Harnessing Biomass Torrefaction in Renewable Energy: Technological Assessment, Current Challenges and Prospective Applications for Sustainability

Mentor: Satish Upadhyay, *Executive Director NTPC & Mission Director, National Mission on Biomass*

Author: Prafulchandra Dongre, *Joint Director CPRI & Member, National Mission on Biomass*

Co-Author: Abhinav Kumar, *Executive Biomass, NTPC & National Mission on Biomass*

ABSTRACT

India generates substantial quantities of agricultural residues annually, including rice husks, wheat straw, cotton stalks etc. The torrefaction process provides an efficient pathway for valorising these biomass resources, addressing the dual challenge of waste management and environmental pollution from stubble burning. Torrefied biomass, with its enhanced energy density and combustion properties, serves as a viable substitute for coal in industrial boilers and thermal power plants, as well as a potential feedstock for bioenergy production systems. While biomass represents a potential renewable energy source due to its abundance, certain property characteristics such as high moisture levels, volatile content, inefficient storage and handling processes make raw biomass difficult for direct use. To overcome this limitation, pre-treatment is necessary before converting it into an energy-efficient fuel. Torrefaction offers a viable solution to address the challenges associated with biomass feedstock. The pre-treatment process, conducted under anoxic conditions, can yield a solid biomass fuel with high energy density and consistent quality, suitable for combustion and Co-firing applications. Torrefaction is a mild form of pyrolysis performed at 200º C –300º C in an inert environment, resulting in solid biofuels with enhanced physiochemical properties, including increased energy density, higher calorific value, reduced moisture & volatile content, hydrophobic, and improved grindability. To provide a comprehensive review of the progress in biomass torrefaction technologies, this study aims to perform an in-depth literature survey of torrefaction principles, processes, systems, and to identify a current trend in practical torrefaction development and environmental performance. Hence, this paper presents an overview of recent advances in torrefaction technology. In this review, a survey of the recent research work on torrefaction is presented. Additionally, the difficulties faced and the viewpoints from the evolution of torrefaction are highlighted. The production and uses of biochar for resource efficiency and environmental sustainability are supported by this cutting-edge review.

Keywords: Co-firing, Biomass, torrefaction, grindability, thermal degradation, biochar.

1.0 INTRODUCTION

Bioenergy, derived from widely distributed biomass, holds significant potential as a low-carbon energy source. It currently accounts for around 10% of global primary energy demand, according to the International Energy Agency (IEA) [2]. The European Union (EU) aims to reduce greenhouse gas emissions by 40% from 1990 levels and increase renewable energy to 27% by 2030 [1]. Similarly, India's Ministry of New and Renewable Energy (MNRE) targets 500 GW of installed renewable capacity by 2030. Biomass can be directly burned for heat and power, but various conversion technologies i.e. physical, chemical, biological, and thermochemical extend its utility [4].

In 2019–2020, India had an estimated 755 million metric tonnes of crop residue and 228 million metric tonnes of surplus biomass, which can be converted into energy through torrefaction. Reviews by Vander Stelt et al. [3] and Chew and Doshi [5] highlight torrefaction's potential. This process enhances biomass properties, making it suitable for industrial applications like co-firing with conventional fuels and other conversion methods such as combustion and gasification

1.1. Composition and Transformation of Biomass

Biomass is categorized into lignocellulosic and non-lignocellulosic types. Lignocellulosic biomass, consisting of cellulose, hemicelluloses, and lignin, is structurally heterogeneous and has low energy and bulk density, making it difficult to handle, transport, store, and conversion [7-9]. Transformation techniques like gasification, pyrolysis, anaerobic digestion, and fermentation are used to convert raw biomass into solid, liquid, and gas fuels. Fig 1. Shows technological deployment w.r.t. time of various pre-treatment biomass technologies.

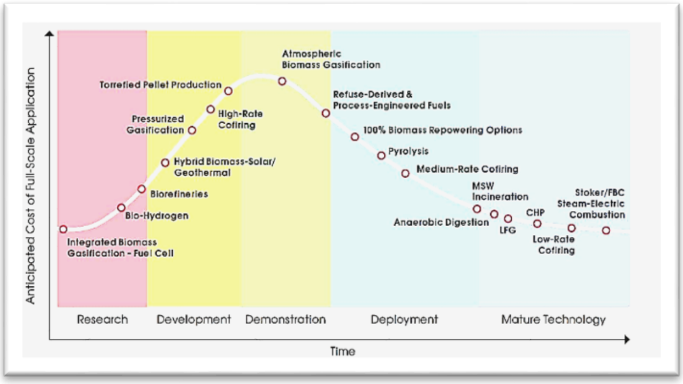


Fig 1: Technological deployment and cost with time

Biomass, while considered a clean fuel suitable for direct use in heat and power generation, faces significant challenges such as high moisture and volatile content, low calorific value, hygroscopicity, and low bulk density. These factors reduce conversion efficiency and complicate collection, grinding, storage, and transport. Torrefaction, a thermochemical process performed in an inert environment at 200–300°C, has gained attention for addressing these issues by upgrading biomass into high-quality biochar [5]. Recent research has focused on optimizing torrefaction parameters and reactor designs to enhance its practicality, but the process remains economically uncompetitive compared to coal and wood pellets. Innovative configurations have been introduced to improve economic viability, yet commercial applications remain limited. Current studies aim to advance torrefaction technologies, explore governing factors for commercialization, and outline future prospects and challenges.

