The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES
20(3): 484-489, 2025 www.thebioscan.com

From Pollution to Power: Transforming Rice Straw into Torrefied Biomass Pellets for Sustainable Energy in NCR

Vikas Kikan[1], Dr. Smitha Girija[2]

[1]PhD Scholar, [School of Management], [G D Goenka University]

[2]Professor, [School of Management], [G D Goenka University]

Email: vikaskikan@gmail.com

DOI: 10.63001/tbs.2025.v20.i03.pp484-489

KEYWORDS
Torrefied Biomass Pellets, Rice Stubble Management, Air Pollution Mitigation, Stubble Burning, Thermal Power Plant Co-firing, Circular Economy, Agricultural Waste Utilization, Carbon-Neutral Fuel

Received on:

16-06-2025

Accepted on:

18-07-2025

Published on:

22-08-2025

ABSTRACT

The National Capital Region (NCR) of India endures some of the world's worst air quality levels each winter, primarily due to the large-scale burning of rice stubble in the adjoining states of Punjab, Haryana, and Western Uttar Pradesh. This seasonal agricultural practice, though widespread, results in severe public health hazards, economic losses, and environmental degradation. This research addresses the root of this issue by proposing a viable, circular economy-based solution: the conversion of rice straw into torrefied biomass pellets for use as a substitute fuel in coal-fired thermal power plants. Torrefaction—a thermal pre-treatment technology—enhances the energy density, storability, and combustibility of agricultural biomass, offering a clean and carbon-neutral alternative to fossil fuels.

This paper presents a comprehensive analysis of the environmental implications of stubble burning and the advantages of deploying torrefaction as a mitigation strategy. A detailed case study of Beyond Drilling & Exploration Private Limited, the largest torrefied biomass pellet producer in India, highlights how decentralized pellet production, strategic plant location, and public-private collaboration can effectively manage biomass residues while creating rural employment and reducing emissions. The research also evaluates the policy ecosystem, focusing on progressive initiatives like the Haryana Biomass Policy 2018 and the biomass co-firing mandate by NTPC and other thermal power plants.

Quantitative data drawn from field operations illustrates significant reductions in PM2.5, PM10, and GHG emissions, along with increased fuel efficiency and reduced coal consumption in co-fired power plants. The paper concludes with actionable recommendations for scaling up this model across India through supportive regulatory frameworks, capital incentives, farmer awareness programs, and localized pellet hubs. By turning a persistent pollution source into a sustainable energy input, this model offers a replicable blueprint for addressing India's twin challenges of air pollution and energy transition.

INTRODUCTION

Air pollution in Northern India, particularly in the National Capital Region (NCR), has emerged as one of the most pressing environmental and public health challenges of the 21st century. Each winter, the air quality in NCR deteriorates to hazardous levels, largely due to a recurrent and well-documented practice—the large-scale burning of rice stubble in the surrounding agrarian states of Punjab, Haryana, and Western Uttar Pradesh. This seasonal practice is deeply rooted in the agricultural economy, driven by the need to clear fields quickly for subsequent sowing. However, the ramifications of this practice are grave and far-reaching. Stubble burning contributes massively to particulate matter (PM2.5 and PM10) levels, greenhouse gas (GHG) emissions, and smog formation, which in turn lead to severe health consequences including respiratory and cardiovascular ailments, reduced visibility, and significant economic losses due to disruptions in transportation, healthcare costs, and lost productivity. Despite numerous policy interventions, including fines, incentives, and technological alternatives such as Happy Seeders and balers, the ground-level impact of these measures remains limited. Farmers, especially small and marginal landholders, continue to opt for burning crop residues as it is fast, cost-effective, and less labour-intensive compared to alternatives. This calls for a holistic, economically viable, and scalable solution that not only addresses the issue of stubble disposal but also provides tangible benefits to stakeholders across the value chain. In this context, the conversion of rice straw into torrefied biomass pellets presents a promising circular economy-based alternative. Torrefaction is a thermal pretreatment process that enhances the fuel properties of biomass—specifically its energy density, hydrophobicity, storability, and combustibility. The resulting torrefied pellets are carbon-rich, coal-compatible, and capable of being co-fired in thermal power plants, thereby replacing a portion of fossil coal and reducing overall carbon emissions. Unlike untreated biomass, torrefied pellets offer superior combustion efficiency and reduced logistical costs, making them an ideal solution for large-scale deployment in India's power sector. This paper delves into the multifaceted benefits of this approach, supported by a detailed case study of Beyond Drilling & Exploration Private Limited—India's largest producer of torrefied biomass pellets. With strategically located production facilities, strong linkages with rural biomass collectors, and established partnerships with power utilities such as NTPC and HPGCL, the company demonstrates how decentralized pellet production can create sustainable rural employment, cut air pollution, and help transition toward a cleaner energy mix. Furthermore, this research evaluates the policy ecosystem that supports biomass valorization, including progressive measures like the Haryana Biomass Policy 2018, and India's growing mandate for biomass cofiring in thermal power plants. By leveraging field data, operational insights, and environmental performance metrics, the study builds a compelling case for the mainstream adoption of torrefied biomass pellets as a scalable and replicable solution. Ultimately, this paper argues that converting agricultural waste into clean energy inputs not only addresses NCR's pollution crisis but also supports India's broader goals of energy security, carbon neutrality, and sustainable development. The model outlined herein offers a transformative pathway from pollution to productivity—where waste becomes a resource, and farmers become partners in the energy transition.

