ASHOKA UNIVERSITY

CENTRE FOR A
People-centric Energy Transition

Balancing Lives, Emissions, and National Development (BLEND)

Socioeconomic Impact of Solid Fuel Blending in Thermal Power Plants

May 2026



Project Investigators

Mr. Vaibhav Chowdhary, Director, ACPET

Dr. Shubham Jain, Research Associate, ACPET

Dr. Anandajit Goswami, Research Lead and Senior Research Fellow, ACPET

Authors

Dr. Shubham Jain, Research Associate, ACPET Mr.

Vaibhav Chowdhary, Director, ACPET

Dr. Anandajit Goswami, Research Lead and Senior Research Fellow, ACPET

About Ashoka Centre for a People-centric Energy Transition (ACPET)

The Ashoka Centre for a People-centric Energy Transition (ACPET) is a research-focused, transdisciplinary centre within Ashoka University, India, established to drive a sustainable, equitable, and "people-centric" shift towards net-zero emissions. It bridges the knowledge gap in energy transition by collaborating with industry and government to create scalable solutions, covering areas like renewable energy, policy, and technology. For further information about ACPET, please visit: acpet.ashoka.edu.in

About Ashoka University

Ashoka University is a private university located in Sonipat, Haryana, providing liberal education in the humanities, social sciences, and natural sciences. The University provides a holistic education that is liberal, multidisciplinary, and interdisciplinary, offering a diverse and inclusive space for its students to think deeply and critically, learn across disciplinary boundaries, express themselves creatively, and communicate with meaning to cause impact and change. For further information about ACPET, please visit: ashoka.edu.in

Suggested Citation

Jain, S., Chowdhary, V., & Goswami, A. (2026). Balancing Lives, Emissions, and National Development (BLEND). Ashoka Centre for a People-centric Energy Transition (ACPET), Delhi, Ashoka University, Sonipat, Haryana. https://doi.org/10.5281/zenodo.22894888

Table of Contents

Abbreviations 6
List of Figures 7
List of Tables 9
Executive Summary 10
1. Introduction 13
1.1. Thermochemical Conversion 13
1.2. Biochemical Conversion 14
1.3. Extraction-Based Conversion 14
1.4 Policy Landscape for Biomass Cofiring 14
2. Biomass Cofiring at NTPC's Thermal Power Plants 16
3. Research Gap, Objectives, and Deliverables of the Project 21
4. Methodology (The BLEND Framework) 22
5. Socioeconomic Impact Assessment 24
5.1. Sampling Strategy and Respondent Groups 25
5.2. Primary Research Findings 28
6. Cow Dung-Biomass Fuel Blends for Cofiring in Coal-fired Thermal Power Plants 75
6.1. Proximate Analysis and Gross Calorific Value 81
6.2. Ultimate Analysis 84
6.3. Ash Fusion Temperature Analysis 85
7. Global Experiences and Regulatory Drivers of Biomass Co-Firing 88
7.1. North America 88
7.2. South America 89
7.3. Australia 91
7.4. Africa 91
7.5. Europe 92
7.6. Asia 95
8. Conclusions and Recommendations 105
9. Future Scope 108
10. References 109
11. Annexures 114

Abbreviations

CAPI	Computer-Assisted Personal Interviewing
CBG	Compressed Biogas
CCTS	Carbon Credit Trading Scheme
CFA	Central Financial Assistance
CHP	Coal Handling Plant
CRM	Crop Residue Management
ESP	Electrostatic Precipitator
FGD	Flue Gas Desulfurization
FGD	Focus Group Discussion
FPO	Farmer-Producer Organization
GCV	Gross Calorific Value
GHG	Greenhouse Gas
IARI	Indian Agricultural Research Institute
MSW	Municipal Solid Waste
NABARD	National Bank for Agriculture and Rural Development
NGO	Non-governmental Organizations
PM	Particulate Matter
RDF	Refused-derived Fuels
RRB	Regional Rural Bank
SAMARTH	Sustainable Agrarian Mission on Use of Agri-Residue in Thermal Power Plants
SMAM	Sub-Mission on Agricultural Mechanization
TPP	Thermal Power Plant

List of Figures

Figure 1: Conversion of biomass to secondary energy carriers 13
Figure 2: Minimum Annual Biomass Pellets Needed in NTPC Dadri and NTPC Jhajjar..... 17
Figure 3: Net Annual GHG Emission Reduction due to Cofiring at NTPC Dadri and Jhajjar..... 20
Figure 4: Various stages of the BLEND Framework..... 23
Figure 5: Biomass supply chain 25
Figure 6: Survey location..... 28
Figure 7: Farmers Disaggregated by District 29
Figure 8: Snapshots from Field: Engagement with Farmers 29
Figure 9: Farmed land owned by farmers 30
Figure 10: Years of Farming Experience..... 30
Figure 11: Total Farmers Disaggregated by Age..... 31
Figure 12: Total Farmers Disaggregated by Education Level..... 31
Figure 13: No. of Adult Females in a Household 32
Figure 14: Other Sources of Livelihood..... 33
Figure 15: Approx Quantity Produced of Crop Residue (In Quintals)..... 33
Figure 16: Crops Grown by Farmers 34
Figure 17: Amount Paid by Farmers for Crop Residue Management..... 35
Figure 18: Change in cropping/harvesting practices due to crop residue demand (N=84)..... 37
Figure 19: Does Crop Residue Management Affect Soil Fertility?..... 38
Figure 20: Cattle Owned by Farmers (N=93) 38
Figure 21: Annual Dung Production Range 39
Figure 22: Utilization of Cattle Dung by Farmers 39
Figure 23: Does Residue Selling Impact Overall Household Well-being?..... 40
Figure 24: Reasons for Increase in Household Well-being (N=52)..... 40
Figure 25: Has the sale of crop residue reduced stubble burning?..... 41
Figure 26: Reasons for Health Improvements Experienced (n=87) 42
Figure 27: Focused Group Discussion at Gumar (Sonipat) and Naraina (Panipat)..... 43
Figure 28: Awareness about the Biomass Industry..... 44
Figure 29: Key Support Measures Required 44

Figure 30: Snapshots from Field: Engagement with Aggregators 45
Figure 31: Total Aggregators Disaggregated by District 46
Figure 32: Total Aggregators Disaggregated by Age 47
Figure 33: Total Aggregators Disaggregated by Education Level 47
Figure 34: Other Sources of Income (other than Biomass Trade) 49
Figure 35: Types of crop residue collected by Aggregators 50
Figure 36: Suggestions to reduce Stubble Burning 54
Figure 37: Main Challenges in Maintaining Supply Chain 54
Figure 38: Support Needed By Aggregators 55
Figure 39: Snapshots from Field: Engagement with Processors 56
Figure 40: State-wise Presence of the Processors (N=20) 57
Figure 41: Distribution of NTPC Plants Processing Units supplying to (N=20) 57
Figure 42: Installed Capacity in tonnes per day 58
Figure 43: Installed Capacity vs. Actual Production 58
Figure 44: Days of Operation of Processing Units 59
Figure 45: Raw Agri-residue Used by Processors 59
Figure 46: Seasonal Variation in Crop Residue 60
Figure 47: Testing Capacity Among Processors 61
Figure 48: Health issues faced by the Workers 68
Figure 49: Support Needed by Processors 69
Figure 50: Snapshots from Field: Engagement with Transporters 71
Figure 51: Snapshots from Field: Engagement with NTPC Staff 73
Figure 52: Surplus Biomass Atlas of India 76
Figure 53: Proximate Analysis (a, c, e) and Gross Calorific Value (b, d, f) of the Developed Fuel Blends 82
Figure 54: Comparative Evaluation of the Developed Fuel Blend with Coal (a) Proximate Analysis (%) (b) Gross Calorific Value (kcal/kg) 83
Figure 55: Ultimate Analysis of the Developed Fuel Blends and Their Comparative Evaluation with Coal 85
Figure 56: Ash Fusion Temperature Analysis of the Developed Fuel Blends and Their Comparative Evaluation with Coal 86
Figure 57: Estimation of the Initial Deformation Temperature of the Mixtures of Coal with Various Proportions of the Developed Fuel Blends 87

List of Tables

Table 1: Current status of biomass cofiring at various coal-fired thermal power plants of NTPC 18
Table 2: List of Indicators 23
Table 3: Cost of the Machines Involved in Aggregation 51
Table 4: Costing and Details of Machinery and Equipment Required in Processing Units 62
Table 5: Biomass Pellets/briquettes Demand in the Market 64
Table 6: Profile of Workers Engaged in Biomass Processing Units 66
Table 7: Workforce size in biomass processing units 67
Table 8: Annual Surplus Biomass Residue Available in India [19] 78
Table 9: Status of Biomass Cofiring Across the Globe [26] 99

Executive Summary

Solid fuel blending in thermal power plants refers to the co-firing of alternative solid fuels, such as biomass and refuse-derived fuel, with coal to partially substitute conventional fossil fuel use. In India, this practice is gaining significant momentum, driven by sustained policy support from the Government of India. Recent mandates requiring 7% solid fuel blending in thermal power plants located in the National Capital Region and adjoining areas, and 5% blending in plants across other regions, are expected to accelerate the adoption of biomass co-firing at scale. The conversion of raw agricultural biomass into pellets for co-firing involves a diverse supply chain that engages multiple stakeholders, i.e, farmers, aggregators, processors, transporters, and staff at power plants. However, the implications of large-scale co-firing on the livelihoods and socio-economic conditions of these stakeholders remain insufficiently explored. While existing studies have primarily focused on the techno-economic feasibility of solid fuel blending in coal-based power generation, there is a clear gap in understanding its broader socio-economic impacts.

To address this gap, the present study, titled "**Socioeconomic Impact Assessment of Solid Fuel Blending in NTPC's Thermal Power Plants**," undertakes a comprehensive evaluation of the multi-dimensional impacts of biomass co-firing across the entire supply chain. The study assesses how large-scale co-firing contributes to employment generation, income enhancement, and skill development among stakeholders. It also examines gender participation in biomass-related activities such as collection, processing, and transportation, and evaluates improvements in local air quality and associated health benefits resulting from partial coal substitution. In addition, the study investigates the technical feasibility of integrating innovative cow dung-biomass blends for co-firing, which could provide additional revenue streams for farmers. Drawing upon global best practices, the study further derives policy insights to strengthen and inform India's co-firing strategy.

The study introduces the BLEND (Balancing Lives, Emissions, and National Development) framework, a seven-stage, indicator-based approach that underpins the entire analysis presented in this report. By integrating social, economic, technical, and environmental indicators, the framework enables a comprehensive evaluation of biomass co-firing adoption in thermal power plants. The extensive field surveys and stakeholder consultations across farmers, aggregators, processors, transporters, and plant personnel indicate that the intervention is already generating measurable socio-

economic and environmental benefits. A significant reduction in residue burning has been observed, with a majority of farmers reporting improvements in local air quality and associated health outcomes. Additionally, the biomass value chain is creating new livelihood opportunities; however, these benefits remain unevenly distributed and have yet to reach their full potential.

At the farm level, participation in biomass markets remains limited due to structural and institutional barriers. A large proportion of farmers continue to incur costs for residue management, while only a small share receives government incentives in a timely manner. Low awareness of biomass markets, absence of assured pricing mechanisms, inadequate access to machinery, and the lack of decentralized collection infrastructure further constrain engagement. At the same time, the study highlights an untapped opportunity in monetizing cow dung, which could not only enhance rural incomes but also reduce its traditional use as a household fuel, thereby lowering indoor air pollution and improving health outcomes, particularly for women.

Across the downstream value chain, aggregators, processors, and transporters have benefited from increasing demand driven by thermal power plants and other industrial users. However, operational challenges persist, including limited storage capacity, seasonal variability in biomass availability, inconsistent feedstock quality, and payment delays. The workforce in the biomass sector is predominantly unskilled or semi-skilled, with limited formal training. Gender participation remains notably low, with women largely excluded from technical and operational roles. Occupational health risks, particularly from dust exposure in processing units and at the plant's collection site, also require greater attention.

From a technical perspective, the study confirms that biomass and cow dung-biomass blends meet the operational requirements for co-firing in coal-based thermal power plants. The findings demonstrate that blends with varying proportions of cow dung can be safely co-fired at higher blending ratios without significant risks of slagging or fouling, thereby expanding the potential resource base for biomass utilization.

The analysis further underscores the strategic advantage of the biomass sector in supporting India’s energy security and self-reliance objectives. Unlike other renewable energy technologies (solar and wind), which rely heavily on imported components and critical minerals, the biomass value chain is largely supported by

domestically manufactured equipment and locally available feedstock, contributing to the vision of Atmanirbhar Bharat.

Insights from the global review reveal that biomass co-firing has been adopted across regions primarily at low to moderate blending levels, supported by stable policy frameworks, targeted incentives, and region-specific feedstock strategies. These experiences highlight the importance of long-term policy certainty, robust supply chain infrastructure, and phased scale-up approaches for successful implementation.

Based on these findings, the report proposes a set of targeted policy recommendations to strengthen the biomass co-firing ecosystem in India. These include adopting region-specific co-firing targets aligned with biomass availability; promoting long-term, capacity-linked agreements between power producers and biomass suppliers; and enhancing farmer participation through aggregation models, awareness programs, and the introduction of a minimum support price for crop residues. The report also emphasizes the need to strengthen biomass storage infrastructure, particularly through decentralized systems linked with Farmer Producer Organizations, to address seasonal supply disruptions.

Further, it recommends targeted interventions to improve gender inclusion through skill development and support for women-led enterprises, alongside measures to enhance worker safety and reduce occupational health risks. Streamlining procurement processes, ensuring time-bound payments, and rationalizing quality norms are identified as critical to improving supply chain efficiency. The integration of digital tools, including artificial intelligence-based logistics management systems, can further optimize biomass transportation and reduce operational bottlenecks at plant sites.

The report also highlights the potential of integrating biomass co-firing within India's emerging Carbon Credit Trading Scheme, enabling power plants to monetize emission reductions while supporting broader decarbonization goals. Additionally, the promotion of cow dung-biomass blends is identified as a scalable solution for enhancing rural incomes, improving waste utilization, and reducing household air pollution. Overall, the study concludes that biomass co-firing represents a strategically important intervention at the intersection of energy transition, rural development, and environmental sustainability. With appropriate policy support, institutional strengthening, and inclusive implementation frameworks, it has the potential to evolve into a robust and self-sustaining component of India's clean energy transition.

1. Introduction

Bioenergy is a form of renewable energy obtained from biomass, organic materials such as plants, agricultural residues, and waste. Biomass can be converted into secondary energy carriers, such as electricity, biogas, bioethanol, biodiesel, and syngas, through three major technological routes: thermochemical, biochemical, and extraction-based processes (Figure 1). As of 2025, bioenergy contributes around 13% of India's total final energy consumption, including biogas, biomass power, and waste-to-energy systems [1].

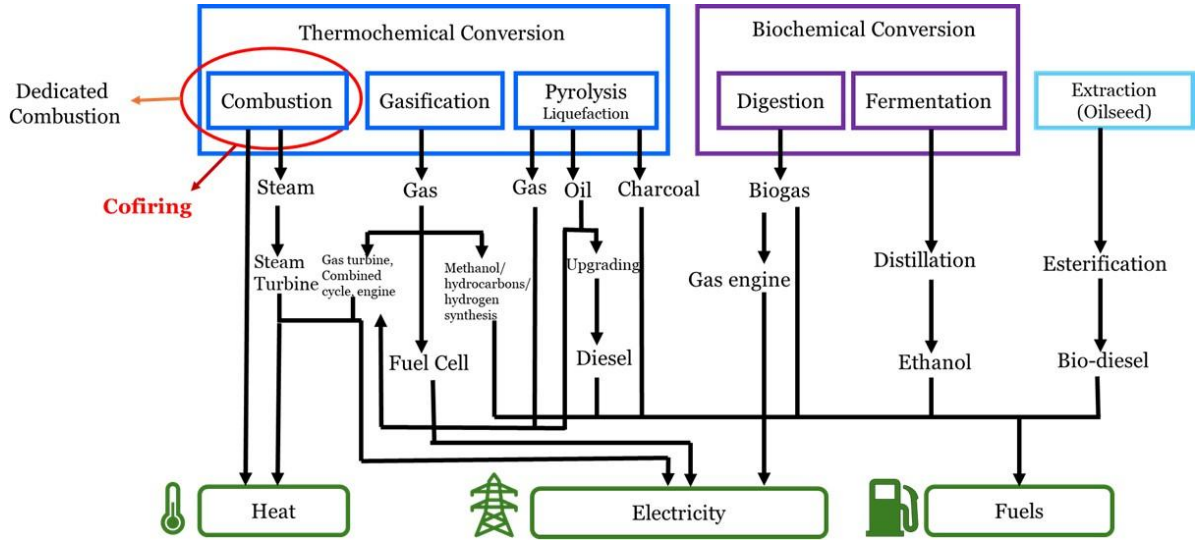


Figure 1: Conversion of biomass to secondary energy carriers

1.1. Thermochemical Conversion

Thermochemical conversion involves transforming biomass into energy through heat-driven processes. Combustion is the direct burning of biomass in the presence of air to produce heat, steam, and electricity, where biomass can be used alone or co-fired with other fuels such as coal. This method is the oldest and most widely utilized bioenergy technology due to its simplicity and reliability. Gasification, on the other hand, converts biomass at high temperatures with limited oxygen into a mixture of carbon monoxide and hydrogen, known as syngas. This syngas can be employed for power generation or further processed into synthetic fuels. Pyrolysis is another thermochemical process in which biomass is heated in the absence of oxygen, resulting in the production of bio-oil, syngas, and biochar. The bio-oil can be upgraded to liquid transport fuels, while biochar serves as a valuable soil amendment and a means for long-term carbon sequestration.

1.2. Biochemical Conversion

Biochemical conversion leverages microorganisms to transform biomass into usable energy carriers. Fermentation is a process in which sugars and starches in biomass are converted by microbes into bioethanol, which can be blended with gasoline to power vehicles. Anaerobic digestion occurs when microbes decompose organic matter under oxygen-free conditions, producing biogas composed of methane and carbon dioxide. This biogas can be utilized for cooking, heating, and electricity generation, or further purified into biomethane for injection into the natural gas grid.

1.3. Extraction-Based Conversion

Extraction-based conversion focuses on producing liquid biofuels from plant or animal lipids. Biodiesel is produced through transesterification, a chemical reaction in which plant oils or animal fats react with alcohol, typically methanol, to generate biodiesel and glycerol. Biodiesel acts as a renewable alternative to conventional petroleum diesel, suitable for use in vehicles and generators, contributing to a cleaner and more sustainable energy system.