2.0 PRE-TREATMENT PROCEDURE OF BIOMASS

I. Mechanical Pre-treatment: Techniques such as milling, grinding, and extrusion significantly alter the physical properties of biomass, increasing its surface area [12].
II. Thermal Pre-treatment favoured for enhancing physical, structural, and chemical attributes of biomass, and increasing biodegradability for biological pre-treatment. It involves subjecting biomass to high temperatures (200-300°C) in an inert environment [37].
III. Hydrothermal Pre-treatment: Biomass is treated with high-pressure water at 180-230°C. Wet torrefaction, a hydrothermal method, uses compressed water, sometimes mixed with acetic acid or lithium chloride [37].
IV. Biological Pre-treatment: Utilizes microorganisms for enzymatic digestion without chemicals, resulting in lower energy consumption compared to other methods.
V. Chemical Pre-treatment: Involves the use of chemicals to alter the biomass structure, making it more amenable to subsequent processing.

Thermal pre-treatment, particularly torrefaction, is highly efficient for transforming biomass into usable products, with both dry and wet methods available and fig 2(a) & 2(b) shows pre-treatment & modes of torrefaction in detail.

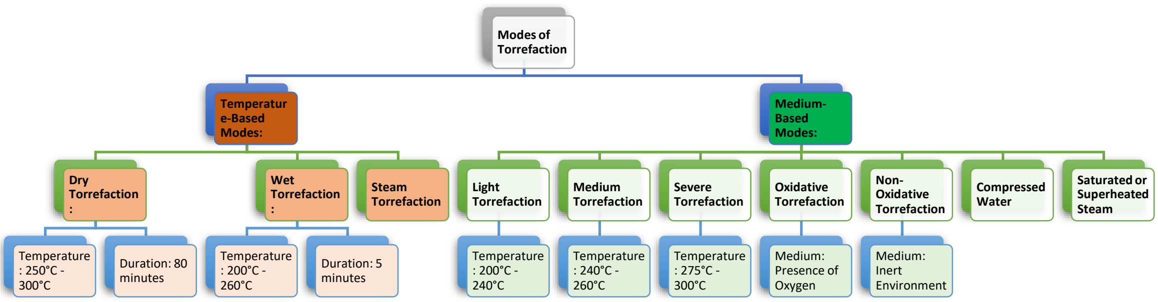


Fig. 2(a) Modes of Torrefaction of Biomass

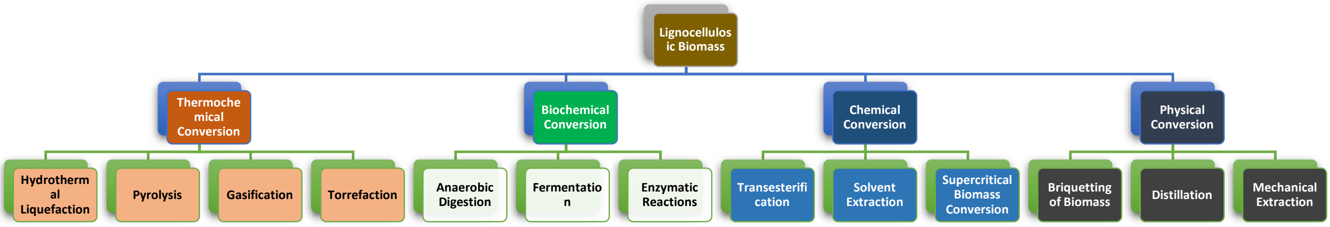


Fig. 2(b) Pretreatment methods

3.0 THERMAL DEGRADATION OF BIOMASS

The most widely used thermochemical conversion techniques include combustion, pyrolysis, gasification, liquefaction, carbonization, and torrefaction [5, 18]. These processes are influenced by oxygen availability and reaction temperature, with all methods except combustion producing solid, liquid, and gaseous biofuels.
Almost all biomass materials can be used in combustion if their calorific values are sufficiently high, reducing reliance on fossil fuels. Biomass can be burned alone or co-fired with coal [10].
A summary of the operational parameters and primary outputs for these thermochemical conversion approaches is provided in Fig 3(a).

