied solid include improved grindability, hydrophobicity, and energy density. Torrefied biomass has been processed successfully in batch-mode and continuous process devices; net thermal efficiencies of the process as high as 90% have been reported. Torrefied biomass has been proposed as a feedstock for coal co-combustion, as well

as for gasification-combustion and Fischer-Tropsch fuel production. Analyses of supply chain impacts indicate that, in some scenarios, torrefaction can be the lowest cost and most energy efficient option for supplying fuel, especially when combined with pelletization of the material (**Ciolkosz and Wallace, 2011**). The process also called mild pyrolysis (as it occurs at the lower temperature range of the pyrolysis process), with removal of smoke producing compounds and formation of solid product, retaining approximately 70% of the initial weight and 80-90% of the original energy content (**Arcate, 2000**).

Biomass Torrefaction is gaining attention as an important preprocessing step to improve the quality of biomass in terms of physical properties and chemical composition. Torrefaction is a slow heating of biomass in an inert or reduced environment to a maximum temperature of approximately 300°C. Torrefaction can also be defined as a group of products resulting from the partially controlled and isothermal pyrolysis of biomass occurring in a temperature range of 200–280°C. At the end of the torrefaction process, a solid uniform product with lower moisture content and higher energy content than raw biomass is produced. Most of the smoke-producing compounds and other volatiles are removed during torrefaction, which produces a final product that will have a lower mass but a higher heating value (**Jaya Shankar et. al. 2011**).

The world is currently facing challenges to reduce dependence on fossil fuels and to achieve a sustainable renewable energy supply. Renewable energies represent a diversity of energy sources that can help maintain the equilibrium of different ecosystems. Among the various sources of renewable energy, biomass is increasingly used as it is considered carbon neutral, since the carbon dioxide released is already part of the carbon cycle (**Arias et al., 2008**). Increasing the utilization of biomass for energy can help reduce the negative CO<sub>2</sub> impact on the environment and help meet the targets established in the Kyoto Protocol (**UN, 1998**). Energy from biomass can be produced from different processes like thermo-chemical (combustion, gasification, and pyrolysis), biological (anaerobic digestion and fermentation), or chemical (esterification), in which direct combustion can provide a direct near-term energy solution (**Arias et al., 2008**). Some of the inherent problems with raw biomass materials, like low bulk density, high moisture content, hydrophilic nature, and low calorific value, limit its ease of use (**Arias et al., 2008**). In fact, due to its low energy density compared to fossil fuels, high volumes of biomass are needed; adding to problems associated with storage, transportation, and feed handling at a cogeneration plant. [Torrefied-wood are shown in Fig. 1.](#)