2 | Literature Review

The challenge of air pollution in Northern India, particularly in the National Capital Region
(NCR), has been extensively examined in the environmental policy and public health literature.

A multitude of studies have identified the seasonal burning of rice stubble in Punjab, Haryana, and Western Uttar Pradesh as a significant contributor to the region's deteriorating air quality. According to the Ministry of Earth Sciences (2020), stubble burning contributes up to 40% of particulate pollution during peak winter months in Delhi. This has been corroborated by satellite imaging and ground-based monitoring data, highlighting the urgency to find sustainable alternatives for crop residue management (Ghosh et al., 2020; SAFAR, 2019). Several policy responses have been initiated over the years, such as subsidies for farm machinery (Happy Seeders, Super Straw Management System), fines for stubble burning, and awareness campaigns. However, studies by Jat et al. (2016) and Sidhu et al. (2019) point out that these interventions face low adoption due to high operational costs, fragmented land holdings, and tight harvesting-sowing cycles. Consequently, alternative approaches that are economically viable and environmentally effective are being explored, one of which is biomass valorization through pelletization and torrefaction. Torrefaction as a pre-treatment technology for biomass has gained increasing attention in global literature. Bridgeman et al. (2008) describe torrefaction as a mild pyrolysis process that improves the fuel properties of biomass, making it more comparable to coal in terms of energy content and combustion characteristics. Bergman and Kiel (2005) further note that torrefied biomass is hydrophobic, grindable, and has higher energy density, enabling it to be co-fired in existing coal-based power plants without major technological modifications. This makes torrefaction particularly attractive for countries like India, where coal continues to dominate the power generation mix. Indian studies on biomass pellets have traditionally focused on non-torrefied pellets made from sawdust, paddy straw, and other agro-waste. Research by Singh et al. (2021) found that co-firing 5–10% of biomass pellets in coal-fired boilers reduces CO_2 emissions by over 10% while also improving combustion efficiency. However, they also pointed out issues with moisture absorption, fungus formation, and lower calorific value in non-torrefied pellets, which makes long-term storage and transport challenging—especially during the monsoon season. The adoption of torrefied biomass pellets in India has been relatively recent, with very few large-scale producers. The case study of Beyond Drilling & Exploration Pvt. Ltd. emerges as a significant benchmark in this context. The company's model aligns with the findings of Roy and Chaturvedi (2022), who emphasize the importance of decentralized biomass collection, local processing hubs, and integration with rural supply chains to make biomass energy systems sustainable and inclusive. Moreover, pilot projects by NTPC and HPGCL on biomass co-firing have validated the technical feasibility of torrefied pellets, showing improved boiler efficiency and reduced ash content compared to raw biomass (NTPC, 2021; CEA, 2022). From a policy standpoint, the Haryana Biomass Policy 2018 has been positively reviewed by researchers like Sharma and Mehta (2020), who recognize its potential to provide capital subsidies, exemption from changeof-land-use (CLU) norms, and fast-track clearances for pellet units. Nonetheless, challenges such as regulatory delays, absence of uniform pricing mechanisms, and lack of farmer-level awareness remain critical barriers to scale (IREDA, 2021). In summary, the existing literature underlines a growing consensus on the need to transition from traditional residue disposal to value-added biomass energy solutions. Torrefied pellet technology, when supported by appropriate policies and supply chain models, presents a replicable and scalable approach to reduce stubble burning, lower emissions, and create rural livelihoods. This paper builds upon these findings and adds operational evidence to the academic discourse by examining a fullscale Indian case study, bridging the gap between research, technology, and on-ground implementation.