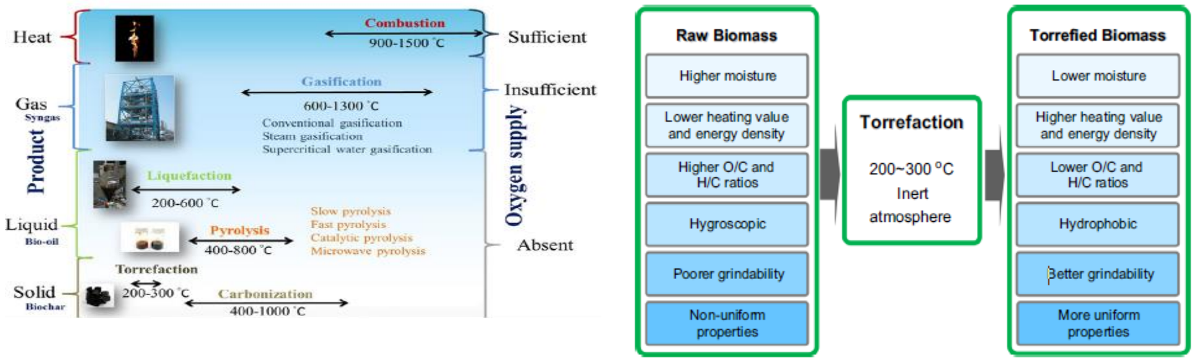


Fig. 3(a).Thermochemical conversion and properties of Torrefied biomass

3.1. Gasification: Biomass with sufficiently high calorific values can serve as a viable alternative to fossil fuels through combustion, either alone or co-fired with coal—a practice long established [10]. In oxygen-deficient environments, biomass combustion produces gaseous fuels or syngas, primarily composed of hydrogen (H_2) and carbon monoxide (CO), alongside carbon dioxide (CO_2), methane (CH_4), and other pollutants. Gasification, occurring at 600–1200 °C, is classified into conventional, steam, and supercritical water types based on the reaction environment [11–13].

3.2. Pyrolysis: Biomass pyrolysis is generally conducted at temperatures between 400°C and 800°C. It can be categorized into fast pyrolysis, slow pyrolysis, catalytic pyrolysis, and microwave pyrolysis, with fixed bed and fluidized bed reactors being used. A comparison of the four pyrolysis technologies is provided in Table 1.

Mild Pyrolysis / Torrefaction	Operating conditions				Bio-oil yield (wt %)	(Reference)
	Temp(oC)	Heating rate (oCmin-1)	Duration (min)	Gas flow (L/min)		
Slow	300-500	3.5-10	10-120	0.02-0.10	23-56	[14]
Fast	300-800	600-36000	0.0017-60	6.67-18	18-77	[14]
Catalytic	350-650	--	0.014-120	0.02-11	21-75	[17]
Microwave	250-800	---	5-60	0.05-20	9-70	[14,18]

Table-1: Comparison of the four pyrolysis technologies

3.3. Torrefaction: This process involves mild pyrolysis of biomass at temperatures ranging from 200 to 300°C. The main objective of torrefaction is to enhance solid biomass as a potential coal substitute. Torrefaction and carbonization are conducted in oxygen-free environments, similar to pyrolysis and liquefaction, but primary aim to produce solid fuels like char coke or bio-char occurring at temperatures between 400 °C and 1000 °C [19]. Slow pyrolysis, characterized by a gradual heating rate and extended residence time, yields a high amount of biochar or solid char. Biomass carbonization produces charcoal, which has various applications:

as a solid fuel for combustion, a feedstock for gasification, and a reducing agent in metallurgical processes [30].

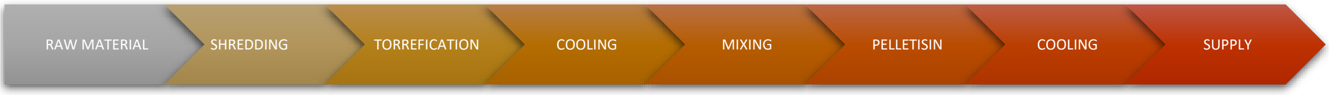


Fig :3(b). Process flow of Torrefied pellet

4.0 CLASSIFICATION OF TORREFACTION

Torrefaction can be classified based on operating conditions and can be categorized into various types of torrefactions.