**Fig 1:** [Torrefied-wood-pile](#)

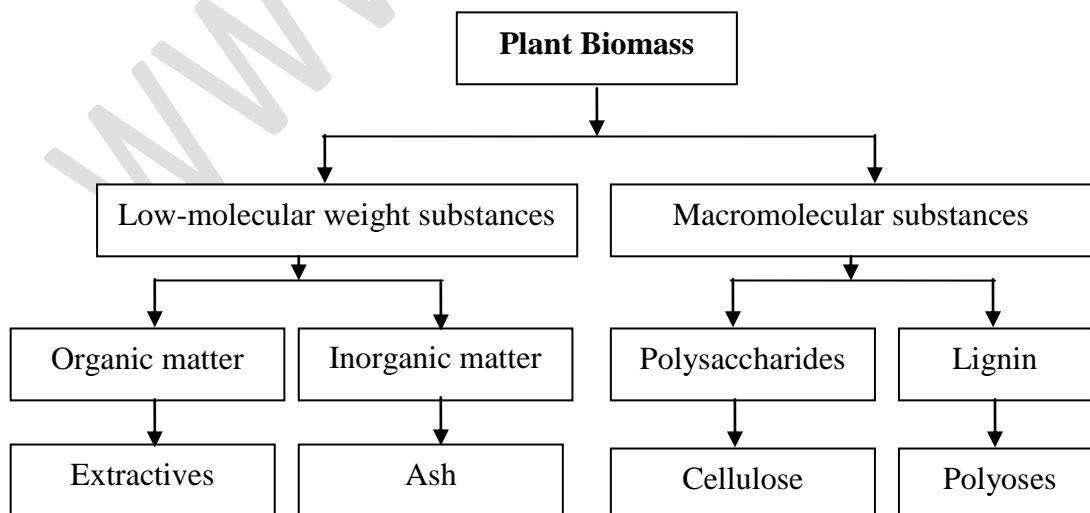
### **TORREFACTION OVERVIEW**

Carbonization of biomass using torrefaction can be good for reducing moisture content and increasing calorific value, which makes biomass energy dense. Torrefaction is a feasible method for improving the properties of biomass as a fuel (Sadaka and Negi, 2009). It consists of heating biomass slowly in an inert atmosphere to a maximum temperature of 300°C (Fonseca et al., 1998) and has been defined as the partially controlled and isothermal pyrolysis of biomass occurring in a temperature range of 200–300°C (Bergman and Kiel, 2005). The treatment yields a solid uniform product with lower moisture content and higher energy content compared to raw biomass. Torrefaction lowers the O/C ratio and makes it more efficient for applications, including gasification and combustion (Bourgois and Doat, 1984; Bourgois and Guyonnet, 1988; Pentananunt et al., 1990; Pach et al., 2002). The initial heating of biomass during torrefaction removes unbound water. Further heating results in the removal of bound water through chemical reactions. It is assumed that most of the bound water is removed by a thermo-condensation process, which occurs above 160°C when the formation of CO<sub>2</sub> begins (Zanzi et al., 2002). Further heating between 180–270°C results in an exothermic reaction and initiates the decomposition of the hemicellulose, which causes the biomass to change color due to loss of water, CO<sub>2</sub>, and large amounts of acetic acid and phenols. The energy values of these compounds are relatively low, resulting in a significant increase in the energy density of the biomass (Zanzi et al., 2002). The process becomes completely exothermic at temperatures greater than 280°C, resulting in significant increases in the production of CO<sub>2</sub>, phenols, acetic acid, and other higher hydrocarbons (Zanzi et al., 2002).

Torrefaction of lignocellulosic materials results in decomposition of more hemicelluloses than lignin and cellulose. These decomposition reactions lead in destruction of hydroxyl groups (OH) and further increase the density and specific heating value of the product. The destruction of hydroxyl groups also results in creating a hydrophobic product that remains stable in abusive storage environments, making fungal degradation unlikely (**Hakkou et al., 2006**). **Arias et al. (2008)** reported that torrefaction of biomass significantly influences the grindability and reactivity of woody biomass. **Bergman et al. (2005a)** mentioned that the torrefaction process increases the uniformity of the final product quality. They have found that round wood, demolition wood, and waste wood had similar physical and chemical properties after torrefaction. They also concluded that seasonal influences on these properties were reduced. The torrefaction process, when carried out at temperatures less than 250°C, is generally endothermic and may decrease its energy efficiency. However, some of the studies carried out on system energy balances and economics indicate that torrefied biomass could be a viable option for co-gasification or cocombustion with coal (**Bergman et al., 2005; Prins et al., 2006a; Kavalov and Peteves, 2005**). Evaluating the design of torrefaction process for both herbaceous and woody biomass is the purpose of this work.

### MAJOR COMPONENTS OF BIOMASS

Fig. 2 indicates the various low molecular weight substances and macromolecular weight substances available in biomass (**Mohan et al. 2006**). Biomass materials are essentially a composite of carbohydrate polymers with a small amount of inorganic matter and low molecular weight extractable organic constituents.



**Fig. 2:** Plant biomass composition (**Mohan et al., 2006**).

Fig. 2 also indicates the lineage for both the low- and high-molecular weight macromolecular polymers and oligomers and lignins. The micro and macromolecular substances in the biomass change with the biomass type (i.e., woody or herbaceous). Lignin generally ranges from 18–35 wt% while cellulosic material typically ranges from 65–75 wt%. Low molecular weight species, including the inorganic matter, generally equal less than 10 wt% of the biomass material.