1.4 Policy Landscape for Biomass Cofiring

To address the dual challenges of excessive coal use and the widespread practice of burning agricultural residue, which contributes to severe air pollution, climate change, and public health issues, the Indian government has mandated the fuel blending of solid biofuels with coal in thermal power plants. Fuel blending in coal-fired thermal power plants involves mixing coal with alternative fuels, such as biomass and waste-derived fuels. This practice reduces greenhouse gas (GHG) emissions and improves energy security by diversifying the fuel mix. The National Bio-Energy Program (2021-2026) encourages biomass co-firing and the development of biomass supply chains [2]. Ministry of New and Renewable Energy, Government of India, launched the Biomass program with an objective to support the setting up of Biomass Briquette/Pellet manufacturing plants and to support Biomass (non-bagasse) based cogeneration projects in Industries in the country [3] . The broader objectives of the scheme are to reduce stubble burning by utilizing surplus agricultural residue, to provide farmers with an additional source of income through the sale of surplus crop residue, and to enable better environmental practices and reduce pollution. The

program provides Central Financial Assistance (CFA) to project developers for setting up of Briquette/Pellet manufacturing plants and Biomass (non-bagasse) cogeneration projects in industries. Provisions were made to provide a maximum of 45 Lakh CFA per plant (Rs. 9 lakh per tonne per hour of manufacturing capacity) to briquette/pellet manufacturing plants. Under the same scheme, provisions were also made for a maximum of 5.0 Crores (per project) of CFA for Biomass (Non-bagasse) cogeneration projects, with Rs. 40 Lakhs/MW (on installed capacity).

As per the mandates of the Ministry of Power (from FY 2025–26), coal-based thermal power plants (TPPs) in NCR and adjoining areas must co-fire 5% biomass pellets (by weight) along with an additional 2% from biomass pellets and/or torrefied municipal solid waste (MSW)-based charcoal, with at least 50% of pellet feedstock sourced from local paddy crop residues. For TPPs in other regions, coal-based plants must achieve a minimum 5% co-firing (by weight) using biomass pellets and/or torrefied MSW-based charcoal. The Government of India's SAMARTH (Sustainable Agrarian Mission on the use of Agri-Residue in Thermal Power Plants) mission focuses on promoting the use of agricultural residues in thermal power plants [4].

To address the burning of crop residue and increased pollution, the government of Haryana, with the support of the Central Government, launched the crop residue management (CRM) program in 2018-19 [5]. Under this scheme, the Government of Haryana has taken several initiatives, including incentives and subsidies on baling equipment. Initially, farmers were given ₹1000 per acre as an incentive to register under the CRM scheme and to refrain from burning crop residue in their fields. The current incentive rate for farmers (2024-25) has also been revised and fixed at ₹1,200 per acre for farmers registering under CRM (In-Situ or Ex-Situ management of crop residue) [6]. In this context, another important policy decision taken by the government to address the issue of stubble burning was to subsidize baling machines. Apart from supporting activities to address stubble burning, this initiative has also promoted rural entrepreneurship [6]. Along with this, the government also provided subsidies on the purchase of implements like Baling Machine, Happy Seeder, Paddy Straw Chopper, etc. During the last couple of years, the Farmer-Producer Organizations (FPOs) have also been roped in under the CRM scheme. These FPOs are promoting a Custom Hiring System (CHS) and providing machinery and other services to farmers to harvest their paddy crop (along with other

crops) and to manage the crop residue generated after paddy harvesting. The Department of Agriculture is working closely with agencies such as the National Bank for Agriculture and Rural Development (NABARD), Regional Rural Banks (RRBs), other commercial banks, and Non-Governmental Organizations (NGOs) to address issues of stubble burning and CRM. Beyond this, the state government is also collaborating with the Indian Agricultural Research Institute (IARI, New Delhi) to monitor cases of stubble burning using satellite imagery [7].

NTPC is also actively executing projects related to biomass co-firing in its existing thermal power plant, becoming the first company in India to commercialize biomass co-firing, integrating up to 10% agro-residue-based biofuel with coal [8]. Recently, they achieved a 20% co-firing of torrefied biomass at their Tanda plant in Uttar Pradesh [8].

2. Biomass Cofiring at NTPC's Thermal Power Plants

Overall, NTPC's coal-based power generation capacity is 62.8 GW as on March 31, 2025, which includes 53.8 GW owned solely by NTPC and another ~9 GW contributed through joint ventures (Table A1 and A2 in annexure). NTPC currently operates a total of 37 coal-based power stations, out of which 20 have already adopted biomass co-firing, while 14 more are in the pipeline for implementation (Table A3 and A4 in annexure). The co-firing approach followed is direct blending, mainly used with pulverized coal boilers that operate through bowl mills. For this initiative, non-torrefied biomass pellets are being utilized, procured directly from vendors. The average Plant Load Factor (PLF) across these stations stands at about 75%. The progress of biomass co-firing across NTPC's fleet shows varying levels of adoption depending on plant type and regional capacity (Table 1). Stations such as Dadri (Uttar Pradesh) and Jhajjar IGSTPP (Haryana) have achieved relatively higher blending rates. In the coming years, NTPC is planning to expand biomass co-firing across several upcoming and existing stations, including Bongaigaon, Barauni, Barh, North Karanpura, Nabinagar, Darlipalli, Talcher, Ramagundam, Telangana, Kanti, Meja, NSPCL captive plants for SAIL, Vallur-NTECL, Patratu, and Jhabua, covering a mix of subcritical, supercritical, and ultra-supercritical units.

NTPC procures biomass pellets directly from vendors through e-tendering, with a preference for non-torrefied agri-residue-based pellets. The technical requirements

include cylindrical pellets with a maximum diameter of 25 mm and length up to 35 mm, gross calorific value (GCV) in the range of 2800–4000 kCal/kg, moisture content below 14%, and fines (≤3 mm) limited to less than 5% (Table A5 and A6 in annexure). For pricing, NTPC follows benchmark costing specified by MoP: torrefied pellets (GCV 3400–5000 kcal/kg, moisture <14%) are valued at ₹2.58/1000 kcal for NCR, while non-torrefied pellets (GCV 2800–3400 kcal/kg, moisture <14%) are benchmarked at ₹2.32/1000 kcal in NCR, ₹2.27/1000 kcal in the Northern region, and ₹2.24/1000 kcal in the Western region (excluding GST and transport) (Table A7 in annexture).

2.1. Biomass Pellet Requirement for Cofiring at NTPC Dadri and Jhajjar for Different Cofiring Scenarios

To understand the demand-supply dynamics, an analysis is conducted to assess the minimum demand for biomass pellets at NTPC Dadri and Jhajjar for different cofiring ratios. As the proportion of biomass in the fuel mix increases, the corresponding demand for pellets rises proportionately, reflecting the direct substitution of coal with biomass on an energy-equivalent basis (Figure 2).

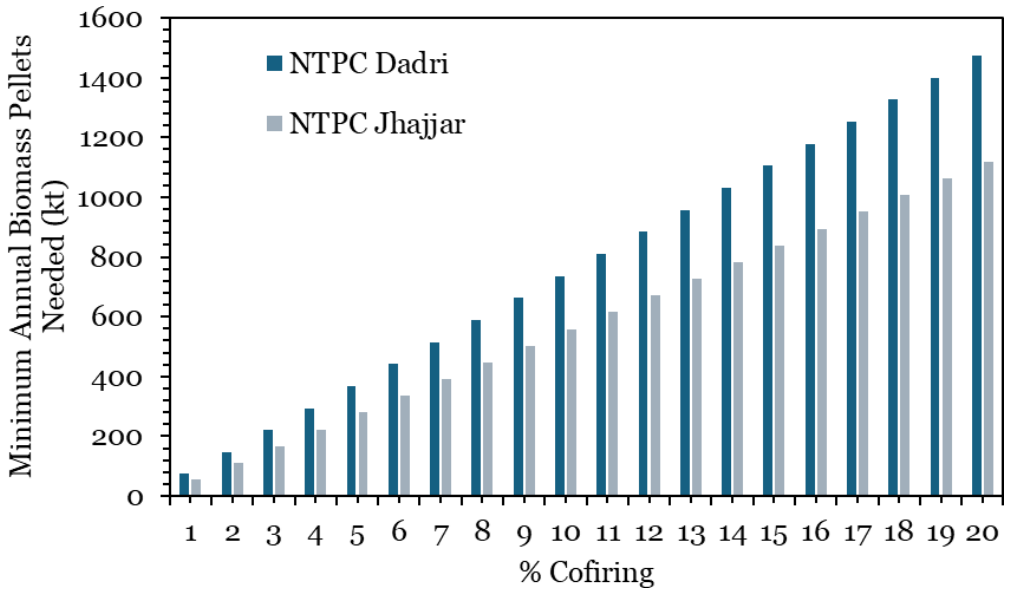


Figure 2: Minimum Annual Biomass Pellets Needed in NTPC Dadri and NTPC Jhajjar

Table 1: Current status of biomass cofiring at various coal-fired thermal power plants of NTPC

Stations/ Year				2024-25	2025-26 (Till June 30, 2025)
Stations	**State**	**Commissioned Capacity (MW)**	**Category**	**% of Cofiring**	**% of Cofiring**
Jhajjar- IGSTPP (JV)	Haryana	1,500	Subcritical	3.73%	6.13%
Dadri	Uttar Pradesh	1820	Subcritical	3.84%	4.57%
Khargone	Madhya Pradesh	1,320	Ultra-supercritical	1.04%	2.63%
Mouda	Maharashtra	2,320	Subcritical and Supercritical	0.72%	1.81%
Gadarwara	Madhya Pradesh	1600	Supercritcal	0.56%	1.26%
Tanda	Uttar Pradesh	1,760	Subcritical	0.39%	1.01%
Solapur	Maharashtra	1320	Supercritcal	0.15%	0.50%
Sipat	Chhattisgarh	2,980	Supercritcal	0.04%	0.33%
Unchahar	Uttar Pradesh	1550	Subcritical	0.00%	0.31%
Korba	Chhattisgarh	2,600	Subcritical	0.00%	0.24%
Vindhyachal	Madhya Pradesh	4,760	Subcritical	0.01%	0.19%
Rihand	Uttar Pradesh	3,000	Subcritical	0.04%	0.07%
Singrauli	Uttar Pradesh	2,000	Subcritical	0.00%	0.07%

Lara	Chhattisgarh	1,600	Supercritcal	0.00%	0.06%
NSPCL Rourkella (JV)	Orissa	370	Subcritical	0.00%	0.01%
Farakka*	West Bengal	2,100	Subcritical	0.00%	-
Kahalgaon*	Bihar	2,340	Subcritical	0.00%	-
Kudgi*	Karnataka	2,400	Supercritcal	0.00%	-
NSPCL Bhilai (JV)*	Chhattisgarh	574	Subcritical	0.00%	-
Simhadri*	Andhra Pradesh	2,000	Subcritical	0.00%	-

*Co-firing has been adopted before FY 2024–25.

Across the entire range of cofiring scenarios, NTPC Dadri consistently shows a higher biomass requirement than NTPC Jhajjar. However, there is abundant raw biomass in the country (annual surplus biomass of 228.51 MMT, which could produce 160 MMT of pellets), but ensuring year-round availability of biomass pellets at the required scale will be critical to sustaining higher cofiring ratios without disrupting plant operations.

2.2. Environmental Impact of Cofiring at NTPC Dadri and Jhajjar for Different Cofiring Scenarios

An analysis was conducted to quantify the reduction in greenhouse gas emissions from fuel combustion resulting from the partial substitution of coal with biomass at NTPC Dadri and Jhajjar power plants. Annual GHG emission reduction increases steadily as the biomass cofiring ratio rises from 1% to 20% at both NTPC Dadri and NTPC Jhajjar. NTPC Dadri consistently shows higher savings than NTPC Jhajjar, with reductions increasing from about 13.31 to 266.23 ktCO2e, compared with 10.1 to 202.09 ktCO2e for Jhajjar (Figure 3). The nearly linear trend suggests that replacing a larger share of coal with biomass directly enhances emission reduction, making cofiring a practical decarbonization pathway for existing thermal power plants. Co-firing results in marginal reductions in SO_2 emissions, while causing a slight increase in CH_4 and N_2O emissions. However, the rise in CH_4 and N_2O is significantly outweighed by substantial reductions in CO_2, leading to an overall net decrease in total GHG emissions (ktCO2e) (Table A7-A12 in Annexure).

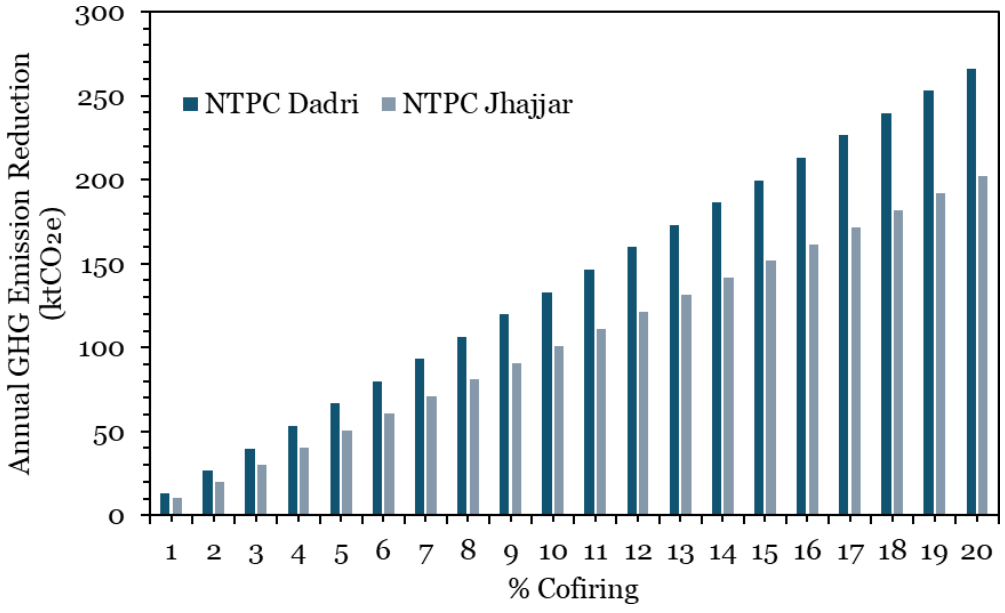


Figure 3: Net Annual GHG Emission Reduction due to Cofiring at NTPC Dadri and Jhajjar

3. Research Gap, Objectives, and Deliverables of the Project

Socio-economic impacts are important to understand how technological interventions affect people and the economy. While several studies have examined the technical and economic feasibility of solid fuel blending in coal-fired power plants, limited attention has been given to its large-scale socio-economic implications [9, 10]. This study addresses this gap by evaluating the socio-economic impacts of biomass co-firing in thermal power plants, with a particular focus on NTPC plants, which are among the largest biomass consumers in India. The scale of biomass utilization in NTPC's thermal power plants is far greater than that of refuse-derived fuel (RDF), making biomass the central focus of this study. Maintaining a continuous supply of biomass is challenging, particularly during the monsoon season. In India, cattle dung is abundant but has scarcely been evaluated for thermal power generation. Therefore, the present study evaluates the feasibility of various cow dung-biomass fuel blends for their utilization in co-firing applications in thermal power plants. In addition, a comprehensive review of co-firing practices adopted globally is conducted to understand the challenges encountered and identify potential solutions. The study also examines international policy frameworks that promote biomass co-firing in coal-fired thermal power plants. The following are the objectives of the present study that are carried forward:

i. **To assess the socioeconomic and health impacts of biomass co-firing in thermal power plants**, with emphasis on:
    - Rural Livelihoods: Understanding how biomass procurement and supply create employment, income, and skill opportunities for rural communities.
    - Gender-Inclusive Supply Chains: Exploring the role of women in the collection, processing, and delivery of biomass, and promoting equitable participation.
    - Air Quality Improvement: Assessing reductions in local air pollution from partial replacement of coal with biomass and the related health benefits.

ii. **Evaluate the feasibility of cow dung-biomass blends** by assessing their technical performance and economic viability, while exploring their potential contribution to sustainable energy generation and rural economic development.
iii. **Conduct a global review of biomass co-firing practices to derive policy advocacy** and best practices that can be adapted to strengthen the cofiring strategy in India.
iv. **Propose actionable recommendations,** with emphasis on socially inclusive and community-centered policy measures.

In this study, a detailed socioeconomic assessment is conducted, with NTPC Dadri serving as the primary case study. The key deliverable of this study is a comprehensive Socio-Economic Impact Assessment Report presenting a detailed analysis of income generation, skill development, job creation, rural economic growth, and community health outcomes associated with biomass cofiring in thermal power plants. In addition, the report includes an in-depth discussion on the suitability of cattle dung-biomass blends supported by characterization results, along with insights and lessons derived from the global review of co-firing practices in thermal power plants.

4. Methodology (The BLEND Framework)

In the present work, a new framework, "***BLEND (Balancing Lives, Emissions, and National Development)***", is developed. The BLEND framework is a seven-stage (Figure 4), an indicator-based methodology. The BLEND framework integrates system scoping, data collection, feasibility analysis, and impact assessment to evaluate the effectiveness of biomass blending strategies. The framework utilizes a comprehensive set of indicators across technical, economic, social, and environmental domains to ensure a holistic evaluation. The intrinsic indicators are selected based on the detailed literature review of the existing literature in this domain (Table 2). These indicators enable quantification of performance, identification of gaps, and formulation of evidence-based policy recommendations supported by global best practices.

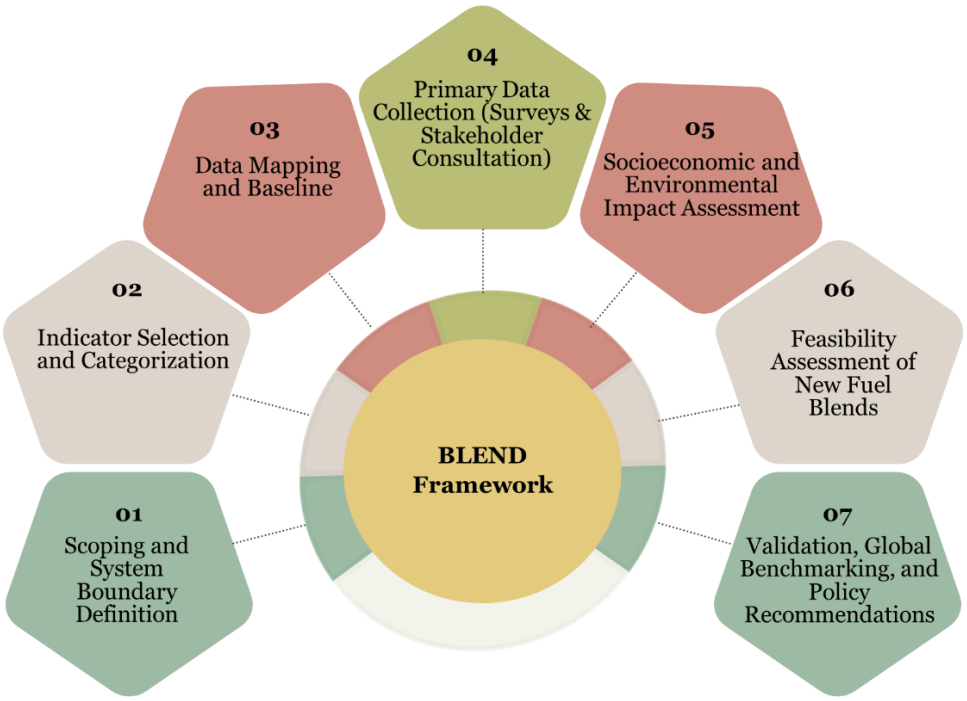


Figure 4: Various stages of the BLEND Framework

Table 2: List of Indicators

Category	Indicator	Unit
Technical	Biomass availability and supply to the plants	tonne/year
	Seasonal variability of biomass	Index (0-5)
	Biomass properties (calorific value, moisture, ash, C, H, N, S)	kcal/kg and %
	Collection radius	km
	Co-firing ratio	%
	Efficiency loss due to co-firing	%
	Optimum proportion of cow dung in biomass blends for co-firing	%
Social	Extra income for farmers, fixed and capital assets	Rs/acre
	Jobs created and skills needed	Number/year

	Income of supply chain workers (collection, transportation, processing)	Rs/year
	Women's participation in the supply chain	%
	Health impact and reduction in stubble burning	Index (0-5)
Economic	Unit cost of various types of biomass at different stages of the supply chain	Rs/tonne
	Investment in biomass supply chain infrastructure (aggregation, processing, and transport)	Rs/year
	Market price of biomass pellets for different end-use sectors (power plants and industries)	Rs/tonne
Environmental	GHG emission reduction	tonne CO_2-eq/year
	PM, NOx, and SOx emissions reduction	kt/year

5. Socioeconomic Impact Assessment

The biomass supply chain transforms agricultural waste into clean energy through four interconnected stages: collection at farms, aggregation and storage, processing through densification plants, and final delivery to power plants, as shown in (Figure 5). The transformation begins immediately after harvest when farmers coordinate with local aggregators and processors instead of burning residues. The mechanized collection process involves cutting, racking, and baling using specialized equipment like stubble shavers, racker, and balers to create compact, manageable bales. Local aggregators serve as vital intermediaries, functioning as community coordinators who collect materials from scattered farms and consolidate them at strategic storage points.