As shown in Fig (4), Dry torrefaction requires to be carried out in a temperature range of 250℃-300℃. It requires nitrogen gas as the medium, and under atmospheric pressure, for approximately 60-80 min [35]. Wet torrefaction is conducted within a temperature range of 200℃ to 260℃, utilizing hot compressed water as the reaction medium under pressures of 14 kg/cm^2 to 18 kg/cm^2 and a residence time of approximately 5 minutes. Light torrefaction occurs within the temperature range of 200℃ to 235℃, primarily leading to the degradation of hemicelluloses [37]. Mild torrefaction, which operates at temperatures between 235℃ and 275℃, involves both hemicellulose degradation and partial effects on cellulose structure [38]. Severe torrefaction takes place in the 275℃ to 300℃ range, where significant depolymerisation of cellulose, hemicelluloses, and lignin occurs [39]. Oxidative torrefaction is performed in an oxygen-rich atmosphere at temperatures between 200℃ and 300℃. Conversely, non-oxidative torrefaction operates in an inert environment, such as nitrogen, to avoid oxidative reactions [40]. Steam torrefaction involves the use of saturated or superheated steam, utilizing the mechanism of steam explosion to facilitate biomass transformation. Through this technique, the severity of torrefaction can be increased either by increasing the steam temperature or by increasing explosion time [41]. When the temperature reaches 200 °C, the degradation of hemicelluloses occurs, including deacetylation and depolymerization reactions. The amorphous phase of cellulose starts to decompose at around 200 °C to increase the relative crystallinity of biomass, while the crystalline phase of cellulose begins to decompose and the depolymerization of cellu- lose occurs at temperatures higher than 270 °C. During biomass torrefaction, the softening of lignin starts at 160-190 °C and the cleavage of aliphatic side chains occurs at around 300 °C[35] as shown in Fig 4.

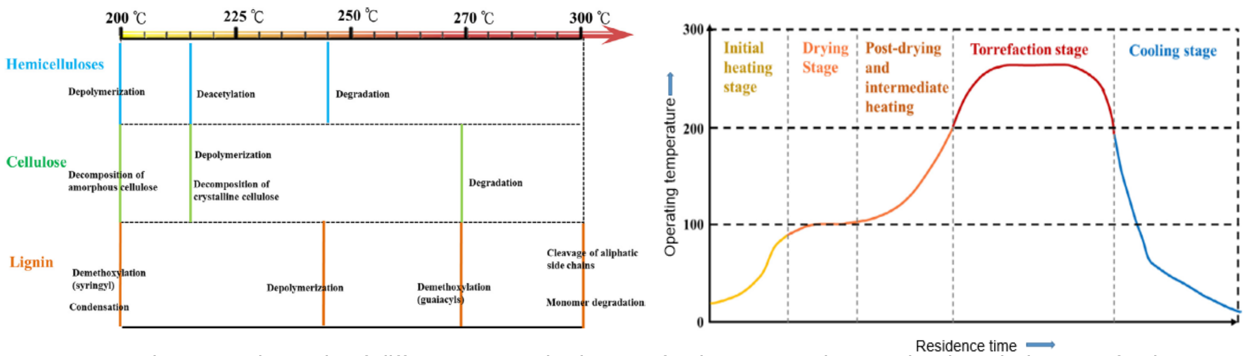


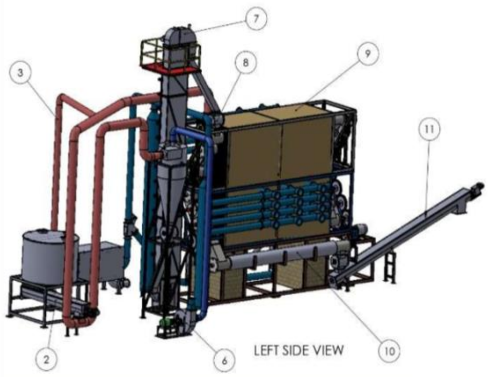
Fig :4. A schematic of different stages in dry torrefaction & Reaction mechanism during torrefaction.

5.0 TORREFACTION REACTORS AND SIGNIFICANCE

Torrefaction can be performed in various reactors, and these have been discussed in details [1,14,24].

Reactor type	Observation & Significance
Multiple Hearth Furnace Reactor	This is a continuous reactor with multiple layers; wherein torrefaction can either take place in a single phase or multiple phases. Biomass is fed from one end of the reactor and after torrefaction, it is mechanically pushed out of the other end of the reactor. This reactor can be scaled up as per the requirement
Compact bed Reactor	This reactor design offers simplicity and cost-effectiveness, along with excellent heat transfer capabilities. Its high capacity allows for processing large quantities of biomass, which is advantageous. However, the presence of dust particles can cause significant pressure drops, potentially triggering automatic reactor shutdowns. These pressure reductions also constrain the dimensions and varieties of biomass that can be introduced into the reactor. Additionally, maintaining precise temperature control in this reactor type proves challenging.