### **PRINCIPLES OF TORREFACTION**

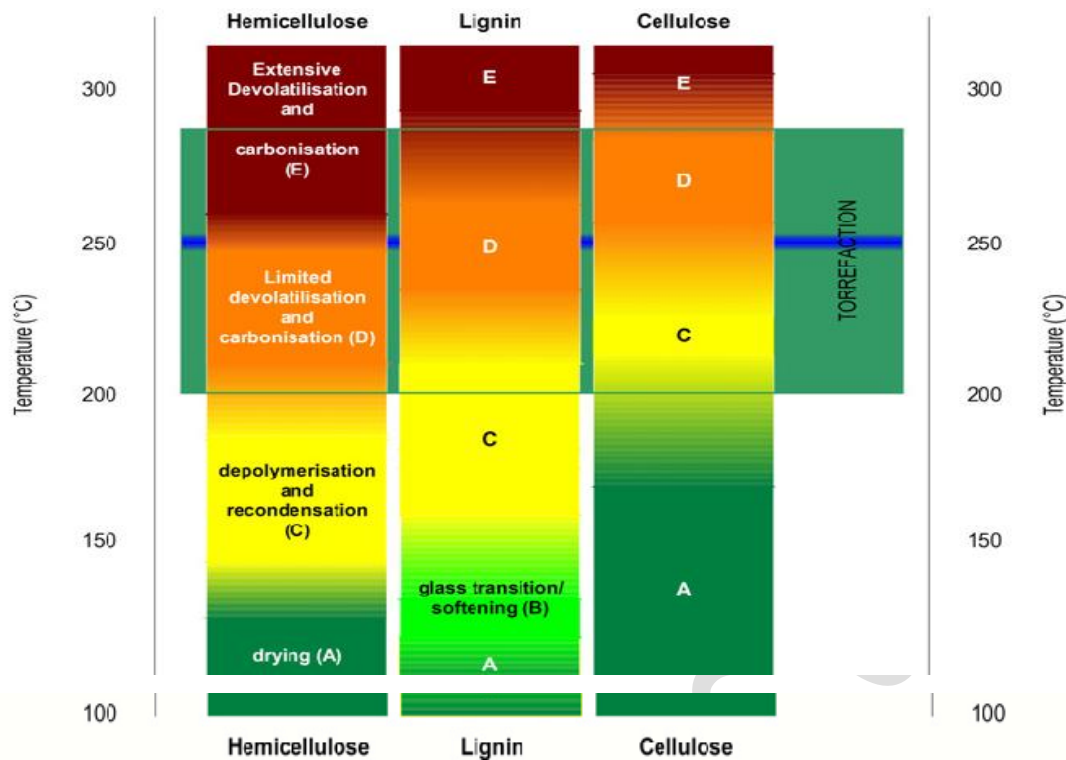
Torrefaction, also referred to as mild pyrolysis, resides before the pyrolysis process in the continuum of temperatures starting at drying and ending at gasification. Torrefaction is a process that effectively lowers the O/C ratio of biomass. The energy consumption during milling is reduced, and at the same time sharp edges and splinters are eliminated in the milled powder, greatly enhancing feeding properties. The torrefied biomass has also proved to have hydrophobic properties, which gives an advantage in long term storage compared to raw biomass.

#### **Torrefaction process technique**

The thermo-chemical process of torrefaction is actually an incomplete pyrolysis process, and is characterized by the following parameters: reaction temperature 200–300°C, heating rate < 50°C/min, absence of oxygen, residence time < 30 minutes at  $T > 200^{\circ}\text{C}$ , ambient pressure, and flexible feedstock. Absence of oxygen in the reactor is of great importance to avoid oxidation and ignition. (Jaya Shankar et., al. 2011).

#### **Biomass reactions**

The cell in woody biomass is a rather complex construction of several building blocks. Polysaccharides are arranged in long chains called microfibrils enclosed in even structures of amorphous lignin and building the core of the crystalline cellulose. The cellulose is encased in a shell of hemicellulose. All these building blocks are more or less influenced by heat, but in different temperature ranges; therefore, they are converted by specific reactions. The physiochemical changes in biomass during torrefaction are shown in Fig. 3.