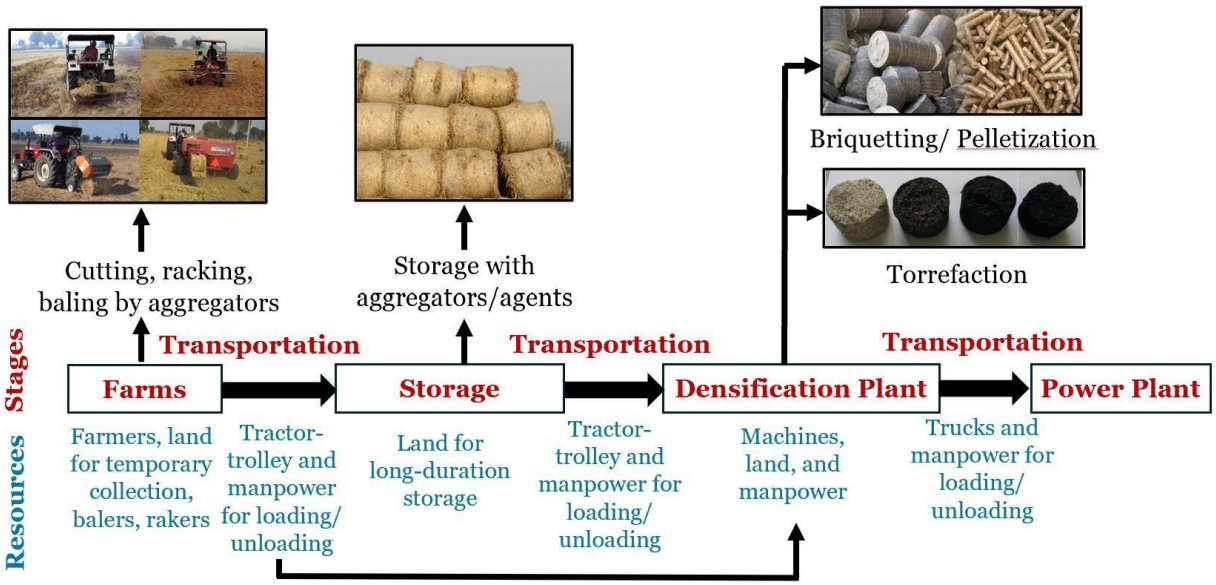


Figure 5: Biomass supply chain

The bales are further transported to the densification plants and industries. At densification plants, technology transforms loose, bulky crop residues into energy-dense fuels through systematic processing involving size reduction (chopping/grinding), moisture conditioning (drying if needed), and final densification via specialized palletization or briquetting presses. This addresses the fundamental challenge posed by raw biomass: its low bulk density compared to conventional fuels. The supply chain offers two distinct processing pathways. The conventional path processes bales directly into standard briquettes or pellets with moderate energy density (600-1200 kg/m^3) but with moisture sensitivity. The advanced pathway incorporates torrefaction technology (thermal treatment) that drives off moisture and volatiles while concentrating energy content. Torrefied pellets ("black pellets") offer higher energy density, better hydrophobic properties, improved grindability, and can be handled like coal with superior storage characteristics.

This section presents the outcomes of the socioeconomic impact assessment of biomass cofiring in thermal power plants across the entire biomass supply chain to the plant. There are five stakeholders in the biomass supply chain: farmers, aggregators, processors, transporters, and the end user (NTPC staff).

5.1. Sampling Strategy and Respondent Groups

Primary data collection is done in the present study, covering the entire biomass supply chain using a mixed-methods approach. The study adopts a purposive, multi-stakeholder sampling strategy designed to capture the functioning of the biomass

supply chain across key agricultural districts of Haryana while ensuring representation of major actors involved in crop residue management. The primary study area covers three districts of Haryana, i.e., Karnal, Panipat, and Sonipat, which are among the most agriculturally active regions with high volumes of paddy and wheat residue generation. A total of 21 villages are covered in these districts (Figure 6). These districts lie along the Delhi-Chandigarh corridor and are closely linked to biomass aggregation and processing networks supplying multiple end users, including NTPC and other industrial buyers. The selected districts represent high-intensity crop residue zones with active implementation of the Government of Haryana's Crop Residue Management (CRM) program.

i. **Sampling of Farmers:** Farmers are the primary stakeholder group in the study. A purposive sampling approach was used to select farmers. They were identified from the official beneficiary lists under the Government of Haryana's Crop Residue Management (CRM) scheme. These beneficiary lists were obtained with the support of the agriculture departments in the Zilla Parishad offices in Karnal, Sonipat, and Panipat. Their inclusion is based on participation in residue management systems. The study adopted this approach to ensure diverse representation of different ways of residue handling practices, including in-situ management, ex-situ removal through aggregators, and other hybrid arrangements. A total of 100 farmers were surveyed across the three districts, with proportional distribution across selected blocks. Although the initial target was 100 farmers, an additional buffer sample was collected to account for incomplete or invalid responses, ensuring a clean final dataset. In addition, 11 farmers (2 female and 9 male respondents) were covered through Focused Group Discussions (FGDs).

ii. **Sampling of Aggregators:** Aggregators are selected through purposive sampling from the lists of beneficiaries of baler and residue management equipment subsidies under the CRM framework. These actors play a critical intermediary role in residue collection and logistics. The sampling captures variation in operational scale, geographic coverage, and linkages with processors. There are two aggregators from the sample who are directly linked to processors supplying to NTPC. Aggregators perform transport functions, and therefore, the information provided by them on transportation management is

recorded as a separate dataset. 20 aggregators were covered through the surveys.

iii. **Sampling of Processors:** Processors selected in this study supply pellets to at least one of the NTPC Dadri or Jhajjar plants, or to both. Given the complexity of procurement networks, the study focuses on standardized logistics patterns and cost bands rather than tracing every physical shipment route. In total, 20 processors were interviewed in this study.

iv. **Sampling of Transporters:** Transport within the biomass supply chain occurs at multiple stages, i.e., farmer to aggregator, aggregator to processor, processor to end user. During the recce visits, it was found that, from farmers to aggregators, and from aggregators to processors, the transport mode was trolleys towed by aggregators' tractors. For the processors to NTPC, supply is made via trucks owned by transport companies. Recognizing these role overlaps (e.g., aggregators acting as transporters), the study adopted a layered purposive sampling strategy. Interviews with 10 aggregators included a specific segment focused on employment generation, logistics cost structures, operational challenges, and labor dynamics in biomass transportation. Additionally, 5 transporters/drivers were interviewed at the NTPC Dadri plant.

v. **NTPC Staff:** Four staff members of NTPC were interviewed, including officials from Coal Handling Plant (CHP), Coal Coordination, Chemistry, and SAMARTH.

The study is designed as a mixed-methods socio-economic assessment. The purposive sampling strategy prioritizes the representation of key functional actors in the biomass ecosystem, diversity of operational models, policy-relevant insights, and feasibility within project timelines. The objective is to generate analytically robust patterns and a system-level understanding rather than statistical generalizations for all farmers or market actors. Mixed-methods data collection is carried out using Computer-Assisted Personal Interviewing (CAPI)-based surveys. Data quality was ensured through enumerator training, continuous field monitoring, manual cleaning, duplicate and consistency checks, and statistical validation (IQR, skewness, distribution analysis).

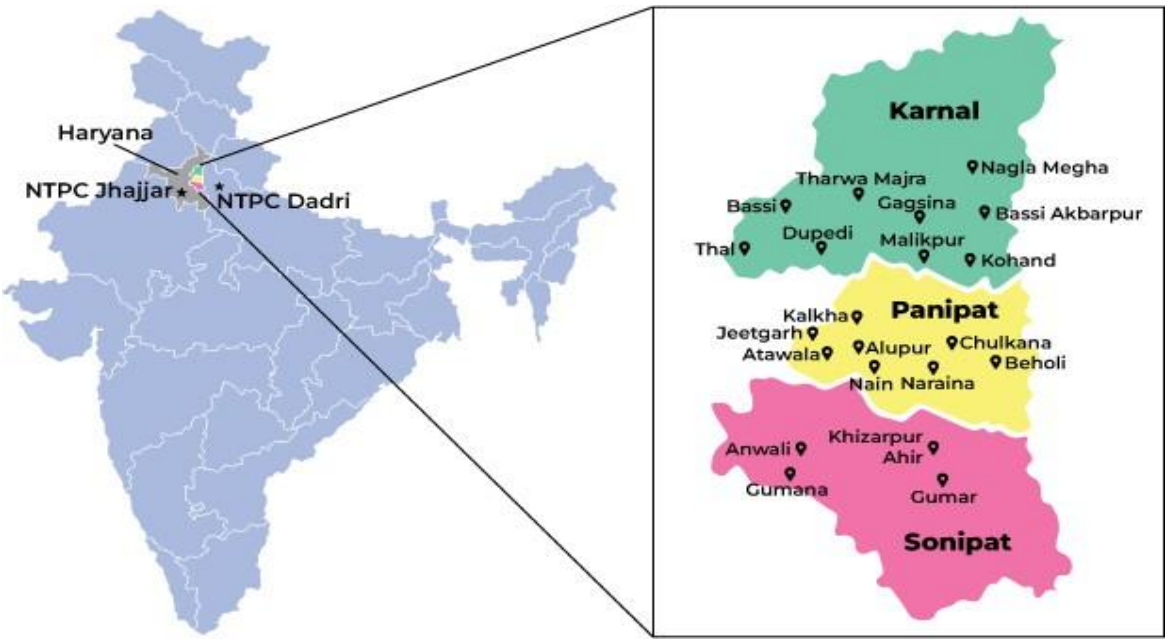


Figure 6: Survey location

5.2. Primary Research Findings

This section presents the discussion on the primary research conducted to assess the socioeconomic impact of biomass cofiring in thermal power plants on the stakeholders involved in the biomass supply chain.

5.2.1. Farmers

Farmers are the primary source of crop residue in the supply chain, as the availability of biomass depends directly on cropping patterns, harvesting practices, and their willingness to provide residue instead of burning it. Their decisions are influenced by factors such as the cost of residue removal, availability of balers, time constraints between crop cycles, and the price offered for crop residue. As a result, farmers play a critical role in determining both the quantity and the timely availability of crop residue for aggregation and further use.

5.2.1.1. Demographic Profile of Participants

A survey is conducted with 100 farmers across three districts of Haryana: Panipat, Karnal, and Sonipat. The distribution of respondents was highest in Panipat (39%), followed by Karnal (34%) and Sonipat (27%) (Figure 7).

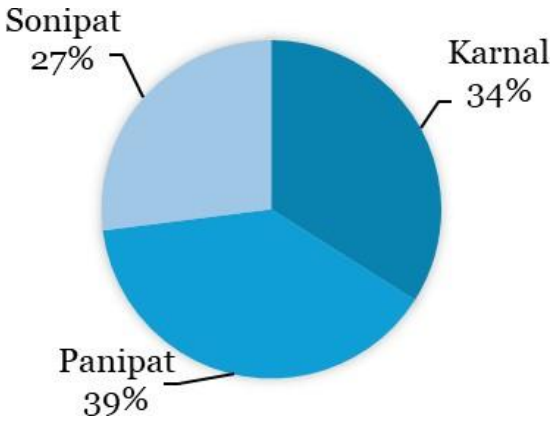


Figure 7: Farmers Disaggregated by District



Figure 8: Snapshots from Field: Engagement with Farmers

The survey covered nine villages in Karnal (Bassi, Bassi Akbarpur, Dupedi, Gagsina, Kohand, Malikpur, Nagla Megha, Thal, and Tharwa Majra), nine villages in Panipat (Alupur, Atawala, Beholi, Chulkana, Jeetgarh, Kalkha, Nain, Naryana, and Urlana Khurd), and three villages in Sonipat (Ahir, Gumana, and Gumar) (Figure 8). The respondent group was largely male, with 98 male farmers and only 2 female farmers participating in the survey, both from Sonipat district. Most farmers have small landholdings, with land sizes below 10 Acres (Figure 9). 63% of the farmers owned their farmland. The respondents also represented a highly experienced farming population (Figure 10).

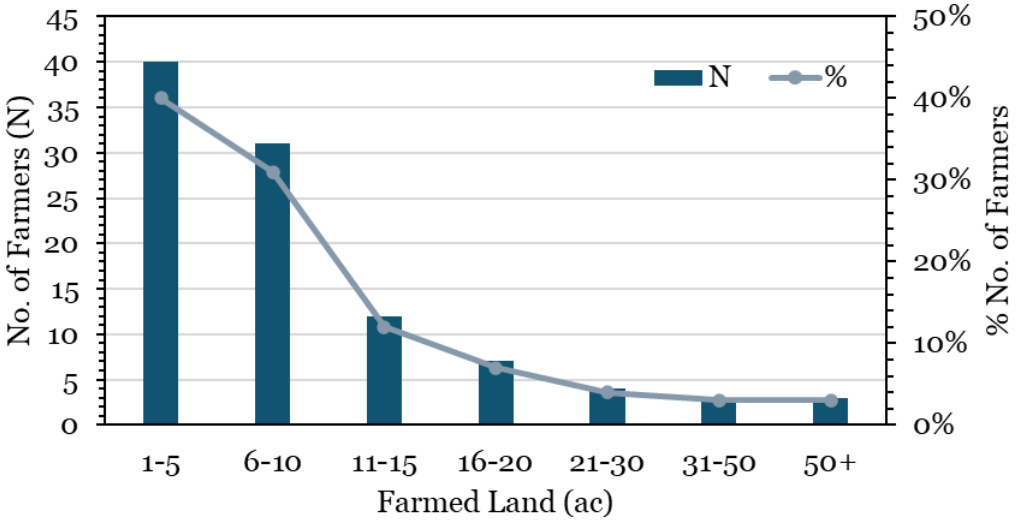


Figure 9: Farmed land owned by farmers

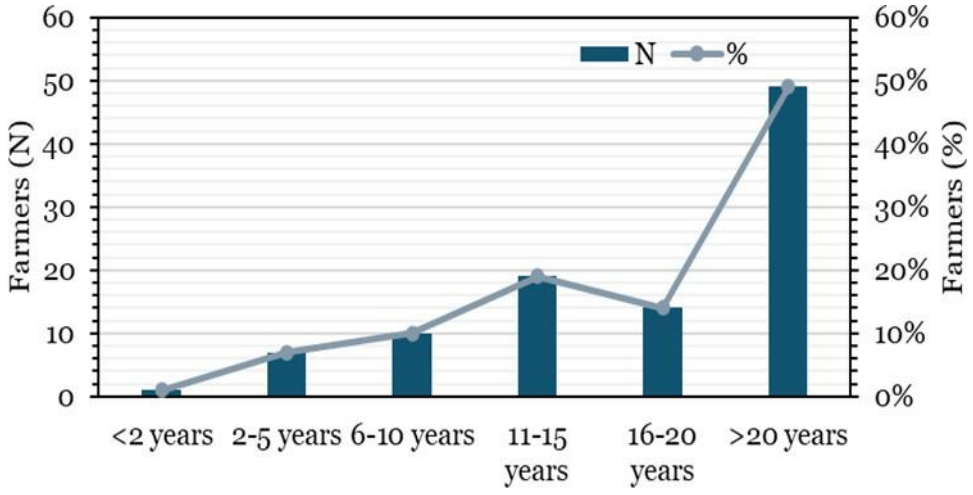


Figure 10: Years of Farming Experience

Nearly half of the farmers (49%) reported having more than 20 years of farming experience. This was followed by 11–15 years of experience (19%) and 16–20 years (14%). A smaller share reported 6–10 years (10%) and 2–5 years (7%), while only one respondent had less than two years of experience. This indicates that the survey largely reflects the perspectives of long-term farmers. The age profile shows that most respondents were in the middle age groups (Figure 11). The largest share (33%) was between 41–50 years, followed by 31–40 years (19%).

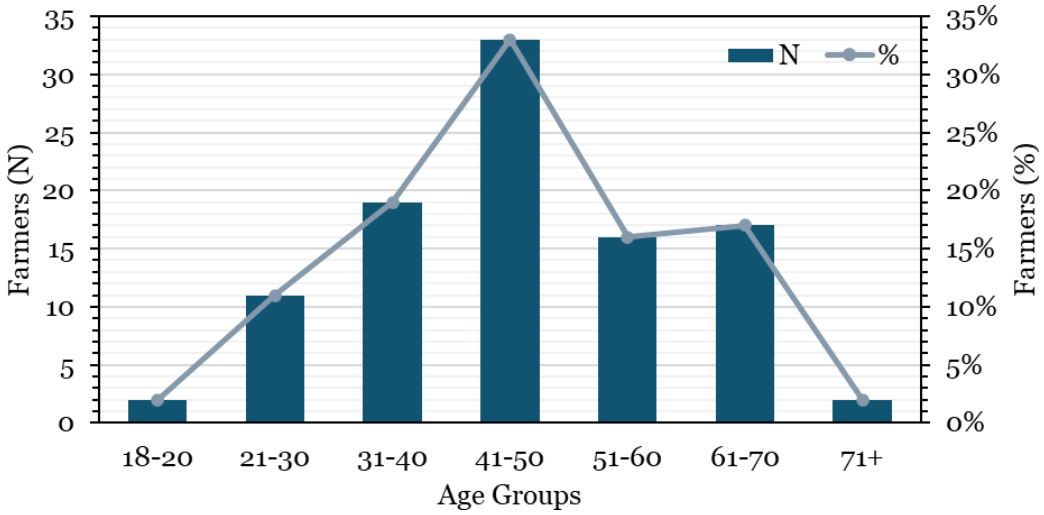


Figure 11: Total Farmers Disaggregated by Age

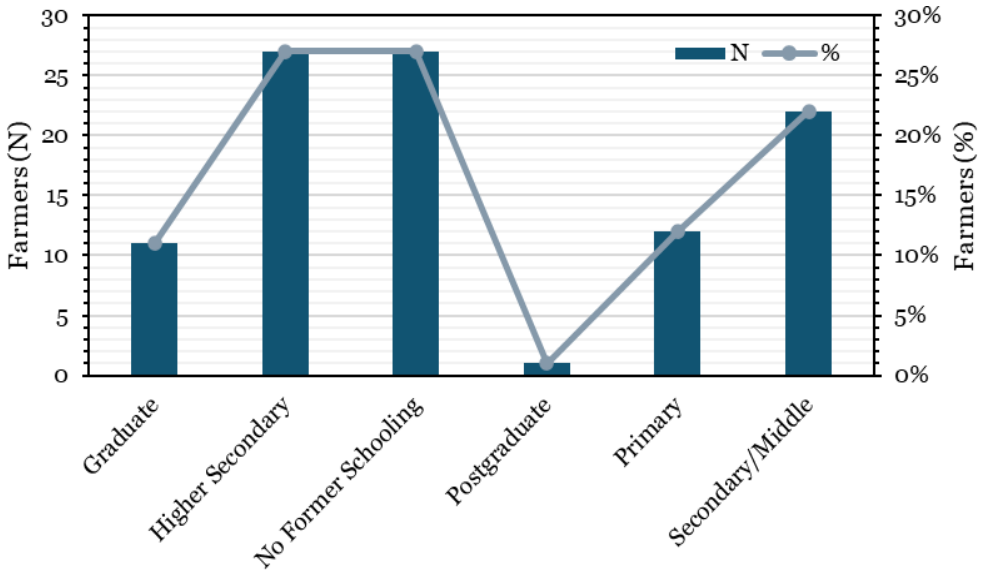


Figure 12: Total Farmers Disaggregated by Education Level

Farmers aged 61–70 years accounted for 17%, while 16% were in the 51–60 age group. Younger farmers were relatively fewer, with 11% in the 21–30 age range and only 2%

each in the 18–20 and above 71 age groups. Overall, the sample largely represents a middle-aged farming population.