Screw type Reactor	This versatile reactor can be positioned either vertically or horizontally, depending on the requirements. It is particularly well-suited for handling biomass flow and offers a cost-effective solution in terms of pricing. The reactor's design allows for the accommodation of biomass in various sizes, providing flexibility in feedstock options. However, the limited mixing of biomass within the reactor results in poor heat transfer. When biomass comes into contact with the reactor walls, it experiences rapid heating, leading to the formation of hot spots. Consequently, this uneven heating process causes non-uniform torrefaction of the biomass.
Rotating drum reactor	This reactor design is particularly well-suited for drying biomass, offering consistent heat distribution and minimal biomass agitation. One of its key benefits is the ability to accommodate biomass of various sizes. However, this reactor has drawbacks, including poor temperature regulation and slow heat transfer rates. The interaction between the biomass and the drum's surface can generate dust. Additionally, this reactor is expensive and requires substantial space for installation. Its capacity is limited to an input of 10-12 TPH and can produce 5 TPH of torrefied materials.
Fluidized bed reactor	It is a potential scalable technology with a good amount of heat transfer. But due to slow response to temperature, limited variation in particle size, less interaction of biomass with the bed, and excessive biomass attrition, this type of setup is not much feasible for torrefaction
Microwave reactor	Biomass heating can be done through non-conventional forms such as microwave heating, and this can be done in a microwave reactor. Uniform heat distribution can be seen in such type of reactor. Though this reactor is quite advantageous for carrying out torrefaction, it is generally not used because of its high setup cost



Sr. no	Description
1	Circular Feeder gear with 5HP Motor Gearbox
2	Dryer Feeding screw conveyor 3 HP Geared Motor
3	Dryer Pipe Line
4	Dryer Cyclone
5	Rotary Airlock valve 3 HP Geared Motor
6	Dryer ID Fan 20 HP Geared Motor
7	Bucket Elevator 5 HP Geared Motor
8	Torreifer Infeed Air Rotary Valve
9	Biomass Torrefier Machine with 40 HP Motor
10	Cooling Screw Conveyor with Geared Motor
11	Out Feed Screw Conveyor Geared Motor
12	Burner with Blower
13	Burner Feeding screw with Geared Motor
14	Diverter Valve Motor
15	Combuster with Oil burner

Fig: 5. A Schematic layout of Torrefier Reactor

6.0 EXPERIMENTAL LITERATURE REVIEW ON TORREFACTION

Type of Biomass	Type of reactor	Parameters	Observations	Ref
Wood pellets	Steel batch reactor	**Sample size:** 1 kg **Temperatures:** 230 ◦C, 250 ◦C, 275 ◦C, 290 ◦C **Residence time:** 30 min, **Heating rate:** 3 ◦C/min, **Medium:inert**	It was observed that hemicellulose degradation increased as the temperature increased and internal hydrogen bonds weakened. This led to a reduction in the pellet density and hardness. This is quite beneficial as less	[20]
Rice husk	Muffle furnace	**Sample size:** 1 kg **Temperatures:** 250 ◦C, 270 ◦C, 290 ◦C **Residence times:** 1, 1.5, 2 h **Medium:** N2 **Furnace capacity:** 37 L **N2 tank capacity:** 15 L/min	Temperature and residence time had a vital impact on the proximate analysis of rice husks.It was seen that the moisture content and volatile matter content decreased with the increase in temperature and residence time. Similarly, HHV also increased as the temperature and residence time increased	[23]
Fruit waste & seed	Self-fabricated electrical heated torrefaction system	**Temperature:** 210, 240, 270, and 300 ◦C **Residence time:** 20, 30, minutes	As the torrefaction intensity increased, the ultimate compositions of the H/C and O/C atomic ratios of both biochar were comparable to those of lignite. which is suitable for sustainable use. Using biochar as a partial substitute for	[24]

			bituminous coal in power plants has good combustibility and environmental friendliness.	
Spruce trees & branches	--	**Temperatures:** 220 ◦C, 240 ◦C, 260 ◦C, 280 ◦C, 300 ◦C **Residence time:** 30 min to 2 h **Medium:** Nitrogen **Flow rate:** 100 ml/min	Upon torrefaction, it was found that the mass fraction started to reduce as time increased. Upon performing ultimate analysis of both samples, it was found that in both cases, carbon content increases along with nitrogen, but hydrogen and oxygen content decrease. All these findings are relevant to the available literature.	[21]
Wheat-barley straw	--	**Sample size:** 2 kg **Temperatures:** 240 ◦C-320 ◦C **Residence time:** 75 min	Upon completion of the process, toxicity tests were conducted for the condensates released during the process, also known as torr gas. It was found that at higher temperatures, a greater number of components were released. The phenolic compounds released are the result of hemicellulose decomposition, and their yield increases at 320 ◦C because of lignin decomposition.	[22]

7.0 ULTIMATE AND PROXIMATE ANALYSIS

Biomass	**Ultimate analysis (wt%)**				**Proximate analysis (wt%)**			**HHV (MJ/kg)**	**Ref**
	C	H	N	O	VM	FC	A		
Rice straw	39.0	5.08	1.03	40.96	68.83	17.46	8.59	17.12	[29]
Wood pellet	48.50	0.05	6.60	44.90	83.05	16.95	0.30	18.58	[27]
Wheat straw	47.30	6.80	0.80	37.70	76.40	17.30	6.30	18.90	[26]
Fruit waste & seed	45.53	5.46	0.45	43.40	--	--	--	17.02	[28]
Pine wood chips	47.21	6.64	0.17	45.76	85.98	13.76	0.27	18.46	[25]