**Fig. 3:** Physiochemical changes in biomass during torrefaction (Bergman et al., 2005a).

### Torrefaction mass and energy balance

A typical mass and energy distribution can be seen in Table 1, which shows the high preservation of mass and energy content in the solid product. Besides the solids, mostly water is produced during torrefaction, and the energy content of the volatiles is preserved in the lipids and organics. Torrefaction operating conditions and biomass properties have a significant impact on the amount of both the solid residue remaining and the volatile and gaseous products produced. As a result, for different studies, their analysis results are not exactly the same. Prins et al. (2006) conducted several typical overall mass balances of torrefaction experiments.

**Table 1:** Mass and energy distribution for torrefaction of willow in 280°C for 17.5 min reaction time (**Bergman and Kiel, 2005**). (daf: dry and ash free basis)

Reaction products	Mass yield	Energy yield (LHV, daf) (%)
Solids	87.5	94.9
Lipids	1.40	3.40
Organics	1.70	1.60
Gases	1.40	0.10
Water	8.00	0.00

These data are reproduced in Figure 4 and show that, for different biomass types, their product distributions have big differences. Larch has the largest yield of solid product, and smallest gas and liquid yield; straw has higher gas and liquid fractions than woody biomass; and willow is between woody biomass and straw. It was also found that an increase in torrefaction temperature leads to a decrease in solid biochar yield and an increase in the volatile fractions, including liquid and non-condensable gases. That is a result of the competition between charring and devolatilization reactions that become more reactive at higher temperatures.

### **Torrefaction products**

During the torrefaction of biomass, three primary products are produced: a) solid product of a brown/dark color; b) condensable liquid including mostly moisture, acetic acid and other oxygenates; and c) non-condensable gases-mainly CO<sub>2</sub>, CO, and small amounts of methane. The last two products can be represented by volatiles. During torrefaction the raw material loses most of its moisture and other volatiles which have a low heat value. Many researchers have worked on identifying the gas composition in terms of quantity and quality. The type and amount of the gas that comes as off-gas during torrefaction depends upon the raw material type and torrefaction process conditions, including the process temperature and residence time.

Numerous reaction products are formed during torrefaction. Their yield strongly depends on process conditions (temperature and time) and on biomass properties. **Bergman et al. (2005)**

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gives an overview of the torrefaction products, classified based on their state at room temperature, which can be solid, liquid, or gas. The solid phase consists of a chaotic structure of the original sugar structures and reaction products. The gas phase includes the gases that are considered permanent gases, but also light aromatic components such as benzene and toluene.

The condensables, or liquids, can be divided into three subgroups which include water, organics, and lipids. The liquid also contains the free and bound water that has been released from the biomass by evaporation. The organics subgroup (in liquid form) consists of organics that are mainly produced during devolatilization and carbonization. Finally, the lipids are a group of compounds that are present in the original biomass. This subgroup contains compounds such as waxes and fatty acids.

#### **CHARACTERISTICS OF AND MARKETS FOR TORREFIED WOOD**

There are other benefits of processing woody biomass through a torrefaction process. In addition to the changes in energy density, torrefaction changes other characteristics in the woody biomass. One of these changes is an increase in hydrophobicity. Because of the chemical changes in the structure of the torrefied wood, the end product does not absorb water. This property provides some advantages over green wood chips. Since the material will not absorb water, weather will not impact the quality of the product. For example, if wood is left in outside storage, it may increase in moisture. Southern Company found that wood chips delivered at 50% moisture content actually increased in moisture due to outside storage before it was conveyed into a power plant (**Boylan et al, 2008**). As these wet chips entered the boiler, the boiler was de-rated as a direct result of the moisture addition. Moisture content variations result in inefficiencies in energy conversion that cannot be accounted for in some existing power plant processes without the addition of a wood chip dryer or covered storage. This is just one example of how the hydrophobic characteristic of torrefied wood chips can be used to improve wood conversion processes and potentially create new markets for the forest products industry.