Educational attainment varied across respondents, although most reported only basic or moderate levels of schooling (Figure 12). Higher Secondary education and no formal schooling were equally common (27% each), followed by Secondary or Middle level education (22%). Smaller proportions had Primary education (12%), while 11% were graduates, and only 1% reported postgraduate education. Household size was generally moderate to large. More than half of the respondents (54%) reported households with 6-10 members. Most of the farmers reported that they had two women in their families (Figure 13).

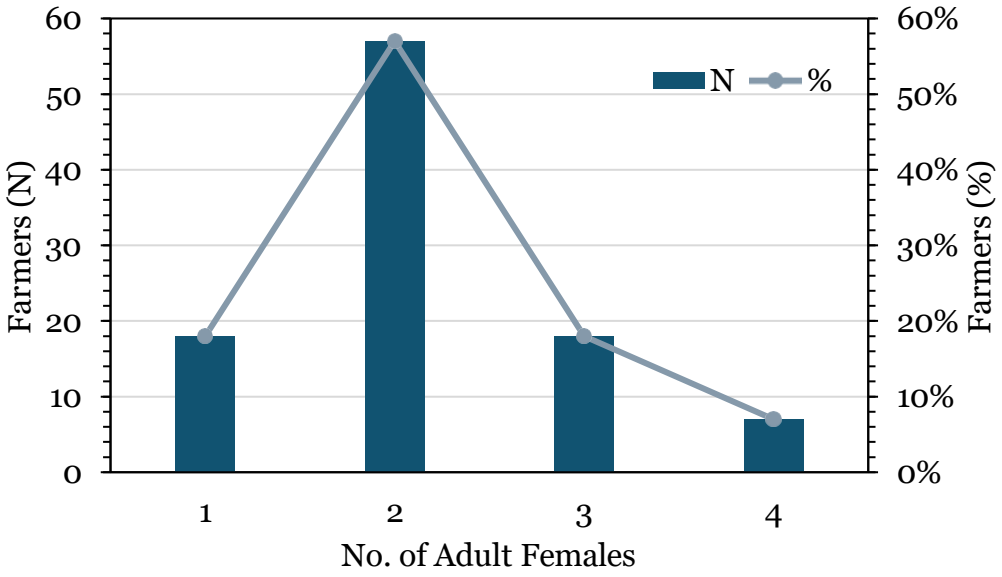


Figure 13: No. of Adult Females in a Household

For most respondents, farming remains the main source of livelihood (Figure 14). As many as 95% reported agriculture as their primary source of income, while only 5% depended primarily on other occupations. At the same time, several households reported additional sources of income alongside farming. Livestock rearing was the most commonly mentioned supplementary activity (28 respondents), followed by fodder cultivation and sale (20) and agricultural labor on other farms (11). These responses indicate that while agriculture remains central, many households rely on multiple income sources to maintain economic stability.

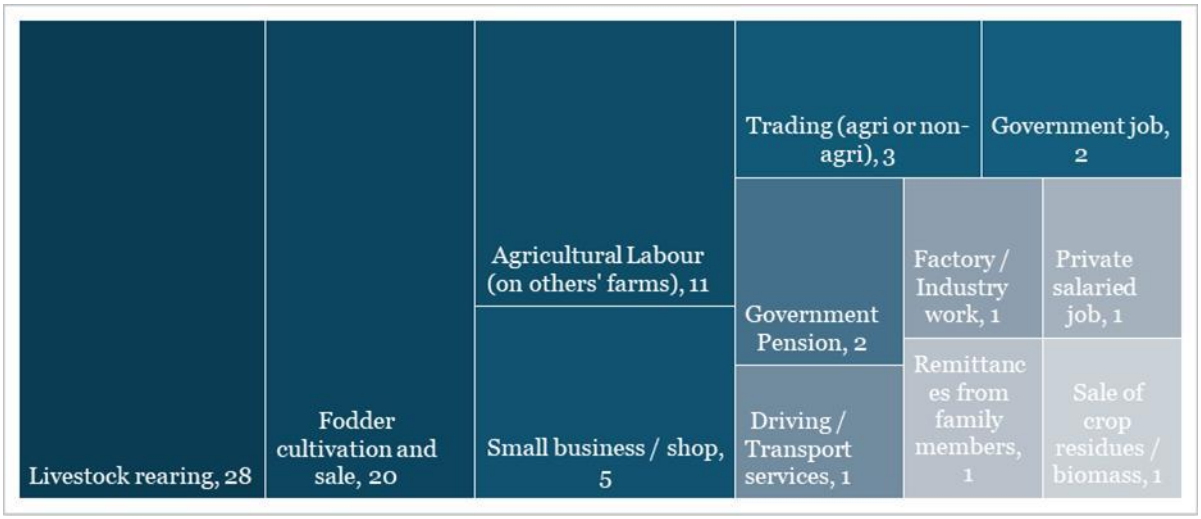


Figure 14: Other Sources of Livelihood

5.2.1.2. Farmers' Engagement in Crop Residue Industry

Most farmers reported producing crop residue in the range of 11-30 quintals per season (Figure 15). 1 acre of land generates approximately 20-30 quintals of paddy residue and 15-20 quintals of wheat residue. The findings indicate that paddy and wheat are the dominant crops grown by farmers, with 100% of respondents cultivating paddy and 97% cultivating wheat (Figure 16).

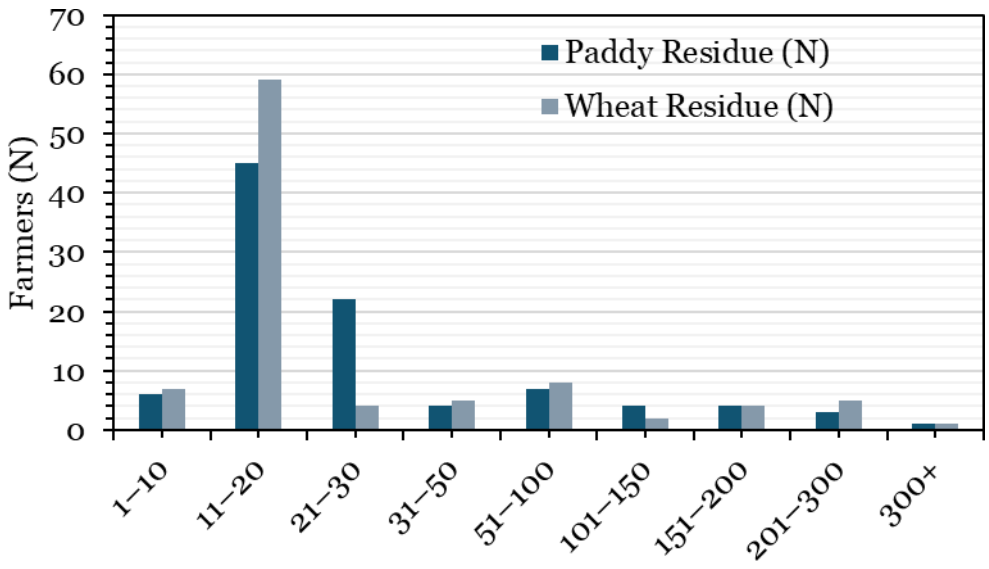


Figure 15: Approx Quantity Produced of Crop Residue (In Quintals)

Only a very small proportion reported growing other crops such as mustard, potatoes, or sugarcane (around 1% each), indicating that cropping patterns in the study area are largely centered around the paddy-wheat cycle. The generation of crop residue follows

the harvest cycles of these crops. Wheat residue is primarily generated during March and April, while paddy residue is generated during September, October, and November, with the highest concentration reported in November. This highlights a seasonal pattern of residue availability, concentrated around the major harvest periods.

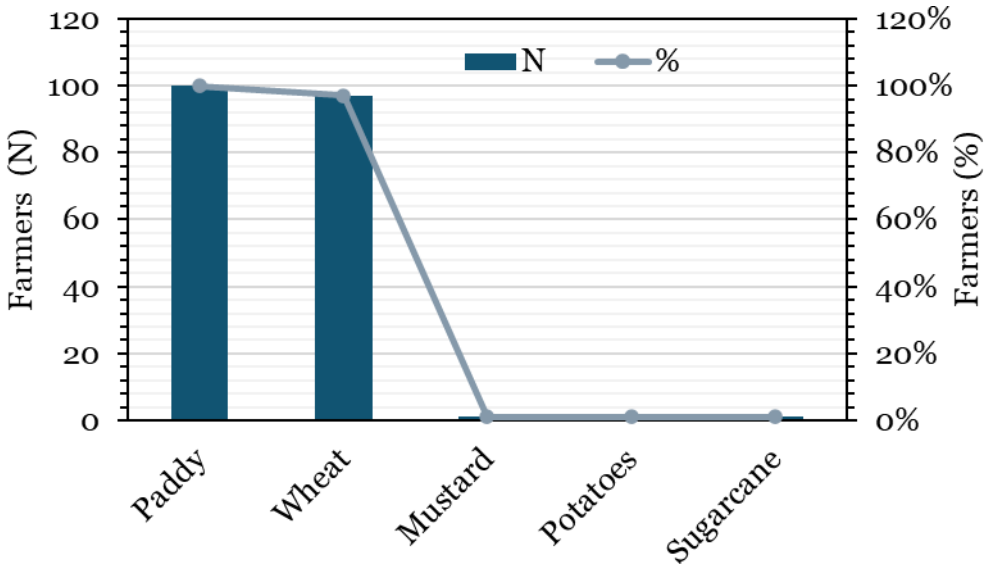


Figure 16: Crops Grown by Farmers

The ways in which farmers dispose of or utilize crop residue reflect both traditional practices and emerging residue management approaches. A major challenge highlighted by farmers was the short time gap between harvesting one crop and preparing the field for the next sowing cycle, typically around 15-25 days. This limited window creates pressure to clear fields quickly so that the next crop can be planted on time. Farmers who own machinery such as Super Seeders are able to manage the residue themselves by mixing it back into the soil. However, findings from the quantitative survey showed that only 12% of farmers own such high-cost machinery, making it difficult for most small and medium farmers to manage residue independently. In such cases, farmers often depend on external service providers, such as aggregators or balers, who help with clearing fields and collecting crop residue. These services play an important role in enabling farmers to avoid stubble burning. When such support is not available or cannot be accessed in time, farmers reported that they may be left with limited options, and stubble burning is sometimes used as a last resort to clear the fields quickly.

Participants further mentioned that the Government of Haryana provides financial incentives for adopting in-situ or ex-situ crop residue management practices. Under the Crop Residue Management (CRM) scheme, farmers receive an incentive of approximately ₹1200 per acre per year after registering for in-situ or ex-situ residue management. However, field interactions and survey responses indicate that a significant share of this amount is often spent on hiring machinery or service providers for field clearing. Survey findings show that 61% of farmers reported paying for crop residue management or field cleaning (Figure 17). Among those who paid, the most commonly reported expense was around ₹1000 per acre (45%), followed by ₹500 per acre (10%). Only 24% of farmers reported receiving government incentives (₹1200 per acre). Among them, 60% received payments on time, while the remaining 40% experienced delays.

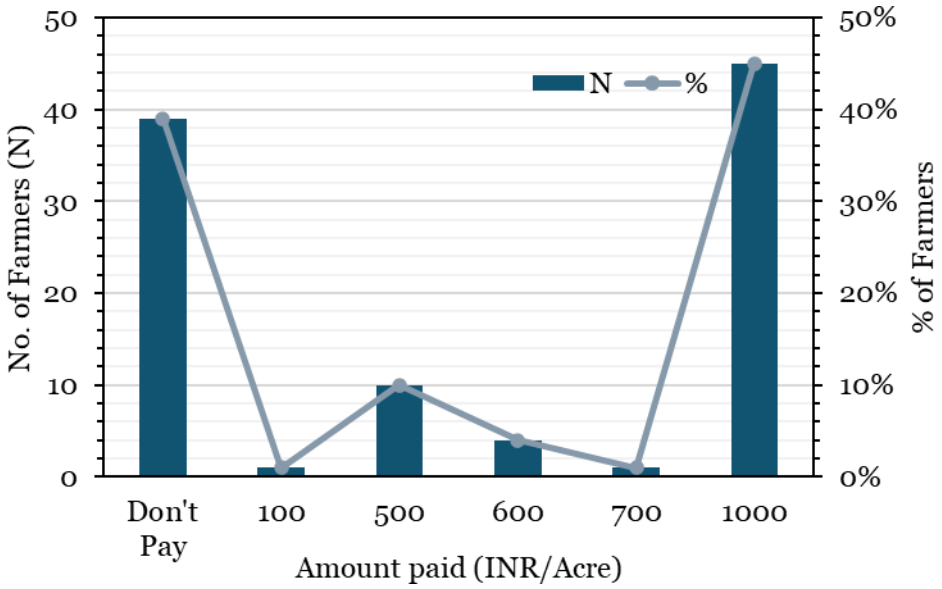


Figure 17: Amount Paid by Farmers for Crop Residue Management

Qualitative findings suggest that this was particularly common among farmers with small landholdings (less than two hectares), who typically do not own agricultural machinery. During the survey and in the FGD conducted in Gumar village (Panipat), participants noted that farmers with larger landholdings are more likely to own farm implements and therefore incur lower external costs for residue management and have a better capacity to negotiate prices for selling their crop residue rather than paying aggregators for clearing their fields and giving away crop residue for free.

Among service providers, almost all farmers (98%) reported relying on balers for residue collection and field clearing, while only a very small share (2%) engaged private service providers. Overall, mechanized residue management through balers appears to be the dominant practice, with farmers often bearing most of the cost despite receiving government incentives. However, a large proportion of farmers spend money on crop residue management (CRM), which reduces land preparation costs even without direct financial returns.

The study also found that the direct sale of crop residue to industrial buyers remains very limited among farmers. Only one farmer reported selling residue to industrial boilers, and one farmer reported selling to pellet or briquette manufacturers. Five farmers mentioned supplying residue to other power plants, while none reported selling directly to NTPC. Instead, the most common channel was through aggregators or biomass collection centres, with 43 farmers reporting that they handed over residue to such intermediaries. Despite this, monetary returns from residue remain rare. Among the 43 farmers who supplied residue to aggregators, only one farmer reported receiving payment (₹500 per quintal), while the remaining 42 stated that they provided the residue without any compensation.

Ownership of machinery among farmers remains limited, which increases dependence on aggregators. None of the farmers reported having formal contracts for selling or supplying crop residue, indicating that transactions in the residue market are largely informal. Farmers also stated that household members are generally not involved in collecting, transporting, or selling biomass residue, and no additional labour is hired specifically for residue-related activities. This suggests that residue management is treated as an extension of harvesting operations rather than as a separate income-generating activity. The role of women in the household is generally limited to collecting, storing, and using crop residue for household purposes, such as fodder. They are usually not involved directly in any income-generating activities.

Taken together, the findings suggest that financial benefits from crop residue are still largely dependent on government incentives rather than market-based transactions. Although aggregator networks and biomass supply chains exist, farmers currently have limited bargaining power and often incur costs for residue management instead of earning income from it.

5.2.1.3. Changes in Cropping Patterns Among Farmers

The increasing emphasis on crop residue management has started to influence farming practices (Figure 18). A large majority of farmers (84%) reported that residue management requirements or demand for biomass have led to changes in their cropping or harvesting practices. The most commonly reported change was the use of balers during harvesting, mentioned by 83% of respondents, indicating a growing shift towards mechanized residue handling. Nearly half of the farmers (46%) also reported adopting different agricultural implements for harvesting, reflecting adjustments in farm operations to manage residue more efficiently. Changes were also observed in crop planning decisions. About 45% of farmers reported changing the crop grown after paddy, while 24% indicated that they had shifted to different varieties of paddy to make residue management easier.

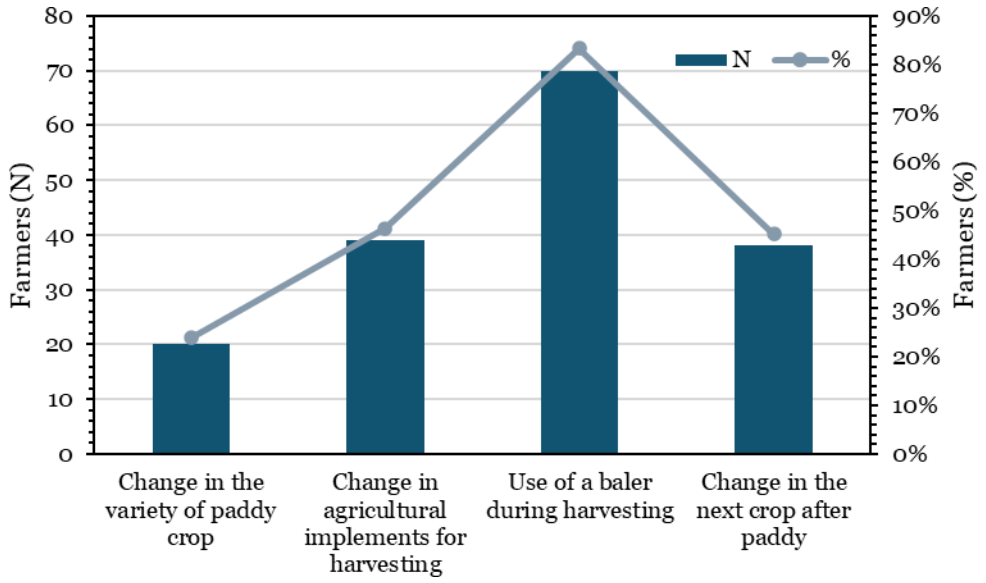


Figure 18: Change in cropping/harvesting practices due to crop residue demand (N=84)

During surveys, 37% of farmers reported that crop residue management has affected soil fertility, whereas 63% did not observe any clear change (Figure 19). Among those who reported an impact (N = 37), the most commonly mentioned reason was an increase in soil organic matter (70%). A smaller share reported a decrease in soil organic matter (16%), while 11% felt that urea requirement had increased, and 5% reported a decrease in urea use. A few respondents (3%) mentioned other effects. These responses indicate that although some farmers perceive improvements in soil quality, the benefits are not consistently experienced across all farms.