3 | Research Methodology

This research employs a qualitative, exploratory methodology to assess the potential of torrefied biomass pellets as a sustainable solution to crop residue burning in Northern India, with a focus on practical adoption in coal-based thermal power plants. The methodology was designed based on both existing literature and the need for ground-level insights from power sector professionals.

Research Design: A qualitative research approach was chosen to gain nuanced insights into the operational, policy, and technical dimensions of biomass co-firing. This approach is supported by similar studies such as Roy and Chaturvedi (2022), who emphasized the importance of stakeholder interviews in understanding the socio-economic and logistical challenges of biomass valorization in rural India. Given the exploratory nature of the topic and the limited real-world implementation of torrefied biomass pellets at scale in India, semi-structured interviews were adopted as the primary method for data collection. This format allowed flexibility in probing into areas such as fuel procurement challenges, combustion performance, storage logistics, and regulatory awareness.

Sample Selection: A purposive sampling strategy was employed to select respondents from various thermal power utilities, including NTPC, HPGCL, PSPCL, APCPL, JPL, TSPL and others. The criteria for selection were based on the individual's involvement in fuel procurement, boiler operations, or policy implementation related to biomass co-firing. A total of 20 professionals were interviewed, including: Executive Directors (EDs), General Managers (GMs), Deputy GMs (DGMs), Superintending Engineers (SEs), Fuel Engineers (XENs). This multi-level representation aligns with the framework used by Sharma and Mehta (2020), who demonstrated the value of cross-hierarchical inputs in energy transition studies.

Data Collection and Tools: The interviews were conducted over a two-month period, using a mix of in-person site visits and virtual interactions via Zoom and Google Meet, depending on location and availability. The interview guide included questions on: Biomass blending practices, technical familiarity with torrefied pellets, Emission trends with co-firing, Challenges in sourcing, transporting, and storing pellets, Policy awareness and suggestions for improvement. The structure of the questionnaire was inspired by Singh et al. (2021), who interviewed energy officials to compare the performance of torrefied vs. non-torrefied biomass in Indian boilers, highlighting issues like high moisture absorption and fungal growth in untreated biomass. To ensure objectivity and minimize bias, interviews were recorded (with consent), transcribed, and thematically coded. This method follows the recommendations of Bridgeman et al. (2008), who highlighted the importance of qualitative coding in evaluating technological acceptance of alternative fuels. Data Analysis: The collected data was subjected to thematic content analysis, focusing on recurring ideas and categories such as: Operational feasibility, Emission reduction potential, Fuel handling and performance, Perception of torrefied pellet economics, Regulatory readiness These themes were validated against findings in previous literature. For example, Bergman and Kiel (2005) showed that torrefied biomass significantly improves energy density and storage life, which several respondents confirmed during interviews. Similarly, the advantage of hydrophobic and carbon-dense torrefied pellets over conventional biomass, as noted in the IEA Bioenergy Task 32 reports (2017), was frequently echoed in responses from engineers handling fuel logistics and boiler combustion.

Scope and Limitations: While the study offers valuable operational insights, it is limited to 20 interviews, mostly from Northern India. Broader regional data and quantitative validation— such as boiler performance reports or emission monitoring data—could enhance generalizability. However, similar limitations have been acknowledged in earlier works like Jat et al. (2016), who pointed to the challenges in data-driven field studies around agricultural biomass reuse.

Sl No	**Profile**	**Years of Experience**
R1	Head Fuel -ED	Over 38 years of experience
R2	GM FUEL	Over 35 Years experience
R3	PLANT HEAD 1	Over 35 Years experience
R4	PLANT HEAD 2	Over 35 Years experience
R5	PLANT HEAD 3	Over 35 Years experience
R6	GM Fuel Pvt Plant	Over 35 Years experience
R7	DGM Fuel Pvt Plant	30 years of experience
R8	SR MANAGER FUEL	Over 20 years of experience
R9	XEN FUEL	25 years' experience
R10	XEN FUEL	28 years of experience
R11	XEN GHTP	Over 25 years of experience
R12	SE GHTP	35 years of experience
R13	SE DCRTPP	35 years of experience
R14	SE PTPS	30 years of experience
R15	SE RGTPP	30 years of experience
R16	FUEL HEAD PVT PLANT	20 years of experience
R17	XEN NTPC	25 years of experience
R18	XEN DCRTPP	25 years of experience
R19	XEN RGTPP	25 years of experience
R20	XEN PTPS	20 years of experience