Another characteristic of torrefied wood is increased friability, or crushability. As wood chips are ‘roasted’, they not only lose moisture, but they become brittle. This characteristic could increase interest in the use of woody biomass in processes where raw materials must pass through a pulverizer or some type of crushing equipment, such as is commonly found in



power plants to crush coal prior to entering the boiler. The moisture content and properties of green wood chips in these types of processes is not as conducive as either dried wood or torrefied wood because green wood does not possess this brittle, easily crushed characteristic. The power requirements to reduce the size of torrefied biomass are similar to coal, and in comparison, can be 70-90% less than the power requirements to reduce wood cuttings (**Bergman and Kiel, 2005**).

In the domestic household market, torrefied wood was tested in Europe as a replacement for charcoal used in grilling (barbecuing). Researchers ([http://techtpt.com/tw%20papers/fao\\_paper.htm](http://techtpt.com/tw%20papers/fao_paper.htm)) surveyed users that compared using torrefied wood to traditional charcoal briquettes. Respondents indicated that the torrefied product was satisfactory in appearance and cleanliness; glowing embers formed more rapidly; the product appeared to be more appropriate to brisk cooking; and the absence of smoke during cooking was noted almost unanimously. However, objective measurements indicate that the ember phase is much shorter for torrefied wood than for charcoal.

### **Physical properties and chemical composition of torrefied biomass**

Torrefaction of biomass significantly changes physical properties like moisture content, density, grindability, pelletability, hydrophobicity, and calorific value, (**Sadaka and Negi, 2009**) and also the chemical composition in terms of carbon, hydrogen, oxygen, nitrogen and sulphur.

**10.1 Moisture Content:** Being a deep drying process, torrefaction reduces the moisture content of the pre-dried biomass from 10% to <6% (**Lipinsky et al., 2002**). Typically the moisture content of the torrefied biomass ranges between 1–6% on a weight basis, depending on the conditions of torrefaction (**Bergman and Kiel, 2005**).

**10.2 Density:** Mass loss in the form of solids, liquids, and gases during the torrefaction process causes the biomass to become more porous. This results in a significant reduction in volumetric density, typically between 180–300 kg/m<sup>3</sup>, depending on initial biomass density and torrefaction conditions (**Bergman and Kiel, 2005**).

**10.3 Grindability:** Biomass is highly fibrous and tenacious in nature, because fibers form links between particles and make the handling of the raw ground samples difficult. During

the torrefaction process the biomass loses its tenacious nature, which is mainly coupled to the breakdown of the hemicellulose matrix and depolymerization of the cellulose, resulting in the decrease of fiber length (**Bergman et al., 2005; Bergman and Kiel, 2005**). There is a significant decrease in the particle length but not the diameter per se, resulting in better grindability, handling characteristics, and the ability of the biomass to flow unhindered through processing and transportation systems. During the torrefaction process the biomass tends to shrink; becomes lightweight, flaky, and fragile; and loses its mechanical strength, making it easier to grind and pulverize (**Arias et al., 2008**). **Bergman and Kiel (2005)** conducted studies on the energy requirements for grinding raw and torrefied biomass like willow, woodcuttings, demolition wood, and coal using a heavy duty cutting mill. They concluded that power consumption reduces dramatically when biomass is first torrefied. The reduction in power consumption ranges from 70–90%, based on the conditions under which the material is torrefied. They have also found that the capacity of the mill increases by a factor 7.5–15. The most important phenomenon they have observed was that the size reduction characteristics of torrefied biomass resulted in a great similarity with coal.

**10.4 Particle Size Distribution, Sphericity, and Particle Surface Area:** Particle size distribution curves, sphericity, and surface area are important parameters for understanding flowability and combustion behavior during cofiring. Many researchers observed that ground, torrefied biomass produced narrower, more uniform particle sizes compared to untreated biomass due to its brittle nature, which is similar to coal. **Phanphanich and Mani (2011)** study on torrefied pine chips and logging residues found that smaller particle sizes are produced compared to untreated biomass. They have also observed that the particle distribution curve was skewed towards smaller particle sizes with increased torrefaction temperatures.