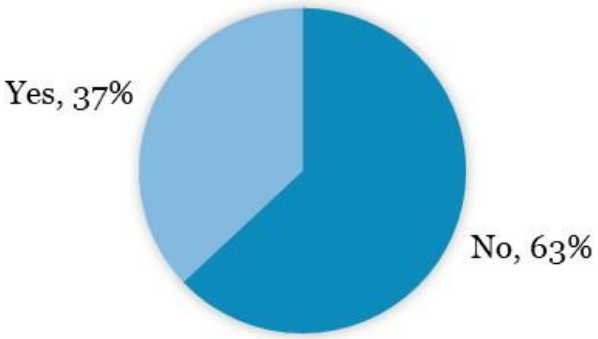


Figure 19: Does Crop Residue Management Affect Soil Fertility?

5.2.1.4. Production & Utilization of Cattle Dung

The findings indicate that livestock ownership is widespread among farmers, with 93% of respondents reporting owning cattle (Figure 20).

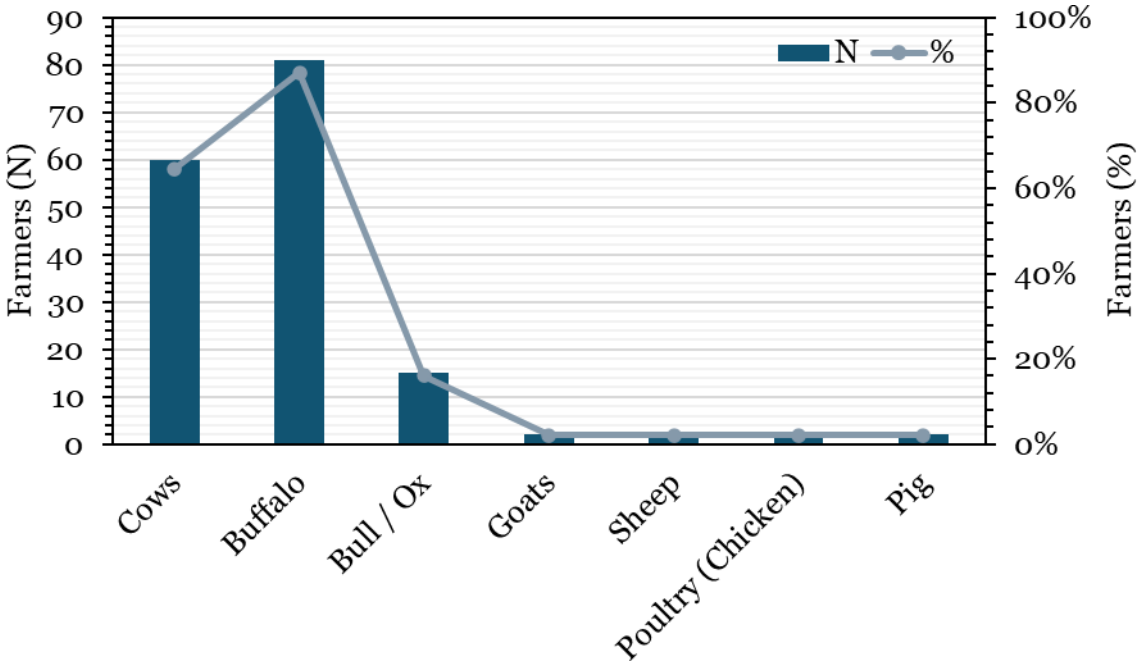


Figure 20: Cattle Owned by Farmers (N=93)

Among livestock types, buffalo ownership was the most common (87%), followed by cows (65%), while a smaller proportion of farmers reported owning bulls or oxen (16%). Only a few respondents reported owning goats, sheep, poultry, or pigs (around 2% each). On average, farmers reported owning about two cattle per household. The survey also shows that livestock contributes to significant dung production at the household level. The largest share of farmers reported producing 26-50 quintals of dung annually (29%), followed by 51-100 quintals (25%). Smaller shares reported 101-

150 quintals (17%) and 1-25 quintals (11%), while relatively few households produced more than 150 quintals annually (Figure 21).

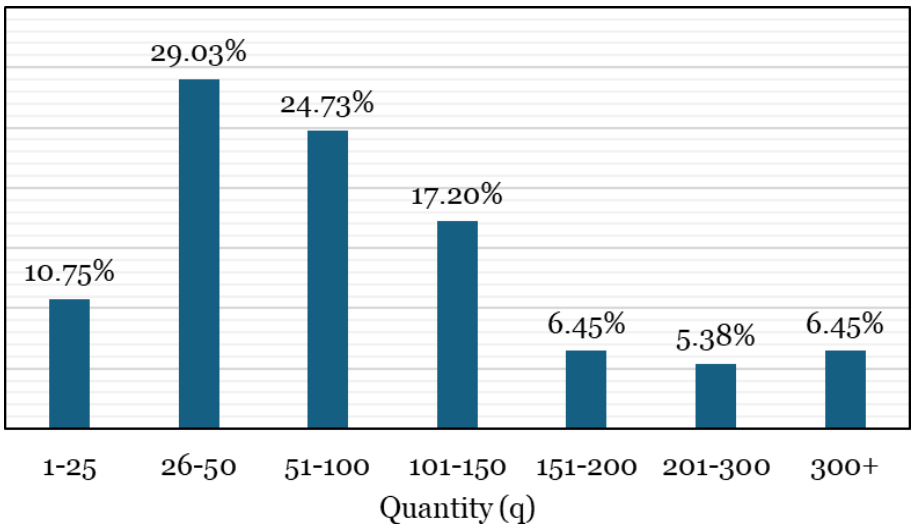


Figure 21: Annual Dung Production Range

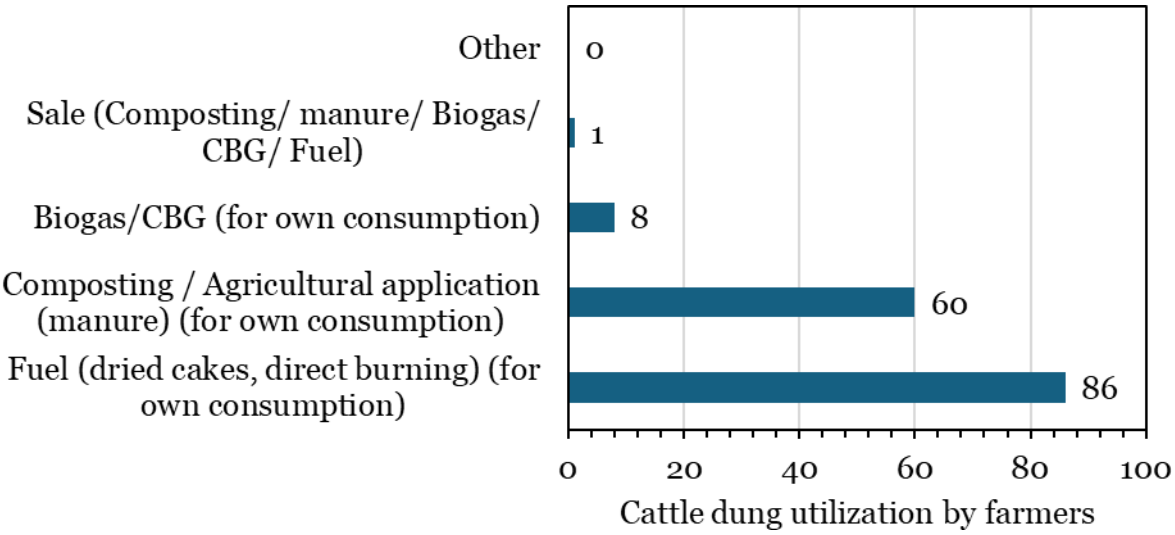


Figure 22: Utilization of Cattle Dung by Farmers

Overall, the findings suggest that livestock remains an important component of farming systems, contributing not only to household livelihoods but also to the availability of organic manure for agricultural use. Most farmers use cattle dung for composting and fuel, and often give it to neighbors for free, though many would prefer to receive payment for it Figure 22.

5.2.1.5. Impact of Crop Residue Management on Farmers

Despite limited perceptions of income gains, slightly more than half of respondents (52%) reported that selling or managing crop residue has contributed to an improvement in their overall household well-being, while 48% reported no noticeable change (Figure 23).



Figure 23: Does Residue Selling Impact Overall Household Well-being?

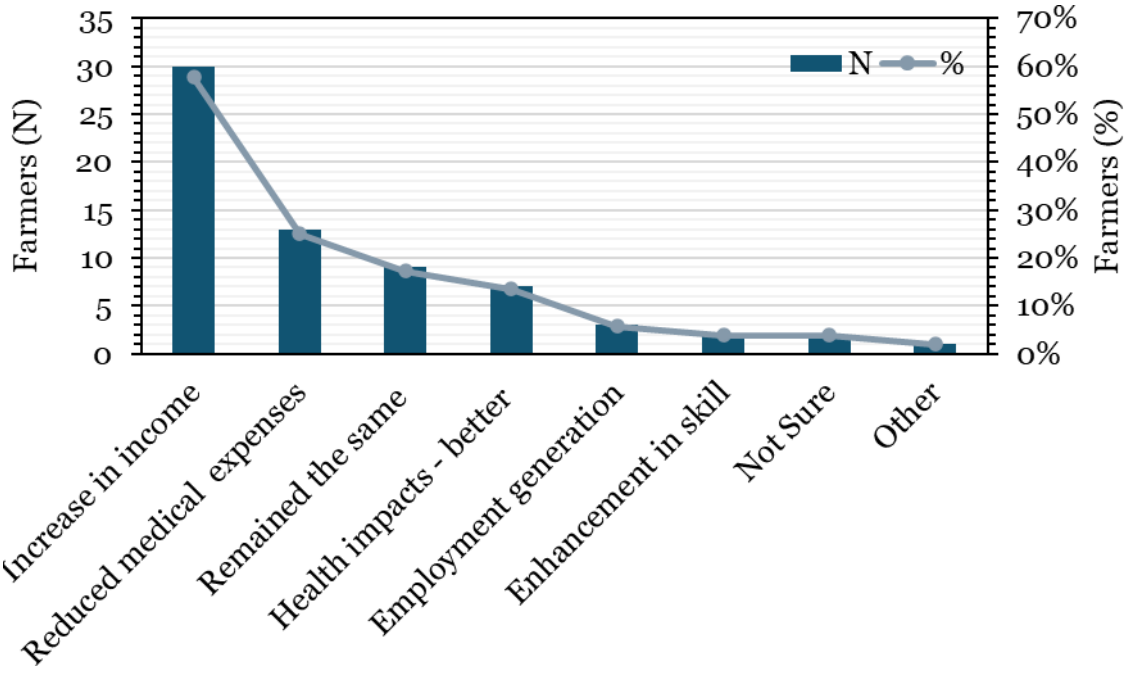


Figure 24: Reasons for Increase in Household Well-being (N=52)

Among those who reported an improvement (N = 52), the most commonly cited reason was an increase in household income (58%) (Figure 24). Other reasons included reduced medical expenses (25%) and improved health outcomes due to lower exposure to smoke from stubble burning (13%). A smaller proportion reported benefits such as employment generation (6%), skill enhancement (4%), and other minor factors (2%).

Overall, the findings indicate that while crop residue management has contributed to improved well-being for some households, the economic benefits are not uniform and are often indirect. In many cases, improvements are linked more to reduced health risks or supplementary income rather than substantial changes in household earnings.

5.2.1.6. Environmental and Health Impact of Crop Residue Management

Crop residue management also appears to have contributed to a reduction in stubble burning. Around 61% of farmers reported that selling or supplying crop residue has reduced burning, while 26% said it has reduced burning only partially. However, 13% reported no change, indicating that burning still continues in some cases, especially where collection services or machinery are not easily available (Figure 25). The finding is consistent with recent evidence showing a significant decline in stubble burning incidents in Haryana [11].

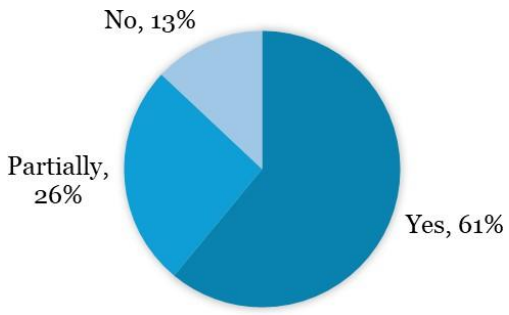


Figure 25: Has the sale of crop residue reduced stubble burning?

Reduced burning was strongly associated with perceived health benefits at the household level. A large majority of respondents (87%) reported that lower levels of crop residue burning had led to improvements in household health, while 13% did not notice any change (Figure 26). Among those reporting improvements (N = 87), the most commonly mentioned benefit was overall better health (63%). Many farmers also reported reduced eye irritation or watering (45%), fewer breathing problems or easier breathing (41%), and less coughing or throat irritation (40%). Other reported improvements included fewer headaches (24%), better sleep due to reduced smoke or smell (21%), and fewer asthma or allergy-related problems (13%). Some respondents also noted indirect benefits, such as children falling sick less often (13%) and elderly family members feeling more comfortable (8%). Overall, the findings indicate that reductions in crop residue burning are widely perceived to have improved air quality

and reduced smoke exposure, leading to noticeable improvements in respiratory health and general well-being in farming households.

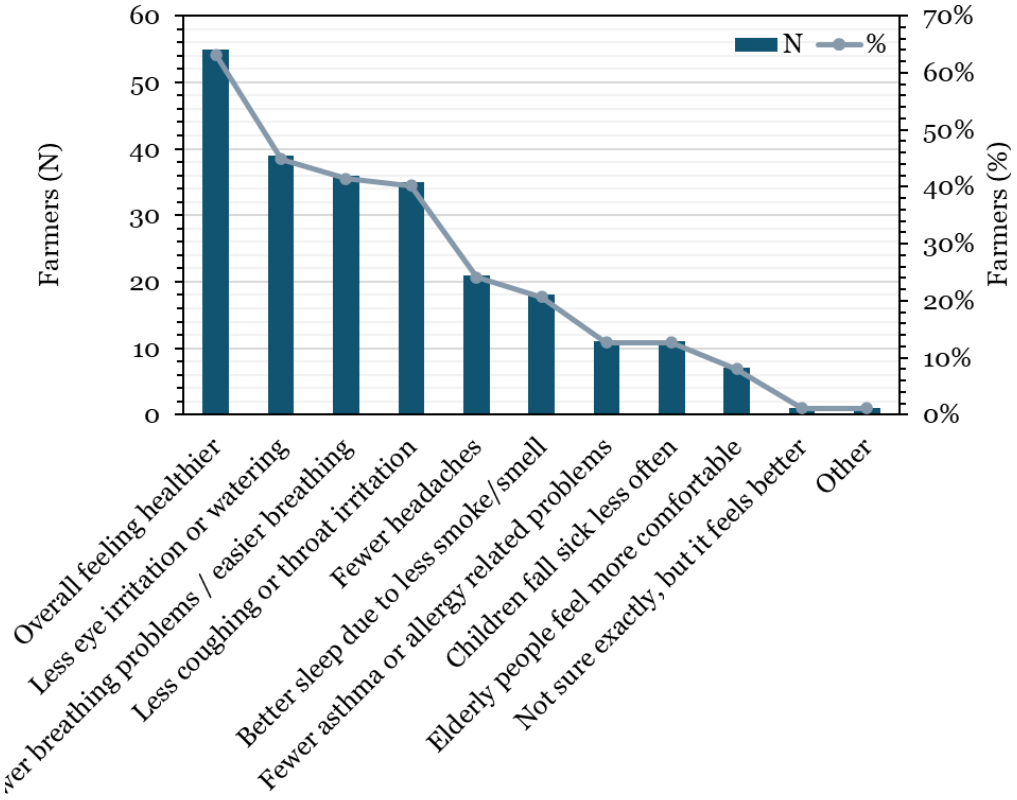


Figure 26: Reasons for Health Improvements Experienced (n=87)

5.2.1.7. Key Insights from Focused Group Discussions

In addition to the survey, two focused group discussions (FGDs) were conducted in Ghumar Village (Sonipat) and Naraina Village (Panipat) (Figure 27). The key findings emerging from these FGDs are as follows:

- Stubble burning has reduced over the past 4–5 years, primarily due to the adoption of balers and super seeders.
- Many farmers still lack information about biomass markets and often give residue-free or pay for its removal.
- Limited farmers receive financial assistance of ₹1,000-1200 per acre for residue management; however, delays in payments and limited awareness of biomass markets remain major concerns.
- Incorporation of stubble into the soil has improved soil fertility, leading to a reduction in fertilizer usage from 4-5 bags to 2–3 bags per season.
- Women's involvement in residue management activities remains minimal.



Figure 27: Focused Group Discussion at Gumar (Sonipat) and Naraina (Panipat)

5.2.1.8. Voices from the Field: Farmers' Expectations

Most farmers are not currently participating in formal crop residue markets. Farmers highlighted that their preferred selling channels would include aggregators or baler operators, direct sales to power plants or industry, or government-supported procurement systems. The results also show limited awareness of the biomass industry among farmers. While 36% of respondents reported awareness of NTPC, awareness of co-firing was lower at 27%, and only 8% were aware that some power plants use biomass for power generation (Figure 28). A majority of farmers reported not being aware of these initiatives. Farmers reported that crop residue management often involves additional costs with limited financial returns. Several respondents noted that they have to pay baler operators to clear the fields, which reduces or eliminates any benefit from government incentives. In some cases, residue is primarily used as fodder for livestock, leaving little surplus to sell. Others mentioned that there has been little change in their situation, with residue management having minimal impact on income. Farmers also highlighted several key support measures required to strengthen crop residue management systems (Figure 29). The most frequently mentioned support was a minimum price guarantee for crop residue (62%), followed by machinery support (49%), improved storage facilities (40%), and training or awareness programs (38%). Most farmers also indicated that the preferred price for selling crop residue would range between ₹200 and ₹500 per quintal, suggesting expectations for stronger economic incentives to participate in biomass supply chains.