Current studies have increasingly examined agricultural crops and agro-forestry by-products. A summary of fuel characteristics for various biomass types, gathered from literature reviews, is presented in Table 1. Despite the wide range of biomass sources investigated, the torrefaction process consistently produces similar product qualities. These include higher energy content, enhanced water resistance, and greater brittleness, which are advantageous for thermochemical processing methods.

Analyzing the elemental improvement in biomass compared to fossil fuel is crucial when exploring biofuel applications. The Van Krevelen diagram graphically depicts elemental changes in biomass, plotting the atomic hydrogen to carbon ratio against the atomic oxygen to carbon ratio.

Figure 6(a) Van Krevelen plot shows the atomic ratios of coal and untreated biomass samples. The diagram's dotted lines represent the dehydration reaction pathway. Before torrefaction, woody biomass samples typically have an H:C ratio of 1.6 and an O:C ratio of 0.75. For torrefaction temperatures between 200–250◦C (Fig. 6(b)), the H:C ratio decreases to about 1.5, while the O:C ratio drops to 0.6. At temperatures exceeding 250◦C (Fig. 6(c)), the Van Krevelen plot indicates that torrefaction shifts biomass elemental ratios closer to those of coal. During torrefaction, changes are attributed to the release of carbon dioxide and water, which is beneficial for gasification and combustion [30]. Comparing the three plots in Figure 2 reveals that the torrefaction decomposition mechanism involves significant dehydration, as evidenced by the changes in biomass H:C and O:C atomic ratios following the dehydration pathway.

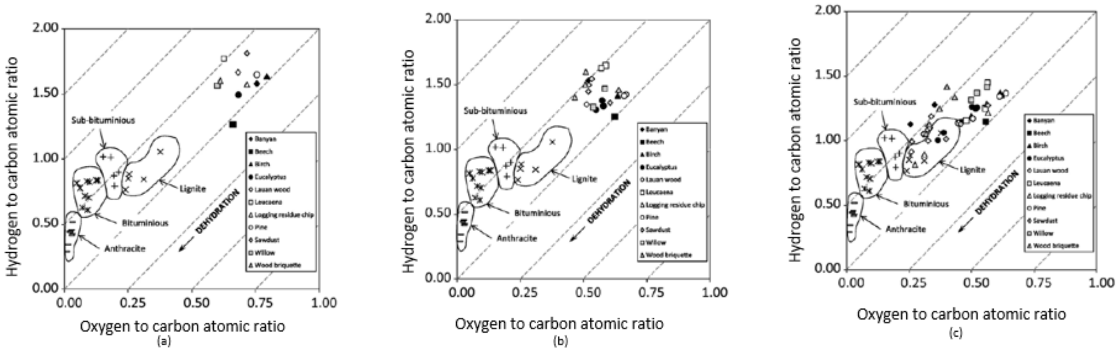


Fig. 6. (a) Coal and untreated biomass sample (b) Coal and torrefied biomass samples at 200-240ºC (c) Coal and torrefied biomass samples above 250ºC.

7.1 Grindability and Volatile organic compounds

Torrefaction enhances the grindability of biomass by making it more brittle and friable. The effectiveness of size reduction in torrefaction studies is commonly assessed by examining the size distribution of ground samples after classification into different size ranges. Research indicates that biomass grindability generally improves following torrefaction, as evidenced by the higher proportion of fine particles produced when torrefaction conditions are intensified [29]. The standard Hardgrove Grindability Index (HGI) used to assess the grindability of coal has been explored in the literature for torrefied biomass samples [30]. The modified HGI study used volumetric measurement for the sample to be milled instead of mass measurement because biomass has lower density than coal. Although treated samples attain comparable grindability to reference coal samples for the extended torrefaction parameter, literature suggests that volumetric HGI may underestimate biomass grinding properties because a considerable fraction of biomass is removed during the pre-milling stage [30]. The volumetric HGI results are not representative of all samples, but they do show a general improvement in the grindability of torrefied biomass. The release of volatile matter during torrefaction poses significant challenges, affecting efficiency and fuel quality. Excessive volatile loss, reduces energy density, while released organic compounds, like acids and phenols, cause environmental and operational issues, including tar formation and equipment fouling. Biomass variability further complicates volatile control, requiring precise monitoring to balance energy retention and improved biomass properties.