Torrefaction also significantly influences the sphericity and particle surface area. **Phanphanich and Mani (2011)** results also indicated that sphericity and particle surface area increases as the torrefaction temperature was increased up to 300°C. For ground, torrefied chips, they found that the sphericity increased from 0.48–0.62%, concluding that an increase in particle surface area or decrease in particle size of torrefied biomass can be desirable properties for efficient cofiring and combustion applications. Also, the bulk and particle densities of ground torrefied biomass increases as it reduces inter and intra particle voids

generated after milling (**Mani et al., 2004; Esteban and Carrasco, 2006**). Research studies have indicated that ground torrefied material results in a powder with a favorable size distribution and spherical particles, allowing torrefied powder to meet the smooth fluidization regime required for feeding it to entrained-flow processes (gasifier and pulverized coal).

**10.5 Pelletability:** Variability in feed stock quality due to differences in the types of raw materials, tree species, climatic and seasonal variations, storage conditions, and time significantly influence the quality of biopellets (**Lehtikangas, 1999**). On the other hand, torrefying the biomass before pelletization produces uniform feedstock with consistent quality. Lignin in the biomass is considered as the basic binding agent; thus the pelletability of any biomass is evaluated based on the amount of the lignin. In general, the higher the amount of lignin, the better the binding and milder the process conditions required for densification. Woody biomass has more lignin than lignocellulosic biomass and binds easily. Torrefaction process opens up more lignin active sites by breaking down the hemicellulose matrix and forming fatty unsaturated structures which creates better binding. The bulk densities of the torrefied pellets are 750–850 kg/m<sup>3</sup> (**Bergman and Kiel, 2005**).

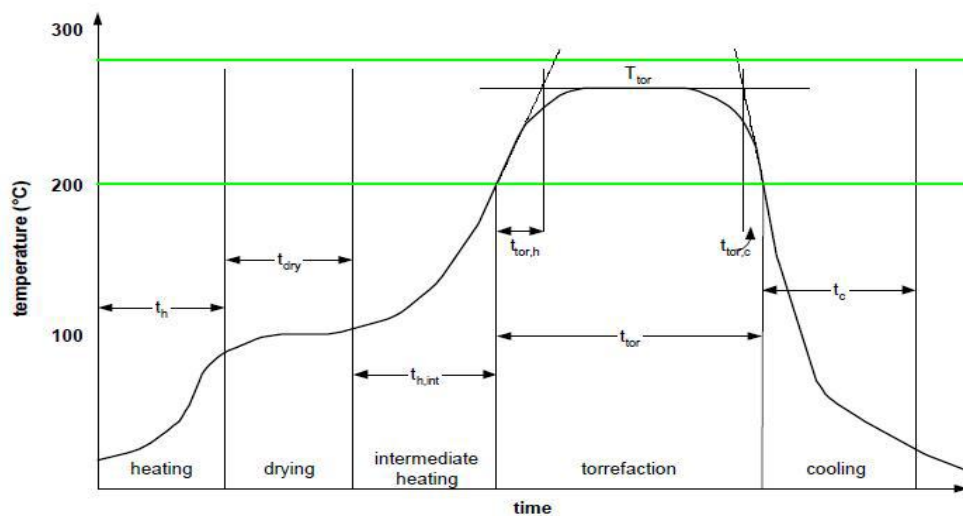
**10.6 Chemical Composition of the Torrefied Biomass:** Besides improving physical attributes, torrefaction also results in significant changes in proximate and ultimate composition of the biomass and makes it more suitable for fuel applications. **Sadaka and Negi's (2009)** study on torrefaction of wheat straw, rice straw, and cotton gin waste at 200, 260, and 315°C for 60, 120, and 180 minutes has concluded that moisture content was reduced at the extreme conditions (315°C for 180) for all three feedstocks by 70.5, 49.4, and 48.6%, and the heating value increased by 15.3, 16.9, and 6.3%, respectively. **Zanzi et al. (2002)**, in their study on miscanthus torrefaction made similar observations, where increasing temperature from 230–280°C and time from 1–3 hours increased the carbon content and decreased the hydrogen, nitrogen, and oxygen content. At 280°C, the carbon content increased to about 52% from an initial value of 43.5% while hydrogen and nitrogen content decreased from 6.49–5.54% and 0.90–0.65% for 2 hours of torrefaction. In general, increased torrefaction temperatures result in increased carbon content and decreased hydrogen and oxygen content due to the formation of water, CO, and CO<sub>2</sub>.