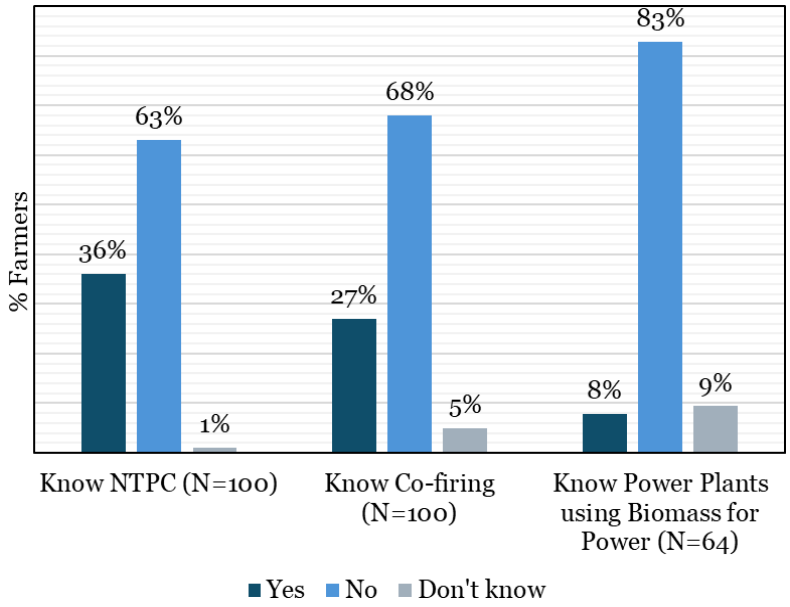


Figure 28: Awareness about the Biomass Industry

Farmers highlighted the need for a locally available residue collection center that can provide services when required. Providing additional income from cow dung will encourage farmers to sell it rather than use it as cooking fuel, thereby reducing household air pollution and improving the life expectancy of women, who are primarily involved in cooking. Overall, farmers indicated that better market linkages, price assurance, and access to machinery would be essential to encourage greater participation in residue market.

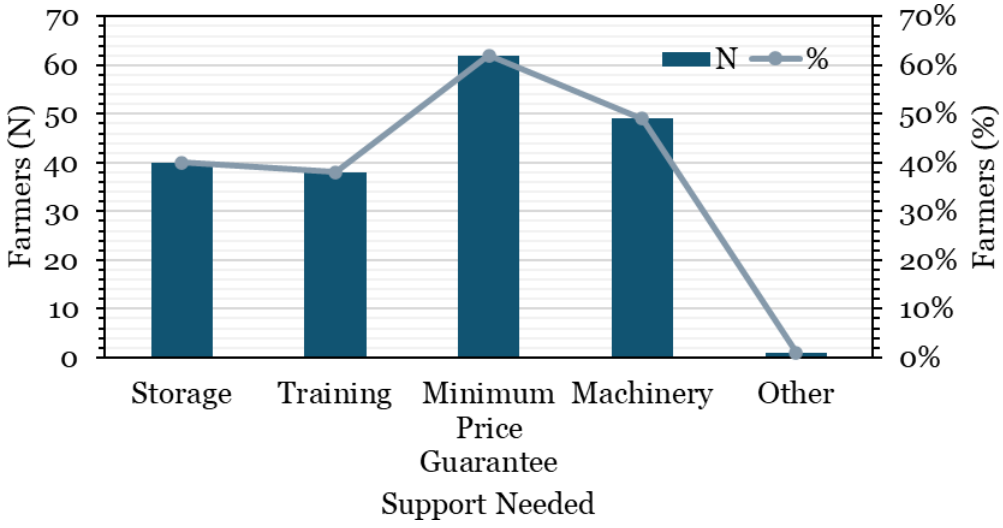


Figure 29: Key Support Measures Required

5.2.2. Aggregator

Aggregators, locally referred to as balers, play a central role in the crop residue management supply chain (Figure 30). They are being promoted by the state government as rural entrepreneurs who can support farmers at the local level in managing crop residue without burning.



Figure 30: Snapshots from Field: Engagement with Aggregators

To enable this, the government provides subsidies for the purchase of baling machines and related equipment such as cutters, rakers, and tractors. During the peak harvesting season, especially in the kharif cycle, balers are required to cover large areas

within a short period of time. Clearing a single field typically involves multiple operations, including cutting, raking, baling, and transporting the residue. As a result, machines and laborers often need to visit the same field three to four times, and the entire process may take two to three days to complete. Field interactions revealed that, due to limited baler availability, repeated operations, and the time involved, many balers charge farmers for the service. At the same time, balers also sell the collected biomass to various end users, generating additional income from bale sales. The possibility of earning through resale has encouraged the entry of intermediaries and agents who procure agricultural residue from farmers or balers and further supply it along the value chain. This has gradually led to the emergence of a more commercialized supply network around crop residue collection and utilization.

5.2.2.1. Demographic Profile of Participants

A total of 20 aggregators were surveyed across three districts of Haryana, Karnal, Panipat, and Sonipat, and all respondents were male. Nearly half of the respondents were from Karnal (45%), followed by Panipat (40%) and Sonipat (15%) (Figure 30). The survey covered six villages: Gharaunda and Assandh in Karnal; Samalkha, Panipat, and Bapoli in Panipat district; and Ganaur in Sonipat.

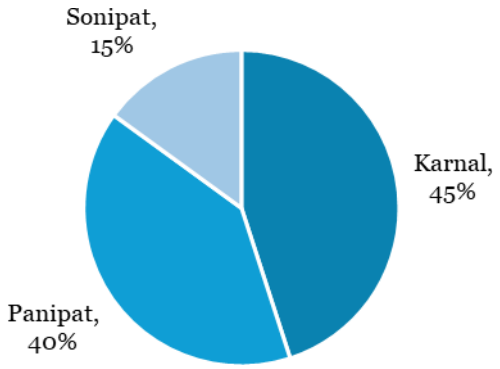


Figure 31: Total Aggregators Disaggregated by District

The age profile shows that aggregators are largely middle-aged, with the majority (55%) falling in the 31–40 year age group, followed by 25 percent in the 41–50 group (Figure 31). Smaller proportions were found in the younger (21–30) and older age brackets (51–60 and 61–70). Educational levels varied, though most respondents had moderate levels of formal education (Figure 32). About 35 percent had completed

higher secondary education, and another 35 percent had studied up to secondary level. Around 20 percent had primary education, while only a small proportion had graduate (5%) or postgraduate (5%) qualifications. Overall, the profile indicates that aggregators are predominantly middle-aged men with moderate education levels.

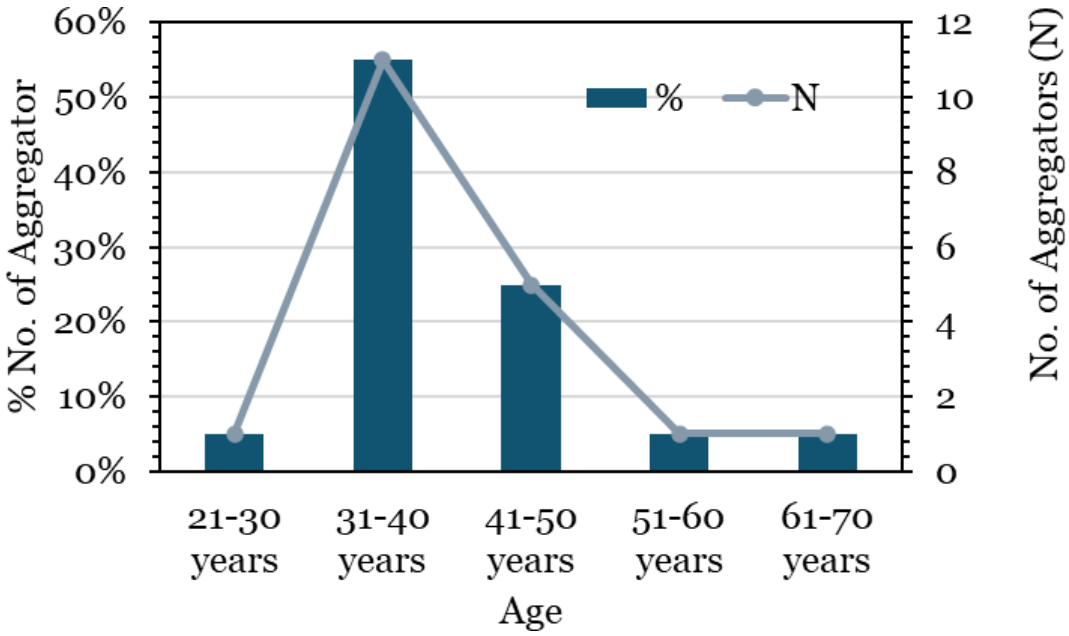


Figure 32: Total Aggregators Disaggregated by Age

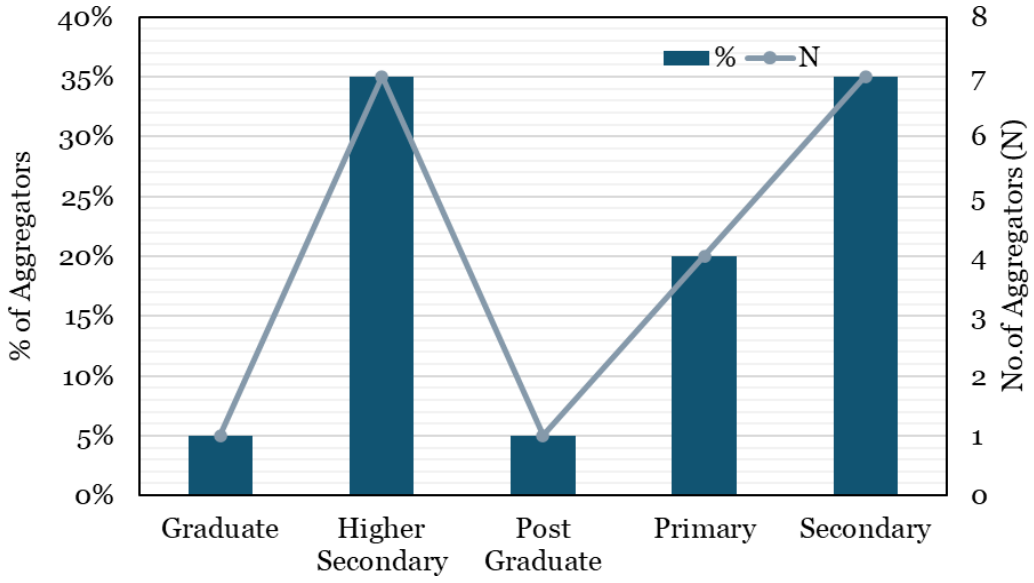


Figure 33: Total Aggregators Disaggregated by Education Level

Most aggregators operate individually, with 90 percent working as independent operators. In terms of experience, many are relatively new to the biomass trade, with

55 percent reporting one to three years of experience. For most respondents, biomass

Box 1: Role of Agents in the Ecosystem of Crop Residue and Biomass Supply Chain

During the primary research, a new entrant in the supply chain was observed, "Agents," who play an important intermediary role. They facilitate the aggregation and movement of crop residues from dispersed farms and farmers/aggregators with smaller landholding to processors and end users such as power plants. They play the role of stockists by investing money to stock bales in massive quantities and supplying them to end users.

These agents identify farmers willing to sell residues, organize collection and baling activities, and arrange transportation to aggregation or processing points. Their local knowledge and networks enable them to mobilize biomass efficiently in regions where farmers may have limited direct access to organized markets. At the same time, the presence of agents reflects the fragmented nature of the supply chain, where individual farmers produce relatively small quantities of residue, aggregators consolidate the residues and require intermediaries to stock and sell these. While agents help reduce transaction costs and logistical challenges for aggregators and processors, their role may also influence price negotiations and margins within the supply chain.

aggregation is not the primary source of income. Over half (55%) reported that it contributes only 0-10% of their total earnings. To supplement their income, aggregators are engaged in multiple other livelihood activities. The most common were trading (reported by eight respondents) and livestock rearing (seven respondents). Some also reported fodder cultivation and sale, government service, private salaried work, or agricultural labor on other farms, while a few chose not to disclose additional income sources. Overall, the findings suggest that for most aggregators, biomass collection and trading remain a supplementary livelihood rather than a primary occupation, and their continued involvement in the system is influenced by seasonal demand, market prices, and availability of machinery support.

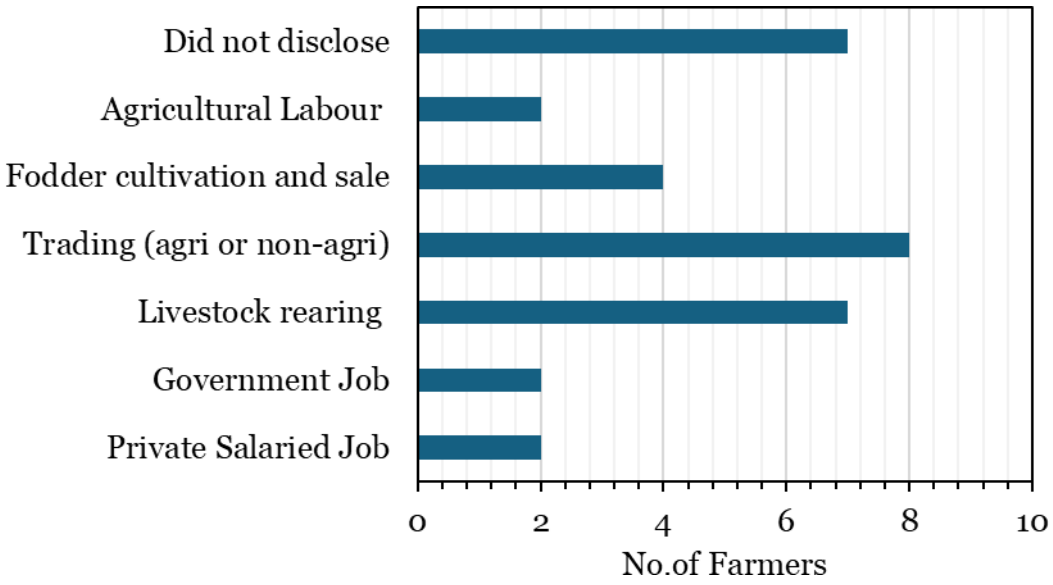


Figure 34: Other Sources of Income (other than Biomass Trade)

5.2.2.2. Economic Impact on Aggregators

Aggregators, commonly referred to as balers, occupy a central position in the crop residue management supply chain and play a critical role in linking farmers with downstream users such as industries, processors, and energy producers. Their primary activity involves collecting crop residue from farmers, baling it, storing it temporarily, and selling it to different buyers depending on demand and price conditions. Field findings indicate that aggregators typically source crop residue from a large number of farmers within their operational area. On average, each aggregator reported procuring around 1,027 tonnes of crop residue annually, sourcing from approximately 234 farmers. Paddy residue is the most commonly collected biomass (reported by 83% of respondents), followed by wheat (42%) and sugarcane residue (33%) (Figure 35). While most aggregators procure residue locally, many reported traveling long distances (60 km) during peak season. The collected crop residue is usually stored at different locations based on proximity to fields and availability of space, and then sold according to demand. During the peak harvesting season, balers often sell the bales directly from the field, whereas in lean periods they rely on stored stock. Prices fluctuate considerably across the year. Paddy straw may sell at around Rs. 160 per quintal during peak availability, while prices can rise to Rs. 350 per quintal during the lean season. On average, aggregators reported receiving about Rs. 212 per tonne for crop residue, with an estimated margin of around Rs. 173 per tonne, indicating modest but steady returns.

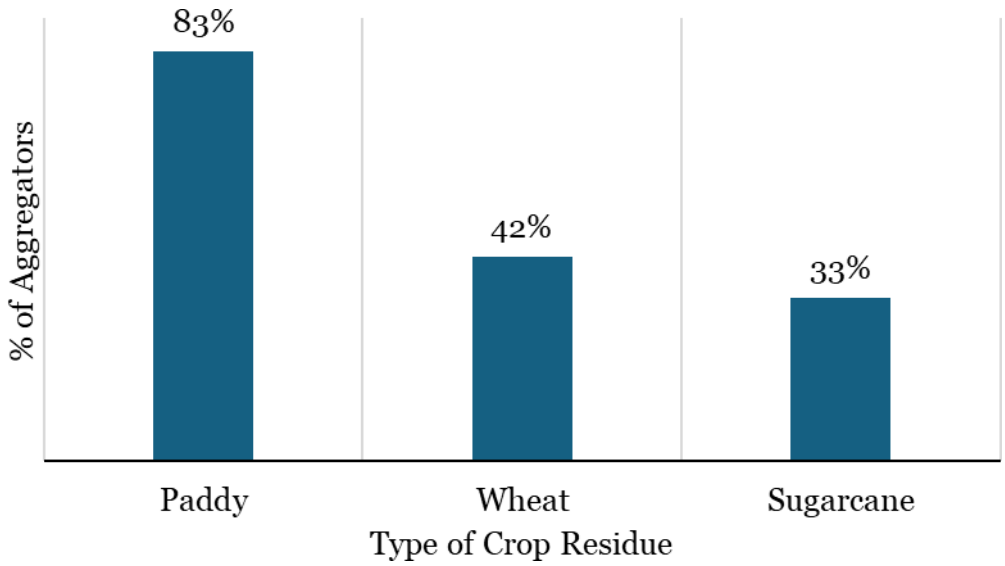


Figure 35: Types of crop residue collected by Aggregators

Aggregators employ several strategies to manage residue availability and price fluctuations. The most common approach (95%) is increasing procurement during peak seasons to secure supply. A smaller share reported storing biomass (15%), adjusting selling prices across seasons (10%), or changing buying prices in different seasons (5%). However, storage capacity remains limited for many small aggregators, which restricts their ability to enter long-term supply agreements. In terms of market linkages, aggregators primarily supply crop residue to local industrial users, especially industrial boilers. Aggregators sell the agri residue bales to various industries such as paper mills, textile industries, brick manufacturers, beer factories, and pellet/briquette manufacturers. It is observed during the primary data collection that aggregators can get higher revenues by selling raw biomass to pellet and briquette manufacturers (₹2000–4500/tonne), compared to supplying industries such as textile (₹2800/tonne), paper (₹1600/tonne), and beer (₹1300–1800/tonne), indicating a stronger market incentive in the densified fuel supply chain.

Because of limited storage capacity and inconsistent supply, most small aggregators do not enter into formal contracts with end users. Only a few respondents reported having written or verbal agreements, usually for short durations and with conditions related to moisture content and delivery schedule. This gap has created space for agents and larger stockists, who invest in bulk procurement and storage of crop residue. These intermediaries are able to enter into contracts with large buyers

such as bio-CNG plants, refineries, and distilleries, and often secure better prices due to assured supply.

Overall, the findings suggest that the crop residue aggregation business is gradually evolving from a local, seasonal activity into a more organized supply system linked to industrial and energy markets. However, for most aggregators, the activity still remains supplementary, with earnings dependent on seasonal demand, storage capacity, and access to reliable buyers. Strengthening market linkages, improving storage infrastructure, and enabling more stable contracts could significantly enhance the economic viability of crop residue aggregation and support the broader objective of reducing crop residue burning.

5.2.2.3. Investment in Machinery and Equipment

Crop residue aggregation requires significant upfront investment in machinery and related equipment. 90% of the aggregators have their own aggregation machinery, including baling machines, tractors with trolleys, cutters, and racks. None of the surveyed aggregators reported owning processing units, indicating that their role remains limited to collection, baling, and supply rather than value addition.

Table 3: Cost of the Machines Involved in Aggregation

Machine	Cost (in lakhs)	Make
Baler (Small bales)	15-20.5	New Holland, Fieldking (India), John Deere
Cutter	1.5-2	Shaktiman (India)
Raker	15-20.5	Fieldking, Dasmesh (India)
Tractor (45-60 HP) and Trolley	7.5-27	Mahindra, Swaraj, Sonalika, and trolley local made (India)
Total	**41.5-63**	-

The cost of machines involved in aggregation is shown in Table 3. The costs of multiple equipment components differ significantly, with the baling machine (for small bales) itself being a major contributor, costing approximately ₹15–20.5 lakhs. In addition, a cutter costs around ₹1.5–2 lakhs, and a racker costs around ₹15–20.5 lakhs.