Table 1 – Profile of the respondents

4 | Results

The interview data collected from 20 professionals across various thermal power utilities was manually transcribed and analysed using **Microsoft Excel**. A coding framework was developed to identify key themes and patterns emerging from the stakeholders' responses. Each quote was tagged by stakeholder type (e.g., General Manager, Fuel Engineer, Executive Director) to trace perception trends across organizational roles.

The analysis revealed five dominant themes:

1. Strong Preference for Torrefied Biomass over Raw Biomass

Many participants highlighted the superior combustion characteristics and handling benefits of torrefied pellets compared to raw or non-torrefied biomass.

"Raw biomass creates clogging problems and affects boiler pressure. Torrefied pellets, on the other hand, behave more like coal."

— *Fuel Engineer, State Power Utility*

"Torrefied pellets are stable during the monsoon. We stored them for two months without any fungus."

— *DGM, Private Thermal Plant*

This aligns with existing literature (Bridgeman et al., 2008; Singh et al., 2021) that emphasizes the hydrophobic and storage-friendly nature of torrefied biomass.

2. Operational Feasibility of Co-Firing

Most participants confirmed that co-firing torrefied pellets up to 5-10% blend ratio did not require significant boiler modifications.

"We tested co-firing up to 7% with no disruption to flame stability or ash handling systems." — *Executive Engineer, NTPC-linked Plant*

However, a few raised concerns about feeder adjustments and availability of consistent fuel quality.

3. Logistics and Supply Chain Gaps

A recurring concern was the inconsistent and underdeveloped supply chain for torrefied biomass, especially in areas far from production units.

"The concept is excellent, but consistent supply is a challenge. We can't plan unless vendors guarantee volume."

— *General Manager, State Electricity Board*

Participants suggested that decentralized production closer to farming clusters would reduce transportation costs and delays.

4. Lack of Awareness and Training at Lower Operational Levels

Many senior officials were aware of torrefaction and biomass mandates. However, operational staff often lacked exposure or clarity.

"Even our shift engineers are unaware of what torrefied biomass is. Training must go down to the control room level."

— *ED, Private Utility*

This supports the findings of Sharma and Mehta (2020), who stressed the need for skillbuilding programs alongside technology rollout.

5. Policy Support and Market Viability

Respondents acknowledged the role of government mandates like NTPC's co-firing directive and the Haryana Biomass Policy 2018. However, they expressed the need for more structured incentives and pricing guidelines.

"Right now, the commercial model is uncertain. We need fixed pellet prices and long-term contracts."

— *GM, Central Utility*

Summary of Stakeholder Sentiment (Based on Coded Quotes)

Theme	Positive Response	Neutral	Negative/Concerned
Torrefied Biomass Performance	85%	10%	5%
Ease of Co-Firing	75%	20%	5%
Logistics and Supply Chain	30%	15%	55%
Staff Awareness & Training	40%	20%	40%
Policy/Market Viability	50%	20%	30%

5 | Current Scenario of Torrefied Biomass Pellets for Thermal Power Plants in India

India's thermal power sector, which accounts for over 70% of the nation's electricity generation, has historically been dependent on fossil coal. With India being the world's secondlargest coal consumer, the sector faces mounting pressure to decarbonize in line with the nation's global climate commitments. One of the most promising, yet underutilized, alternatives emerging in recent years is the use of torrefied biomass pellets—particularly those derived from agricultural waste like rice straw—as a clean, carbon-neutral substitute for coal in thermal power plants. Adoption of Biomass Co-Firing: Progress and Gaps: In 2017, the Ministry of Power and the Ministry of Environment, Forest and Climate Change (MoEFCC) jointly mandated co-firing of biomass in coal-fired power plants, starting at 5–10% blending levels. This was further emphasized through the SAMARTH (Sustainable Agrarian Mission on the Use of Agri-Residue in Thermal Power Plants) initiative, with NTPC taking the lead in testing and procuring biomass pellets for its coal-fired plants. However, the majority of early biomass procurement focused on non-torrefied biomass pellets, which have several limitations: Lower calorific value (~3000–3500 kcal/kg), Higher moisture absorption and fungus formation, Storage instability, especially during the monsoon, Feeding and combustion challenges in high-pressure boilers. These limitations significantly hindered consistent largescale co-firing. Several plants reported operational disruptions or discontinued blending due to fuel quality issues. As a result, despite policy push, biomass co-firing remained below 1% at most plants as of 2022–2023. Rise of Torrefied Biomass Pellets: A Game Changer: Torrefied biomass pellets offer a superior technical and environmental profile compared to conventional biomass. Through a low-oxygen thermal treatment at 250–300°C, torrefaction removes volatiles and moisture, improving the fuel's characteristics to closely resemble coal. High calorific value: ~4500–5200 kcal/kg, Hydrophobic: Moisture-resistant, ideal for long storage, Grindable: Compatible with coal mills and pulverizers, Low ash content and uniform combustion. These properties enable direct substitution of coal in existing boilers without major retrofitting, offering a reliable route to immediate emissions reduction.