This process also causes the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios to decrease with increasing torrefaction temperature and time, which results in less smoke and water-vapor formation and reduced energy loss during combustion and gasification processes. In torrefaction studies of reed canary grass and wheat straw torrefaction at 230, 250, 270, and 290°C for 30-minute residence times, **Bridgeman et al. (2008)** found that the moisture content decreases from an initial value of 4.7%–0.8%. They found that carbon increased 48.6–54.3%, and hydrogen and nitrogen content decreased from 6.8–6.1% and 0.3–0.1%, respectively.

### BIOMASS TORREFACTION FOR ENERGY APPLICATION

Torrefaction involves heating of the feedstock at moderate temperatures under an inert atmosphere (**Bergman et. al., 2005; Drift et. al., 2004**). Fig. 4 shows a typical torrefaction batch process. The total torrefaction process consists of drying, torrefaction and cooling. At beginning of the process the moisture in the biomass is released by drying. When the temperature of biomass ranges between 200°C to 300°C, only in this temperature range, the torrefaction decomposition reactions occur.

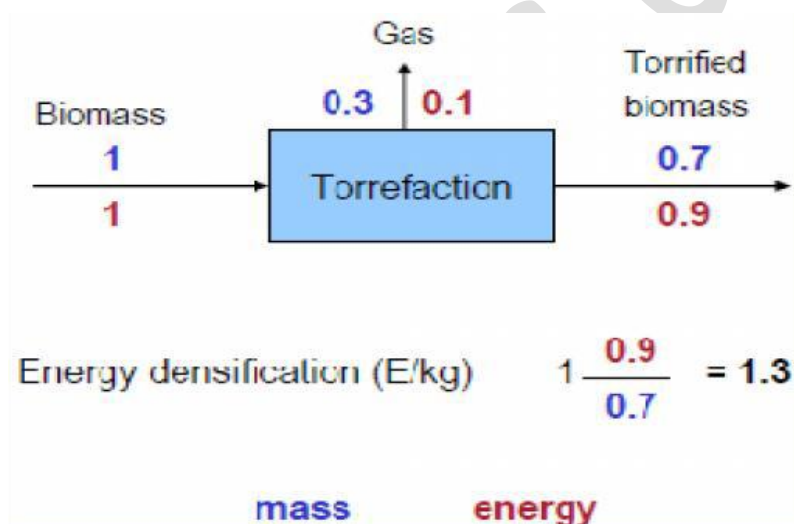
Three time temperature phases are recognised in torrefaction window. The reaction time of torrefaction is defined as the sum of heating time from 200°C to desired temperature plus reaction time/holding time at desired torrefaction temperature ( $t_{tor,h} + t_{tor}$ ) and the duration of the torrefaction stage is around 30 minutes. After torrefaction, the last stage is cooling the biomass from 200°C to the ambient temperature.



**Fig. 4:** Heating stage of drying biomass during a typical torrefaction batch process (**Bergman et. al., 2005**)

Explanation:  $T_{tor}$ : Torrefaction temperature.  $t_h$ : heating time to drying.  $t_{dry}$ : drying time.  $t_{h.int}$ : intermediate heating time to torrefaction.  $t_{tor}$ : Reaction time/holding time at desired torrefaction temperature ( $T_{tor}$ ).  $t_{tor.h}$ : Heating time from 200°C to desired temperature  $T_{tor}$ .  $t_{tor.c}$ : Cooling time from  $T_{tor}$  to 200°C.  $t_c$ : cooling time to ambient temperature.

Fig. 5 explains the concept of energy densification of biomass fuel by torrefaction (Bergman et. al., 2005). Typically, 70% of the feed mass is retained after torrefaction as solid products (torrefied biomass) which contained 90% of initial energy. The rest of 30% of the feed mass is converted to the gas products, but the energy contains only 10% of the initial energy. The energy densification  $E_d$  could be used to prove the energy density of torrefied solid product is increased by torrefaction; in this case the energy density of torrefied biomass increases by factor 1.3.