Supporting logistics are handled by a tractor (45–60 HP) with a trolley, costing ₹7.5–27 lakhs depending on capacity and specifications. Overall, the total capital investment for these combined pieces of equipment ranges between ₹41.5–63 lakhs, indicating that baling operations are capital-intensive and require significant upfront investment for efficient biomass aggregation and handling. Field discussions suggest that subsidies (up to 50%) are available in Haryana for baling machines under the Crop Residue Management (CRM) Scheme (Haryana) and the Sub-Mission on Agricultural Mechanization (SMAM) scheme (Government of India). Most of the machinery used in biomass aggregation is indigenous, which is encouraging for promoting local manufacturing and reducing dependence on imports.

In addition to machinery, some aggregators invest in storage infrastructure, though this is generally limited. 67% of aggregators rent storage facilities ranging from 3 to 10 acres. Storage areas typically range between three and five acres, with relatively modest annual investments, often between Rs. 1–2 lakh, and occasionally up to Rs. 3–5 lakh. This indicates that aggregators tend to prioritize investment in machinery, while storage capacity remains constrained, affecting their ability to hold stock and negotiate better prices.

Aggregators reported using their own vehicles for both procurement and sale of biomass, and none reported facing transportation-related challenges. Procurement from farmers is largely localized, with aggregators typically sourcing biomass from villages within their own vicinity or district, indicating a relatively short-distance supply network centered around nearby rural areas.

5.2.2.4. Labor Requirements and Nature of Employment in Aggregation

Biomass aggregation activities are largely dependent on a seasonal workforce, primarily consisting of unskilled or semi-skilled male laborers with low levels of formal education, who are typically hired for 2 to 7 months during the peak aggregation season. During field visits, aggregators mentioned that most laborers are migrant workers, commonly coming from western Uttar Pradesh across the Yamuna River, who travel to Haryana during the harvesting season for temporary work. The operations are labor-intensive, involving tasks such as cutting, raking, baling, and transporting biomass from fields to storage. In addition to this, a smaller segment of the workforce includes skilled personnel such as tractor drivers and machine operators, who also possess basic repair and maintenance capabilities for handling

equipment. On average, each aggregator employs around 23 workers per season, although this number can rise to nearly 100 in the case of large-scale operations. Daily wages for workers vary between ₹600 and ₹1,500, depending on the nature of work and skill level.

The findings suggest that both investment requirements and labor dependence shape the scale at which aggregators can operate. High equipment costs limit entry into the sector, while limited storage capacity restricts the ability of smaller aggregators to hold stock or enter long-term supply contracts. Similarly, the seasonal nature of labor availability affects the speed at which fields can be cleared, especially during peak harvesting periods. Because of these constraints, many aggregators operate on a relatively small scale and depend on local markets, while larger operators with more machines, storage space, and labor are better positioned to supply bulk buyers and enter formal agreements. Overall, crop residue aggregation remains a capital-intensive and labor-dependent activity, with profitability closely linked to scale, access to machinery, and the ability to manage seasonal fluctuations in supply and demand.

5.2.2.5. Environmental and Health Impact of Biomass Aggregation

All aggregators reported observing a reduction in stubble burning, noting that fewer farmers are burning crop residue and that farmers' livelihoods have improved due to biomass trade opportunities. This results in better local air quality, improves respiratory health, and reduces medical expenses. Respondents also expressed a need for greater awareness and clarity regarding the Biomass Trade Market. Aggregators also highlighted several measures that could further reduce stubble burning. The most frequently suggested intervention was ensuring better prices for crop residue (80%), followed by increasing the availability of balers and machinery (40%). Other suggestions included timely payments to farmers (20%), awareness and training for farmers (15%), subsidies for residue management machines (15%), stronger government monitoring or penalties (10%), and improvements in transport and storage infrastructure (5%). Overall, respondents emphasized that market incentives and improved access to machinery are key to sustaining reductions in stubble burning (Figure 36).

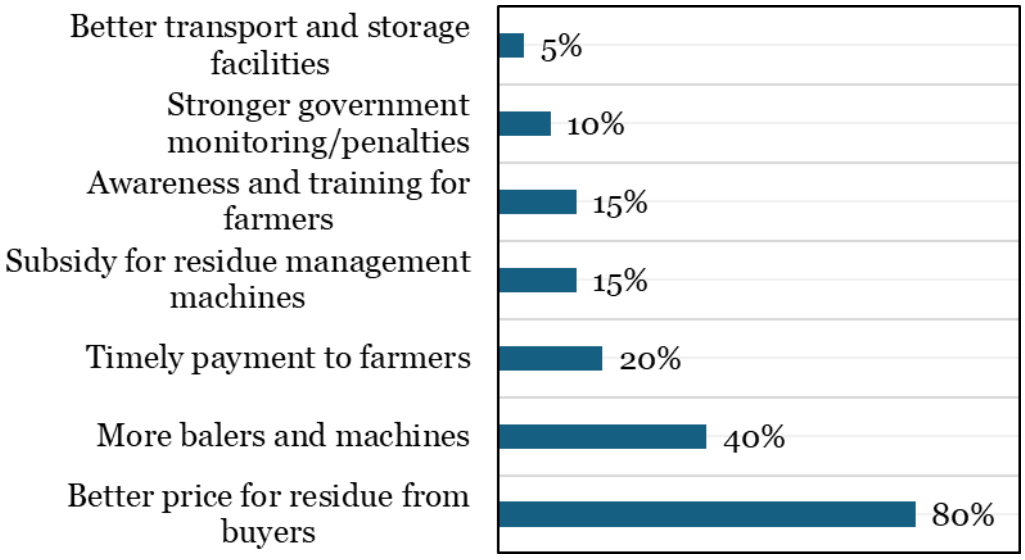


Figure 36: Suggestions to reduce Stubble Burning

5.2.2.6. Challenges Faced by Aggregators and Support Needed

Most aggregators reported relatively few operational challenges in maintaining the biomass supply chain, with 35% indicating no major issues. However, an equal proportion (35%) highlighted rate differences in the market as a key challenge. Other concerns included toll taxes or traffic fines (15%), seasonal variation, equipment maintenance, and storage space (5% each) (Figure 37).

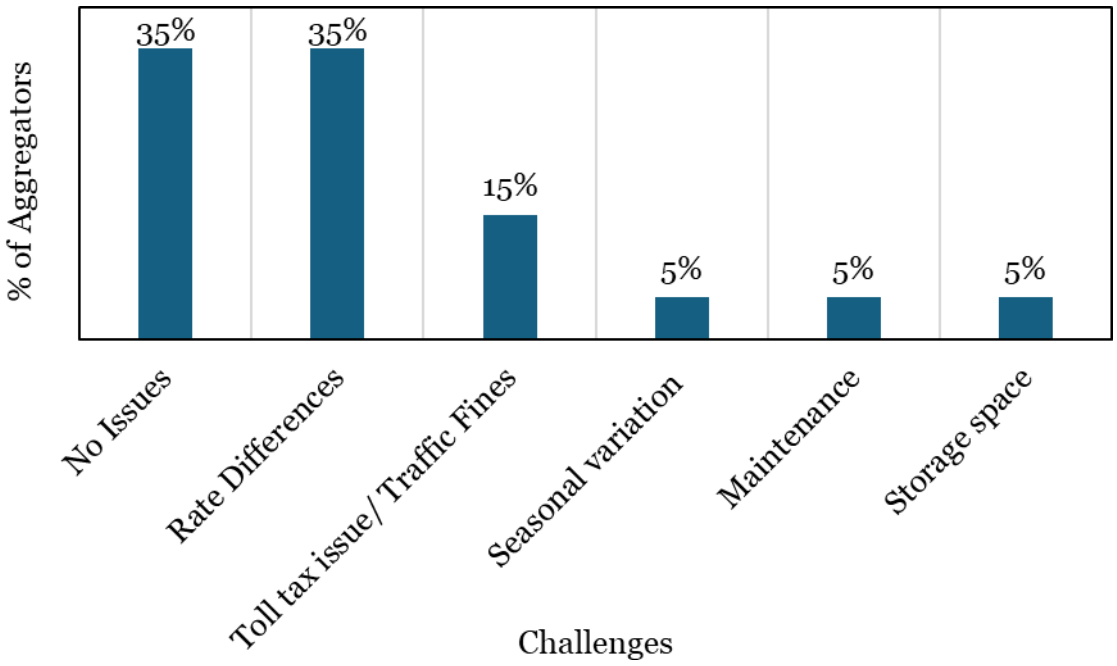


Figure 37: Main Challenges in Maintaining Supply Chain

In terms of support needs, aggregators emphasized the importance of policy and market stability. A majority expressed the need for government support through price guarantees (95%) and subsidies (85%) to strengthen the biomass market. From the private sector, the most sought-after support was access to improved technology (90%), while a smaller share (10%) indicated a need for better access to finance. Overall, respondents highlighted that stable pricing mechanisms and technological support would significantly improve the efficiency and sustainability of the biomass aggregation supply chain (Figure 38).

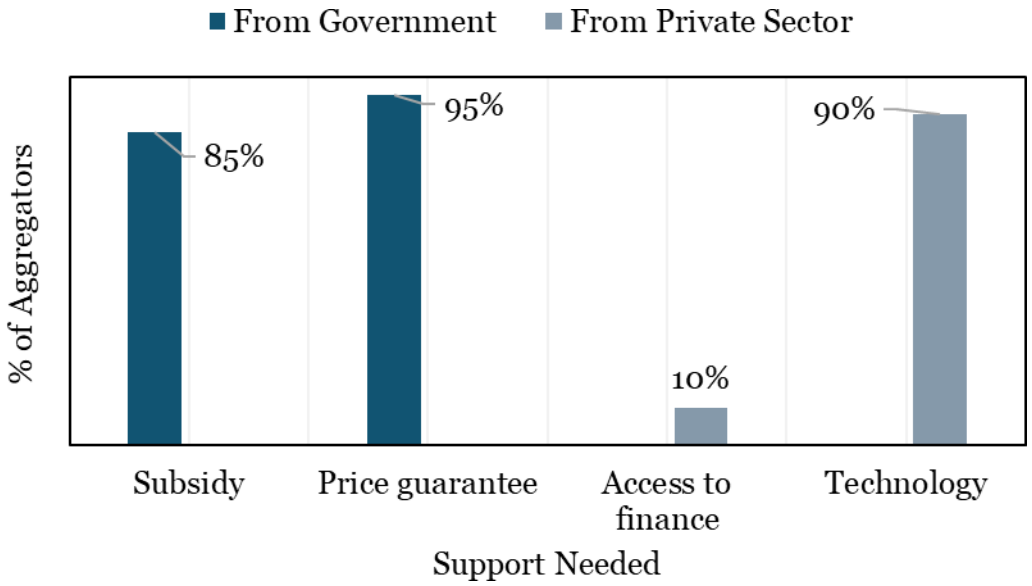


Figure 38: Support Needed By Aggregators

5.2.3. Processors

The third stakeholder in this supply chain is the processor, who owns the processing plants to make pellets and/or briquettes from crop residue (Figure 39). The respondents, all male, represented companies operating across multiple states in North India, with the highest concentration from Haryana and Rajasthan (Figure 40). Out of the 20 respondents, eight companies were based in Rajasthan and seven in Haryana, indicating that these two states constitute the primary operational hubs for the companies included in the study. A smaller number of respondents were from Delhi and Uttar Pradesh, with two companies each. In addition, one respondent reported operations spanning both Haryana and Rajasthan. Out of the 20 processors interviewed, 16 reported supplying to the NTPC TPP in Dadri, and 2 are supplying to the NTPC TPP in Jhajjar, and the remaining two are supplying to both plants (Figure

41). A majority (13 out of 20) of the processor companies were private limited companies.



Figure 39: Snapshots from Field: Engagement with Processors

The respondents represented companies with varying years of operational experience, though many were relatively recent entrants to the sector. Several entities (9) reported between two and six years of experience, while a smaller number (5) had been operating for over a decade; three respondents did not provide this information. Most processor companies reported no other business engagements, with eight respondents indicating that they operate solely in this sector. However, a few respondents reported involvement in diverse activities such as coal trading, construction and brick

manufacturing, biofuel production, plastics supply, and financial asset management, while seven respondents did not provide a response.

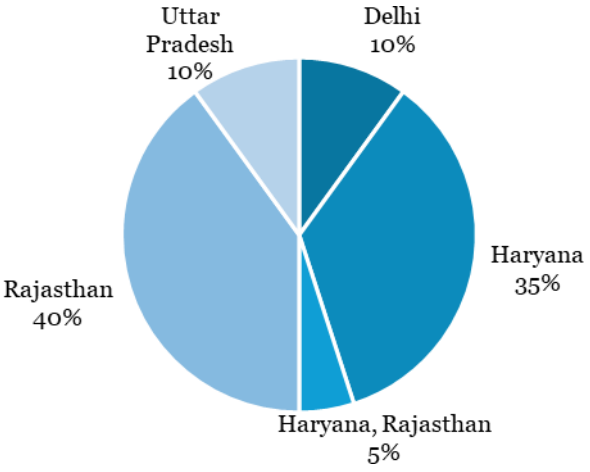


Figure 40: State-wise Presence of the Processors (N=20)

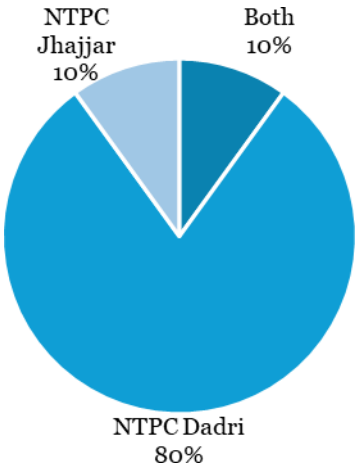


Figure 41: Distribution of NTPC Plants Processing Units supplying to (N=20)

5.2.3.1. Biomass Processing Business

Most units produce pellets, while a few produce both pellets and briquettes both. The distribution of installed capacity across processing units shows that most processors operate at small to medium scales. The highest concentration of units falls within the 100–199 tonnes per day (TPD) category, followed by the 0–99 TPD range, indicating that a large share of processors have relatively modest installed capacities (Figure 42). A smaller number of units are present in the higher capacity ranges of 300–499 TPD and 500–600 TPD, suggesting the presence of a few larger players in the market. Overall, the distribution reflects a mixed structure of small and mid-sized processing units with limited representation of large-scale operations.

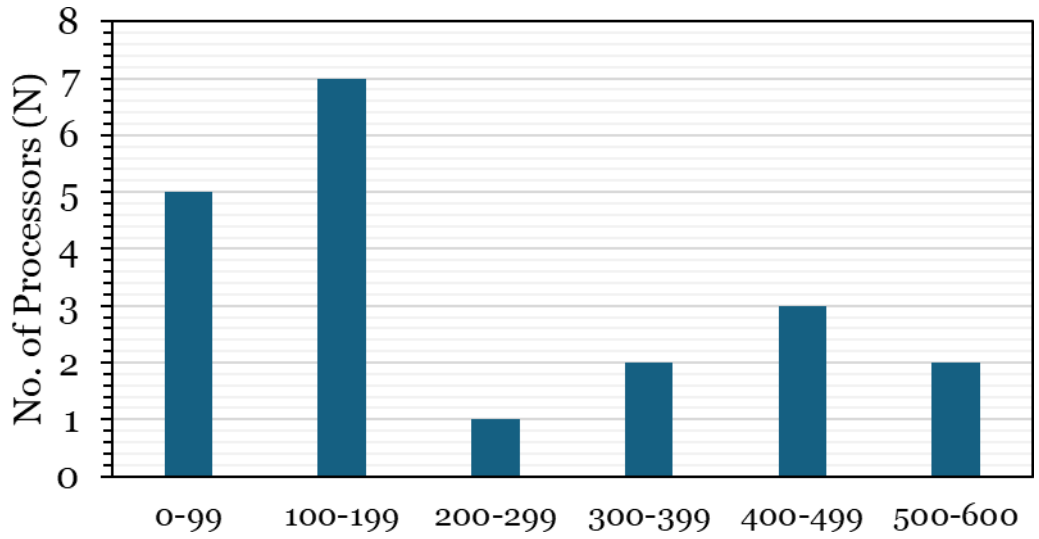


Figure 42: Installed Capacity in tonnes per day

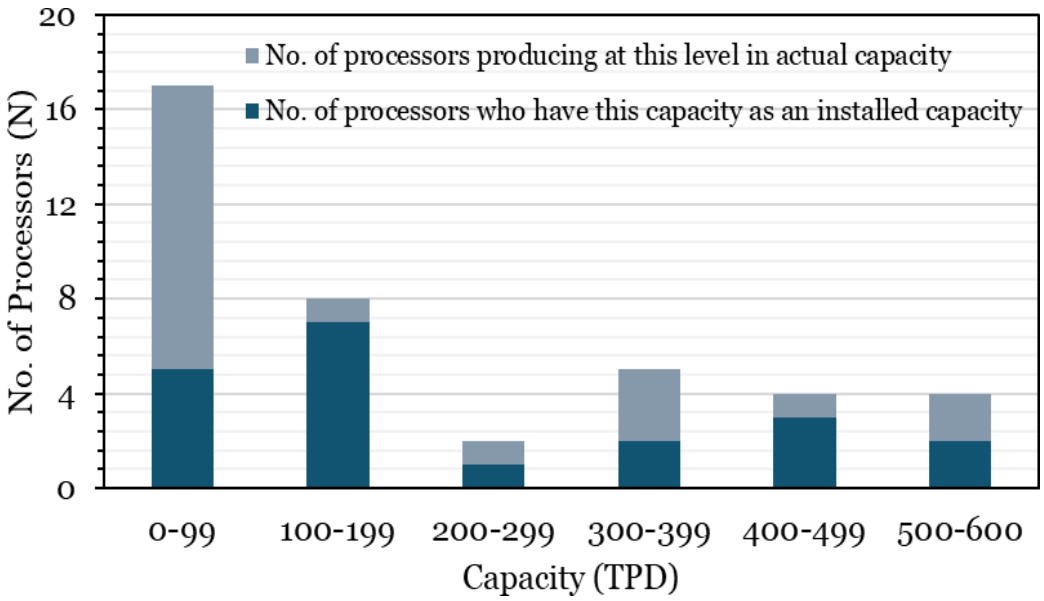


Figure 43: Installed Capacity vs. Actual Production

A comparison between installed capacity and actual production levels indicates that most processors are not operating at full capacity (Figure 43). While a significant number of units have installed capacities in the 100–199 TPD range, actual production is more concentrated in the 0–99 TPD category, suggesting underutilization. This gap between installed and operational capacity is attributed to factors such as irregular feedstock supply, high moisture content, logistical constraints, and market uncertainties. The findings point to system inefficiencies and supply-side constraints limiting optimal utilization of processing infrastructure.