8.0 CHALLENGES AND PERSPECTIVES

8.1. Technical and Operational Challenges:

- Biomass feedstocks, such as wood, agricultural residues, and forest residues, exhibit significant variability in chemical and physical properties. This variability leads to inconsistent torrefaction outcomes, which complicates achieving uniform product quality.
- The high and fluctuating moisture content in raw biomass further increases energy demand during pre-treatment. This added energy demand complicates process efficiency and makes it challenging to maintain an optimal temperature range (200–300°C) necessary to prevent over or under torrefaction.
- The production of torrefied biomass faces significant financial challenges, primarily due to the high cost associated with the manufacturing process. Achieving a volatile matter (VM) content of 22% in torrefied biomass is particularly challenging, as it results in substantial weight reduction of the feedstock. This weight loss is attributed to the generation of by-products such as bio-oil and torr gas during the thermal decomposition process. These factors not only increase the cost per unit of torrefied biomass pellets but also pose technical challenges to the optimization and economic viability of the torrefaction technology, thereby hindering its large-scale adoption.
- Determining the ideal residence time for various feedstocks is complex and demands precise process control. Inadequate control can lead to either over-torrefaction, which degrades product quality, or under-torrefaction, which fails to achieve desired properties.
- The drying and heating stages of torrefaction are highly energy-intensive, potentially reducing the net energy yield of the torrefied biomass. Inefficient heat recovery from process gases exacerbates energy losses, further impacting overall process efficiency.
- Ensuring uniform torrefaction across a biomass batch remains particularly challenging at industrial scales. The brittleness of the torrefied product can also pose handling and transportation challenges, adding to operational difficulties.
- Additionally, the process releases volatile organic compounds (VOCs) and other gases that require adequate treatment to meet environmental compliance. Effective utilization of condensable liquids (e.g., tars) and non-condensable gases is essential to enhance the sustainability of the process.

8.2. Emissions and Ash-Related Challenges:

- The torrefaction process increases the ash content in final products, limiting their applications in combustion and gasification. Ash-related problems such as alkali-induced slagging, silicate melt-induced slagging, and corrosion occur in biomass-fired furnaces [33].
- Washing pre-treatment offers a promising approach to reducing pollutant emissions during torrefaction while removing ash from the torrefied biomass. Studies have shown that washing can effectively eliminate problematic chemical species such as potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), iron (Fe), chlorine (Cl), sulphur (S), and phosphorus (P) from biomass [34].
- Hot water washing, in particular, improves the efficiency of removing these compounds. The reduction of sulphur and chlorine content lowers the production of acidic gases, thereby mitigating boiler corrosion and minimizing environmental impacts [34].

8.3. Scaling Up and Economic Challenges:

- Scaling up torrefaction from laboratory to industrial levels requires significant capital investment and technical expertise. Integrating torrefaction units within existing biomass supply chains and energy systems adds logistical complexity.
- High initial costs for reactors and associated equipment, coupled with competition from other renewable energy sources and fossil fuels, creates economic barriers. Securing a consistent and sustainable supply of biomass feedstock is challenging, particularly in regions with seasonal production fluctuation patterns.
- Additionally, the transportation costs and logistics of bulky raw biomass to torrefaction facilities can be prohibitive, further complicating the economic feasibility of the process.

8.4. Commercialization Challenges:

- Financing, market maturity, and product availability are the main commercial obstacles. Torrefied biomass is not currently competitive according to economic analyses, primarily due to the higher cost of the torrefaction reactor and encouragement in demand of product.
- Therefore, torrefaction suppliers require sufficient development power to optimize and scale-up their torrefaction concepts and overall need of the product. Achieving product standardization is also necessary to make the market more transparent and reliable.

9.0 CONCLUSION AND FUTURE WORK

9.1. Enhancing Biomass Torrefaction for Sustainable Energy

- Recent studies examining the fuel characteristics of various torrefied biomass feed stocks have yielded encouraging outcomes. The literature review conducted in this research demonstrates that torrefaction enhances the raw biomass's suitability for subsequent processing. The process results in several beneficial property modifications, including higher energy density (HHV), decreased mass and energy yield, lower moisture content, less volatile content, better grindability, and reduced particle size for industrial applications like co-firing with conventional fuels. These improvements make torrefaction an attractive option for increasing fuel flexibility in major utilities while maintaining environmental friendliness. Additionally, torrefied biomass can be utilized in other conversion methods such as combustion and gasification, further enhancing its properties and enabling the extraction of value-added products.

9.2. Exploring Additional Benefits and Applications

- Moreover, torrefied biomass and biochar have shown potential as effective adsorbent alternatives for the removal of acid gases [32], warranting further exploration in future studies. Torrefied biomass can also be gasified and used in Combined Heat and Power (CHP) systems, thereby increasing the system's overall efficiency [42]. Specific properties of torrefied biomass, such as high heating value, low volatile and ash content, and smaller particle size, are favourable in the metallurgical industry. The development of oxidative torrefaction may command future research and development work to enable the cost-effective production of biochar. Additionally, the impact assessment of heavy metal contaminants in the torrefaction of various biomass feedstock must be considered in future works to deeply understand the risks involved in human health and the environment.