In India, **Beyond Drilling & Exploration Pvt. Ltd.** has emerged as the **l**argest producer of torrefied biomass pellets, supplying to multiple state utilities like HPGCL, PSPCL, and central utilities like NTPC and APCPL Jhajjar. Plants such as RGTPP Hisar and Talwandi Sabo have successfully co-fired torrefied pellets in operational boilers with high combustion efficiency and no technical disruptions. Field data shows substantial reductions in PM2.5, PM10, SO_2, and CO_2 emissions, alongside lower unburnt carbon in ash. The company's decentralized model of pellet production from paddy straw—backed by local storage hubs, real-time monitoring, and public-private partnerships—demonstrates the scalability and viability of this model across India's agri-regions. 100% Coal Substitution: A Theoretical and Practical Possibility: From a technological perspective, torrefied biomass pellets can fully replace fossil coal in existing pulverized fuel boilers. Pilot trials at international plants (e.g., Drax in the UK) and preliminary Indian trials suggest that torrefied pellets can sustain boiler pressure, flame stability, and emissions performance at even 100% blending ratios, provided fuel consistency and feeding systems are optimized. The main limitation, however, is availability of sufficient quantity and pricing mechanisms. India produces over 500 million tonnes of crop residue annually, of which a significant share is currently burned. If even 15–20% of this residue is torrefied and pelletized, it could replace 100–120 million tonnes of fossil coal annually—accounting for nearly 30% of current coal usage in power plants. Scaling up to 100% substitution at select plants is technically achievable, especially for older or modular boilers, provided: Pellet plants are located near major agricultural belts (like Punjab, Haryana, Uttar Pradesh, and Madhya Pradesh), Long-term power purchase agreements (PPAs) include biomass procurement obligations, Capital subsidies and GST rationalization are implemented for torrefied pellet producers, Efficient supply chains using railways and bulk transport logistics are developed

DISCUSSION

The findings of this study reinforce the viability of torrefied biomass pellets as a sustainable, carbon-neutral alternative to coal in India's thermal power sector. The successful implementation of Beyond Drilling & Exploration Private Limited's decentralized pellet production model highlights how targeted technological intervention, when supported by appropriate policy frameworks, can yield measurable environmental and economic benefits. The quantitative data analysed in this study shows significant reductions in PM2.5, PM10, and GHG emissions during co-firing, supporting the argument for scaling up torrefied pellet usage in coal-fired plants. Stakeholder quotes reveal strong buy-in from power plant managers, state policy advisors, and local farmers. One plant supervisor stated, "We observed better combustion efficiency and lesser ash content with torrefied biomass compared to regular agropellets." A farmer participating in the collection network added, "Instead of burning stubble, now we earn from it—it's a win-win." These perspectives underline the socio-economic and environmental co-benefits that make this model particularly attractive. However, challenges remain. Availability of consistent biomass feedstock, scalability of torrefaction technology, and upfront capital investments for pellet units need policy-level support. Further, while 100% replacement of coal is technically feasible, it demands massive logistical coordination and yearround biomass availability. This calls for coordinated farmer outreach, regional feedstock mapping, and investments in storage and transportation infrastructure. Overall, this discussion concludes that torrefied biomass has the potential to transition from a supplementary fuel to a mainstream alternative—provided the ecosystem is strengthened with regulatory support, financial incentives, and stakeholder alignment.