**Fig. 5:** Typical mass and energy balance of torrefaction process (Bergman et. al., 2005).

Energy densification could be expressed as Equation (1)

$$E_d = \eta_{torr} / M_{torr} \quad (1)$$

where  $\eta_{torr}$ : energy of the torrefied biomass in percentage of initial energy

$M_{torr}$ : mass of torrefied biomass in percentage of feed biomass

Energy of the torrefied biomass in percentage of initial energy could express as Equation (2)

$$\eta_{torr} = E_{torrefied} / E_{untreated} \quad (2)$$

where  $E_{torrefied}$  is the energy of torrefied biomass and  $E_{untreated}$  is the energy of feed biomass which could be calculated by Equations (3) and (4)

$$E_{\text{torrefied}} = HHV_{\text{torrefied}} * m_{\text{torrefied}} \quad (3)$$

$$E_{\text{untreated}} = HHV_{\text{untreated}} * m_{\text{untreated}} \quad (4)$$

where  $HHV_{\text{untreated}}$  is high heating value of untreated biomass and  $HHV_{\text{torrefied}}$  is high heating value of torrefied biomass. Both are determined by bomb calorimeter 6300 Oxygen.

The mass of torrefied biomass in percentage of initial mass could express as Equation (5):

$$M_{\text{torr}} = m_{\text{torrefied}} / m_{\text{untreated}} \quad (5)$$

### TORREFIED BIOMASS APPLICATIONS

Pulverized fuel combustion in coal-fired power stations and entrained flow gasification are particularly interesting product outlets for biomass. In both applications, biomass has to be fed to the reactor as a powder, which is difficult, costly, and achievable only at very low capacity in classical coal-mills. Due to this limitation, wood pellets are currently the state-of-the-art for cofiring, as they consist of sufficiently small particles. Consequently, wood pellets also have some limitations in terms of energy content and moisture uptake during storage and transportation. Torrefied biomass being energy dense and hydrophobic in nature can be a good replacement for wood pellets in co-firing and gasification plants. The high fuel quality of torrefied biomass makes it very attractive for combustion and gasification applications. Due to high CVs, the thermal energies of the combustion and gasification system can be improved significantly (**Bergman and Kiel, 2005**). However, there is no data on milling, handling, storing, transporting, and combusting large amounts of torrefied biomass at a commercial scale. Other applications include (1) high-quality smokeless solid fuels for industrial, commercial, and domestic applications; (2) solid fuel for cofiring directly with pulverized coal at electric power plants; (3) an upgraded feedstock for fuel pellets, briquettes, and other densified biomass fuels; and (4) high quality biomass solid fuel for advanced bioenergy application.

### CONCLUSION:

Torrefied biomass in general defines a group of products resulting from the partially controlled and isothermal pyrolysis of biomass occurring at a temperature range of 200–300°C. The common torrefaction reactions include (a) devolatilization and carbonization of hemicelluloses and (b) depolymerization and devolatilization of lignin and cellulose. Torrefaction reduces the variability in biomass feedstocks and helps to develop a uniform

feedstock with consistent physical, chemical, and biochemical composition. Torrefaction of biomass improves: Physical properties like grindability and pelletability, thereby increasing energy density; Ultimate and proximate composition by increasing the carbon content and calorific value and decreasing the moisture and oxygen content. Biochemical composition by decomposing the hemicelluloses and softening the lignin, resulting in better binding during pelletization. Densification of torrefied material at 225°C reduces the energy consumption and increases the throughput by a factor of two. During torrefaction, the biomass loses most of the low energy content of the material (a) solids, which include original sugar structures and other newly formed polymeric structures; (b) liquids, which are condensables like water organics and lipids, and (c) gases like CO and CO<sub>2</sub>. Off-gas emissions from a torrefied biomass during storage are less when compared to raw biomass. Torrefied biomass, being hydrophobic, does not absorb moisture from the environment and remains stable for long storage times. Torrefied biomass has a wider range of application, especially when densified and used in power generation plants along with coal. Biomass is an important energy source to create a more sustainable society. Torrefaction aids nature to keep developing its wide diversity of biomass species. But when time is ready, it converts this diversity within a narrow range of fuel specifications. But at the end it starts to feed nature with green CO<sub>2</sub>.

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