9.3. Future Prospects of Torrefaction in India

- The Government of India has taken significant steps to promote the use of biomass torrefaction technology in thermal power plants as part of its broader commitment to sustainable energy and environmental conservation. The Ministry of Power have mandated policy on use of biomass pellets in thermal power plants along with coal. The government has introduced policies and incentives for providing financial support for setting up torrefaction units. Initiatives like the SAMARTH" (Sustainable Agrarian Mission on Use of Agro Re sidue in Thermal Power Plants) also working in research and development areas of torrefied biomass as,

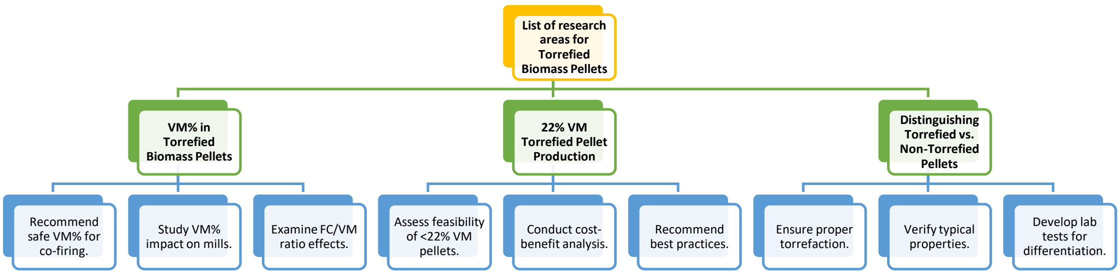


Fig: 7. Research initiatives by SAMARTH Mission on Torrefaction shown in details in fig (7) apart from achieving the objectives as per the policies of Govt. of India while co-firing biomass pellets along with coal in thermal power plants and to reduce carbon footprints of the atmosphere and thereby improving efficiency of thermal power plants.

- The below graph show cases a promising torrefied biomass manufacturing capacities across Indian states maintaining the growth trajectory in states with higher contributions to meet sustainability goals efficiently. The states demonstrate a wide range of torrefied plant capacities, from the lowest value of **2,190 MTPA** in Chandigarh to the highest value of **247,470 MTPA** in Haryana. The total capacity of **403,690 MTPA** torrefied capacities demonstrates significant potential for biomass-based energy in India. This would contribute to meeting renewable energy targets and promoting sustainable practices.

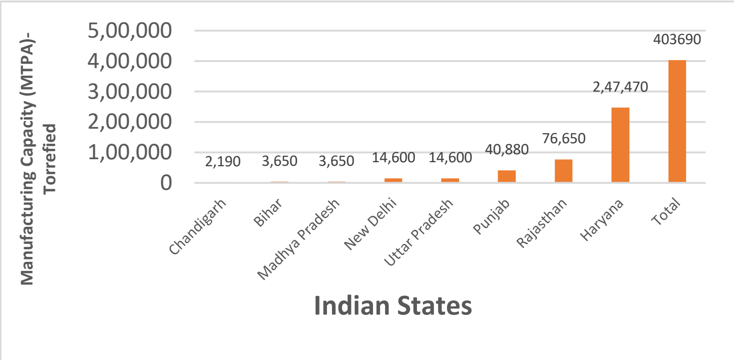


Fig:8. Manufacturing Capacity of Torrefied biomass(MTPA)

- The production capacity of torrefied biomass has been scaled up in various states of India with the initiatives of **SAMARTH Mission** as shown -in Fig 8. **SAMARTH Mission** plays a significant role in advancing the adoption of torrefaction technology for pellet production. Through targeted awareness campaigns, the mission educates stakeholders and industry participants about the benefits of torrefied biomass pellets, such as enhanced energy density, reduced moisture content, and improved grindability for co-firing applications in thermal power plants. Demonstration projects funded under the mission highlight the operational and economic viability of torrefaction, showcasing its potential to improve pellet quality and combustion efficiency. Additionally, SAMARTH facilitates capacity-building programs, offering technical training for setting up and maintaining torrefaction units. In this regards a pilot 10 TPD torrefied plant has also been set up at NTPC NETRA. Financial incentives and subsidies are provided to encourage investments in torrefaction infrastructure. Furthermore, **SAMARTH Mission** strengthens market linkages by connecting pellet manufacturers with thermal power plants, ensuring a consistent demand for torrefied biomass. These concerted efforts address technological, financial, and market challenges, promoting sustainable biomass utilization and fostering the large-scale adoption of torrefaction technology and thus made a rapid stride in energy transition towards a cleaner environment and sustainability in the field of renewable energy.

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