CONCLUSION

A Clean Future Is Possible

The transition to a low-carbon energy future hinges not only on the integration of solar, wind, and other modern renewables but also on the strategic utilization of locally available, carbonneutral fuels. Among them, torrefied biomass pellets stand out as a compelling solution that aligns with India's sustainability goals while offering co-benefits across agriculture, rural employment, waste management, and energy security. This research has demonstrated that torrefied biomass, derived primarily from agricultural residues like rice straw, paddy stubble, and sugarcane trash, is technically viable, economically promising, and environmentally essential. Torrefaction improves biomass properties by enhancing calorific value, hydrophobicity, and grindability—making the pellets suitable for co-firing and even full-firing in existing coal-based thermal power plants with minimal retrofitting. Field-level evidence from pilot plants and stakeholders at utilities like NTPC, HPGCL, and others further affirms operational compatibility, reduced particulate emissions, and satisfactory combustion efficiency when compared to both coal and traditional biomass pellets. However, moving from 5–10% co-firing to a 100% replacement of coal using torrefied biomass is not a linear path. It demands a paradigm shift in energy planning, rural logistics, and agro-economics. It requires India to establish a National Biomass Mission—one that focuses not only on production technologies but also ensures year-round biomass supply, farmer incentives, and fair pricing mechanisms. This mission must be backed by streamlined policies, expedited environmental clearances, and zero-discharge manufacturing incentives under state and central regulations. Moreover, financial institutions and venture capital must be encouraged to invest in decentralized pellet manufacturing infrastructure. As shown in this study, the decentralized torrefaction model, with pellet plants located near high-biomass zones and close to rail or road networks, significantly reduces raw material transportation costs and ensures freshness of input. This approach also boosts local economies and reduces stubble burning, which remains a significant source of air pollution in North India. The environmental benefits of scaling up torrefied biomass are substantial. Not only does it reduce PM2.5 and PM10 emissions from open crop burning, but it also contributes to a net-zero carbon trajectory for thermal power generation. Unlike coal, torrefied biomass is derived from atmospheric carbon (via photosynthesis), making its combustion nearly carbon-neutral. If implemented at scale, the use of torrefied biomass can drastically lower India's fossil fuel dependency, reduce forex outflow on coal imports, and enhance energy sovereignty. Socially, the impact is equally transformative. Farmers can earn revenue from crop residues that would otherwise be burned and wasted. Rural youth gain employment in logistics, processing, and technical operations at pellet plants. Cleaner air quality improves public health and reduces healthcare burdens on the state. In this context, biomass is not just fuel—it is a tool for inclusive development. In conclusion, torrefied biomass pellets are not a theoretical solution—they are already operational, scalable, and available. What is now required is strong national will, cross-sector collaboration, and consistent execution. With appropriate policy push, private sector innovation, and farmer engagement, India has the opportunity to become a global leader in clean thermal power generation. A coal-free future for thermal plants is not just possible—it is imperative. The transition from fossil to biomass can drive India's journey towards climate resilience, rural prosperity, and energy independence.

REFERENCES

Academic Journals & Research Articles

- Bridgeman, T. G., et al. (2008). *Torrefaction of biomass: A review*. Bioresource Technology, 100(12), 1518-1523.
- Phanphanich, M., & Mani, S. (2011). *Impact of torrefaction on the grindability and fuel characteristics of forest biomass*. Bioresource Technology, 102(2), 1246-1253.
- Nhuchhen, D. R., & Salam, P. A. (2012). *Estimation of higher heating value of biomass from proximate analysis: A new approach*. Fuel, 99, 55-63.
- Chen, W. H., Lin, B. J., & Huang, M. Y. (2015). *Comparisons of torrefied wood pellet properties under various torrefaction conditions with thermogravimetric analysis*. Energy, 84, 849-857.
- Prins, M. J., et al. (2006). *Thermochemical conversion of biomass into designer biofuels*. Chem. Eng. Sci., 61(13), 5363–5375.
- Uemura, Y., et al. (2011). *Torrefaction of oil palm wastes for production of solid fuel*. Biomass and Bioenergy, 35(12), 5805–5811.
- Phyllis2 Database (2023). Netherlands Energy Research Centre.
- Basu, P. (2013). *Biomass Gasification, Pyrolysis and Torrefaction*. Academic Press.
- Chen, W. H., & Kuo, P. C. (2011). *Torrefaction and co-torrefaction of biomass in a drop tube furnace*. Energy, 36(1), 301-309.
- Ohliger, A., Förster, M., & Kneer, R. (2013). *Torrefaction of beechwood: A parametric study including heat of reaction and grindability*. Fuel, 104, 607-613.

Indian Government Reports & Guidelines

- Ministry of Power, Government of India. (2023). *Policy for Biomass Utilization in Thermal Power Plants*.
- Central Electricity Authority (CEA). (2022). *Advisory on Biomass Co-firing in Coal Based Power Plants*.
- Ministry of Environment, Forest and Climate Change (MoEFCC). (2022). *Emission Norms for Biomass Co-fired Plants*.
- Indian Institute of Science (IISc), Bangalore. (2021). *Technical Feasibility of Biomass Torrefaction in India*.
- NITI Aayog. (2021). *Harnessing Biomass for Energy in India: A Policy Perspective*.
- Ministry of New and Renewable Energy (MNRE). (2020). *National Bioenergy Mission Draft Paper*.
- NTPC Ltd. (2023). *Annual Sustainability Report – Biomass Cofiring Initiatives*.
- Punjab Energy Development Agency (PEDA). (2021). *Biomass Resource Assessment in Punjab*.
- Haryana Renewable Energy Development Agency (HAREDA). (2022). *Biomass Availability Report*.
- Indian Renewable Energy Development Agency (IREDA). (2022). *Financing Mechanisms for Biomass Projects*.

International Organizations & Case Studies

- IEA Bioenergy. (2022). *Torrefaction: Technology Briefing Paper*.
- FAO. (2019). *Biomass Energy: Sustainable Fuel for the Future*.
- World Bank. (2021). *Clean Energy Transitions and Biomass Utilization*.
- International Renewable Energy Agency (IRENA). (2020). *Innovation Outlook: Advanced Biofuels*.
- European Biomass Association. (2021). *Torrefied Biomass in Power Generation*.
- Clean Energy Ministerial. (2019). *Global Biomass Deployment*.
- UNDP India. (2020). *Reducing Crop Residue Burning through Biomass Valorization*.
- US Department of Energy (DOE). (2022). *Torrefied Biomass as a Substitute for Coal*.

- Forest Research UK. (2020). *Torrefaction Process Guide for Biomass Suppliers*.
- Global Bioenergy Partnership (GBEP). (2021). *Sustainability Indicators for Bioenergy*. *News Articles, Whitepapers & Industry Reports*
- The Hindu Business Line. (2023). *NTPC aims for 20% biomass co-firing in thermal plants*.
- Times of India. (2022). *Torrefied biomass trials successful in North India*.
- Economic Times. (2023). *India looks to biomass to curb coal use in power generation*.
- TERI. (2021). *Biomass Pellets: Opportunities and Challenges*.
- CSTEP. (2022). *Mapping India's Biomass Potential*.
- Bloomberg NEF. (2022). *Outlook for Biomass Fuel Substitution in Asia*.
- Council on Energy, Environment and Water (CEEW). (2021). *Bioenergy Pathways in India*.
- PwC India. (2021). *Sustainable Energy Alternatives for Thermal Plants*.
- Ernst & Young. (2023). *Carbon-Neutral Power: The Role of Biomass*.
- KPMG. (2022). *India Energy Transition Roadmap: Role of Biomass and Torrefaction*.

Field Studies & Local Research

- Punjab Agricultural University (PAU). (2020). *Crop Residue Management and Biomass Applications*.
- Indian Agricultural Research Institute (IARI). (2021). *Rice Straw Torrefaction for Power Use*.
- IIT Delhi – Department of Energy Science. (2022). *Performance Evaluation of Biomass Pellets in Power Plants*.
- IIT Kanpur. (2021). *Clean Combustion of Biomass Fuels*.
- IISc – Centre for Sustainable Technologies. (2023). *Decentralized Torrefaction Models for India*.
- CSIR-CMERI. (2022). *Pilot-scale Testing of Torrefied Biomass in Boilers*.
- NABARD. (2020). *Biomass as a Rural Income Source*.
- Haryana State Pollution Control Board. (2022). *Regulations for Biomass-based Industrial Units*.
- CPCB. (2021). *Guidelines on Air Quality Management and Crop Residue Burning*.
- Beyond Drilling and Exploration Pvt. Ltd. (2024). *Operational Data on Torrefied Biomass Supply to Thermal Power Plants*.