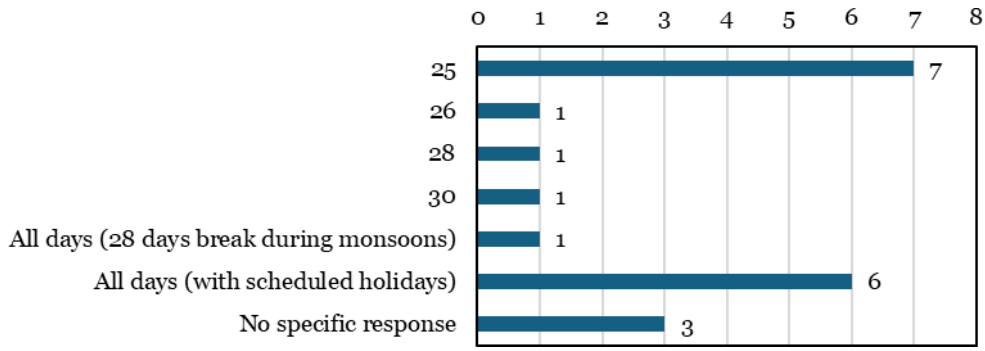


Figure 44: Days of Operation of Processing Units

The operational patterns of processing units indicate that most plants run throughout the month, either with scheduled holidays or with short breaks during the monsoon period (Figure 44). A smaller number of processors reported operating for 25–28 days per month, while a few provided no specific response. The data suggests that, despite supply and operational challenges, processors aim to maximize utilization of installed capacity through regular operations, without breaks.

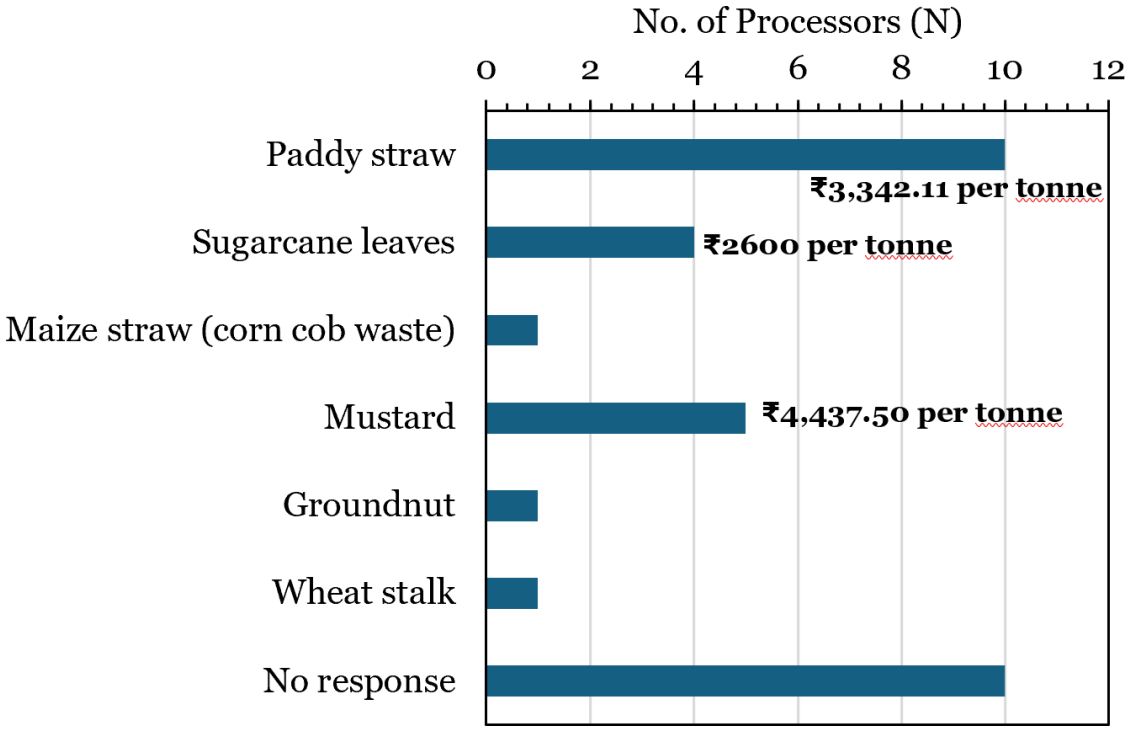


Figure 45: Raw Agri-residue Used by Processors

The primary research findings reveal that a majority of the processors use paddy straw as the source of biomass production, while others mentioned sugarcane leaves, maize straw, mustard, groundnut, and wheat stalk (Figure 45). In addition, other materials

mixed with these crop residues include dust of sunmica, animal dung, isabgol (Psyllium Husk), fennel, etc. These are commonly procured from aggregators (balers) who play an important role in consolidating the biomass from dispersed smallholders and facilitating large-scale supply to processing units. Processors reported paying varying prices for different types of agricultural residues used in biomass pellet production. Paddy straw, which is the most commonly used feedstock, was reported to be procured at an average prices ranging from approximately ₹2,000 to ₹5,000 per tonne, with a average price of about ₹3,342 per tonne. Mustard residue was reported to be relatively more expensive, with an average price of approximately ₹4,437 per tonne. Limited responses also indicated procurement of other residues such as sugarcane leaves and groundnut residue, with reported prices ranging from approximately ₹2,600 to ₹4,000 per tonne.

Season	Sowing Period	Harvesting Period	Climate	Water Requirement	Examples of Crops
Kharif	June–July	September–October	High rainfall, warm temperatures	High	Rice, Maize, Cotton, Groundnut, Soybean, Bajra, Pulses
Rabi	October–December	March–April	Cool temperatures, less rainfall	Moderate	Wheat, Mustard, gram
Zaid	March–June	May–July	Hot, dry conditions, longer daylight	Low to Moderate	Watermelon, Muskmelon, Cucumber, Pumpkin, vegetables

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rice												
Wheat												
Maize												
Sugarcane												
Mustard												
Groundnut												

Figure 46: Seasonal Variation in Crop Residue

The supply of biomass from various sources is seasonal, with the major crop residues available only between October and December. Wheat residues are available from April to June. In monsoon months, when there is a shortage of these major crop residues, processors address the shortage by stockpiling, sourcing from other areas, or sourcing from aggregators at much higher prices. Since processing units operate year-round, with only calendar holidays, disruptions in feedstock availability result in reduced production and consequent financial losses. Nearly half of the respondents reported that their sourcing radius has increased over time due to changes in biomass availability. However, a comparable number of respondents indicated that their sourcing radius has remained unchanged, while a few did not respond.

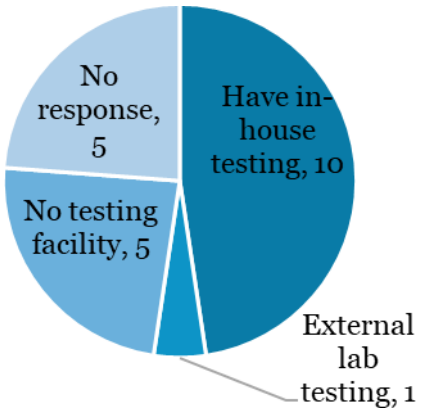


Figure 47: Testing Capacity Among Processors

Quality testing practices among processors appear to be uneven. Half of the respondents (10) reported having in-house testing facilities for assessing parameters such as moisture content and calorific value, while only one relied on external laboratories (Figure 47). Notably, five respondents indicated that they did not have any testing facility, which may limit their ability to consistently verify product quality. This variation in testing capacity may contribute to inconsistencies in pellet quality across suppliers. On further probing into the challenge of quality testing and monitoring, nine respondents reported experiencing rejection of processed biomass by buyers due to quality concerns, while seven indicated that they had not faced such rejections. Overall, the findings reveal that basic quality norms are widely recognized in the sector, but there are gaps in testing infrastructure, and quality control practices may affect consistency in pellet supply.

The most commonly cited price of the biomass pellets supplied to the end user was approximately ₹7,200 per tonne. Several respondents reported slightly higher selling prices in the range of ₹7,200–₹7,800 per tonne, while some indicated prices of around ₹7,888 per tonne exclusive of GST. Overall, the data suggests that the procurement price for biomass pellets has stabilized within a band of roughly ₹7,200 to ₹7,888 per tonne, depending on factors such as calorific value, tender conditions, and contract terms. The relatively standardized price range indicates that NTPC's procurement mechanisms play a significant role in shaping market pricing for biomass pellets.

The primary data findings suggest that the production costs in biomass processing are influenced by significant variations in energy consumption, fuel use,

maintenance requirements, and plant capacity, which together shape the overall cost structure of processing units. The reported production cost of biomass pellets among the surveyed processor companies ranges from ₹1,500 to ₹3,000 per tonne. The average production cost across respondents is approximately ₹2,150 per tonne. Where cost components were reported, electricity, labor, maintenance, loading, and consumables were identified as key contributors to production expenses. According to the respondents in the primary research, the land requirements show a considerable variation, ranging from about 208 sq. ft. per tonne to as high as 13,500 sq. ft. per tonne, with a mean of approximately 2,603 sq. ft. and a median of 1,245 sq. ft. per tonne. This wide variation reflects differences in plant capacity, storage requirements for biomass feedstock, and the layout and operational scale of individual processing units.

Table 4: Costing and Details of Machinery and Equipment Required in Processing Units

Processing Stage	Machine / Equipment	Typical Make / Supplier	Country	Approx. Cost Range
Pre-processing (Cleaning & Size Reduction)	Grinder / Separator	Satyajit	India	₹18 lakh (sometimes combined units)
	Dust Collector	Satyajit, Hi-Tech	India	₹8–15 lakh
	Hammer Mill	Yulong, Lehra, Shree Engineering, Baba Agro	China / India	₹10–65 lakh
	Shredder	Vision Automotive, Hi-Tech, Eco-Stall	India	₹20–58 lakh
Pellet Production Equipment	Pellet Machine (General)	Lehra	India / China	₹25–60 lakh
	Pellet Mill	Yulong, Lehra, JSW	China / India	₹75 lakh – ₹1 crore

	Pelletizer (Piston Type)	Radhey Engineering, Lehra Fuels	India	₹22 lakh per machine
	Pellet Machine (Flat Die)	JR Agro	India	₹2.65 crore
	Pellet Machine (Piston Type)	Lehra, Ecostan	India	₹2.79 crore
	Pellet Machine (Ring Die)	Yulong, HK Engineering	China / India	₹2.85 crore
	Ring Die Processing Unit	HK Engineering	India	₹31–35 lakh
Material Handling & Feeding	Conveyor	Eco-Stall, Local suppliers	India	₹3–4 lakh
	Auto Feeder	Self-Manufactured / Local	Local	₹8 lakh
Transport & Field Operations	Loader	John Deere	India	₹13–20 lakh
	Tractor	Escort Tractor	India	₹8–15 lakh
Drying Equipment	Biomass Dryer	Local Manufacturers	India	₹24 lakh
Alternative Processing	Briquette Machine	Not specified	—	₹35–65 lakh

As shown in Table 4, biomass pellet processing units require a range of equipment for feedstock preparation, pellet production, drying, and material handling. The cost of machinery varies widely depending on the plant's technology and capacity, with major pellet production equipment, such as pellet mills, representing the largest capital investments. The widespread use of indigenous machinery indicates strong potential for achieving self-reliance in biomass processing technologies. All the processors mentioned grid electricity as the key source of energy. One of them mentioned solar power as a source, while two others mentioned diesel as a source of energy for the production of biomass. The overall capital cost of biomass densification plants varies

with scale, with small units (50–60 TPD) requiring about ₹1–2 crore, medium units (200–300 TPD) ₹3–6 crore, and large units (400–500 TPD) around ₹5 crore.

There is significant demand for biomass pellets/briquetts in the market. Processors reported supplying biomass pellets to a range of other buyers across the energy and industrial sectors (Table 5). These include state and private thermal power plants such as those operated by Haryana Power Generation Corporation Limited (HPGCL), Adani Power, Jhajjar Power Limited, and Nabha Power Limited. In addition, biomass pellets are supplied to industrial users, including textile mills, brick kilns, and industrial boilers for heat generation. Some processors also reported supplying biomass to bioenergy facilities such as compressed biogas (CBG) plants and to traders who subsequently distribute pellets to smaller industries.

Table 5: Biomass Pellets/briquettes Demand in the Market

Sector	Buyer / Organization	Use of Biomass
Public Power Producers	Haryana Power Generation Corporation Ltd (HPGCL), Panipat Thermal Power Station, Deen Bandhu Chhotu Ram Thermal Power Plant (Yamunanagar), Rajiv Gandhi Thermal Power Plant (Hisar)	Co-firing in thermal power plants
Private Power Producers	Adani Power, Jhajjar Power Limited, Nabha Power Limited (L&T Group)	Biomass co-firing for power generation
Bioenergy Plants	Reliance CBG Plant	Feedstock for compressed biogas production
Industrial Users	Textile mills, brick kilns, industrial boilers, and local industries (Faridabad, Gujarat markets)	Industrial heat and fuel
Corporate / Industrial Buyers	Coca-Cola and PepsiCo	Industrial energy use (details not specified)
Traders / Intermediaries	Local biomass traders	Resale to industries

The presence of multiple buyers in the processed biomass market shows that it extends beyond power sector demand and includes a broader industrial fuel market. However, NTPC and other TPPs remain key buyers due to their large and stable procurement volumes. Processors shared that competition within the biomass supply chain occurs primarily in the area of procurement of raw materials, particularly paddy straw and other agricultural residues. Multiple processors and industries compete for the same biomass resources during peak harvesting seasons, which can drive up procurement costs. Price competition also occurs in the sale of processed biomass to buyers, with suppliers competing on both price and quality parameters such as calorific value and raw material composition. Some respondents noted that operational factors such as entry timing, procurement networks, and compliance with quality testing requirements influence competitiveness in the market.

Box 2: Fuelling Self-Reliance: Indigenous Strength of the Biomass Sector

The biomass value chain, from aggregation to densification, largely relies on equipment produced domestically, including balers, cutters, tractors, and processing units supplied by domestic manufacturers. A significant share of supporting systems is also locally fabricated, helping reduce costs and allowing flexibility to suit regional needs. In contrast to solar and wind technologies, which rely heavily on imported components and critical minerals, the biomass sector has much lower external dependence. This strong domestic base aligns with the vision of Atmanirbhar Bharat by strengthening self-reliance, reducing exposure to global supply risks, and supporting local manufacturing and employment generation.

5.2.3.2. Labor Requirements and Nature of Employment in Processing

The responses indicate that biomass processing units employ a mixed workforce consisting of skilled technical staff, semi-skilled operators, and largely unskilled laborers (Table 6).

Table 6: Profile of Workers Engaged in Biomass Processing Units

Workforce Category	Positions Included	Skills / Qualifications	Nature of Employment	Salary Range (₹)
Management and Administrative Staff	Plant managers, in-charges, accountants, sales staff, HR, and communications personnel	Graduate-level education with relevant work experience	Permanent positions	₹20,000 – ₹50,000 per month
Technical Staff	Machine operators, supervisors, electricians, lab operators	ITI training or practical machine operation skills	Mix of permanent and contractual positions	₹25,000 – ₹35,000 per month
Semi-skilled Workers	Drivers, machine assistants, field workers	10th–12th pass with on-the-job training and driving skills	Mostly contractual or seasonal	₹12,000 – ₹25,000 per month
Unskilled Labour	Workers engaged in biomass handling such as loading and unloading, machine cleaning, assisting operators, and raw material handling	No formal qualifications required; basic manual skills	Primarily seasonal and contractual	₹11,000 – ₹22,000 per month (₹400–₹600 per day or ₹800/tonne)

The workforce size in biomass processing units varies depending on the scale of operations. Small units typically employ between 12 and 18 workers, while medium units engage around 20–30 workers, and large units employ approximately 40–50 workers. A breakdown of the staff composition of a medium-sized processing unit is given below (Table 7). Predominantly unskilled labor engaged in biomass handling, supported by semi-skilled workers with secondary education, technical staff with ITI or machine operation skills, and management staff with relevant industry experience. It is important to note that Women's participation is limited and mainly confined to administrative roles.

Table 7: Workforce size in biomass processing units

Role	Approx Number
Management	1–3
Supervisors	2–4
Operators	4–6
Drivers / Tractor operators	2–3
Labourers	10–15

5.2.3.3. Occupational Health Risks in Biomass Processing

While 85% of processors report a decline in local stubble burning, workers continue to face significant dust exposure, leading to persistent health concerns (Figure 48). The commonly reported problems included cough and eye irritation reported by four respondents each, followed by respiratory irritation reported by three respondents. The other issues included asthma and skin rashes. These health concerns were largely attributed to dust exposure during biomass handling and processing operations. Workers engaged in shredding and cutting activities were reported to experience the highest levels of exposure, while machine operators and loaders were described as having moderate exposure. Supervisory staff were reported to have only occasional exposure to dust. The respondents identified several key causes contributing to the issue, including high dust levels generated during shredding and cutting operations, poor ventilation in processing areas, and the high moisture content of biomass. Additionally, the lack of use of protective masks by workers and prolonged exposure during long working hours further aggravate the problem. Several processors shared

that they have adopted basic safety measures to reduce worker exposure to dust and operational risks in biomass processing units.

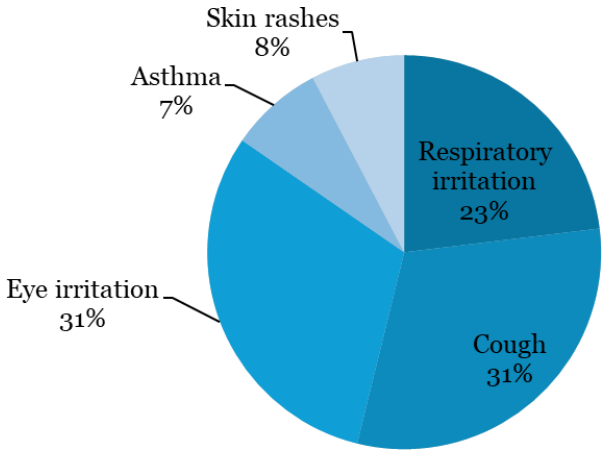


Figure 48: Health issues faced by the Workers

The most commonly reported measures (7 respondents) include the provision of protective masks and safety training. Other protective gear used by workers includes goggles and helmets or caps (reported by five processors each), followed by rubber gloves and gumboots (reported by four processors each). A smaller number of processors reported additional protective measures such as reflective safety jackets, first-aid provisions, fire extinguishers, and protective footwear. While several processors reported providing basic protective equipment and safety training, the uneven adoption of safety measures shows that occupational health protections remain inconsistent across biomass processing units.

5.2.3.4. Challenges Faced by Processors and Support Needed

Processors reported several challenges related to the biomass processing business with NTPC and other industrial procurers of pellets, which are given below:

- Processors reported low procurement prices that are often not aligned with the rising cost of raw materials, along with payment delays of around 2-3 months, affecting cash flow.
- Strict quality norms pose risks of rejection or penalties, while quality-based competition (mixing ratios and calorific value) further intensifies market pressure.

- Logistics challenges such as long truck waiting times at plant sites and administrative hurdles, particularly in e-tendering and payment processes, add to operational inefficiencies.
- There is intense and seasonal competition for raw materials, especially agricultural residues, with price fluctuations driven by aggregators and balers during peak procurement periods.
- A key technical challenge is the high moisture content in biomass feedstock, especially during monsoon and winter harvesting periods, which reduces pelletization efficiency and lowers calorific value.
- Inconsistent feedstock quality due to variations in residue type, moisture levels, and handling practices across sourcing locations further impacts processing performance.
- High maintenance requirements of equipment are also a concern, as fibrous and abrasive residues like paddy straw lead to frequent wear and tear of grinders, hammer mills, and pellet machines.

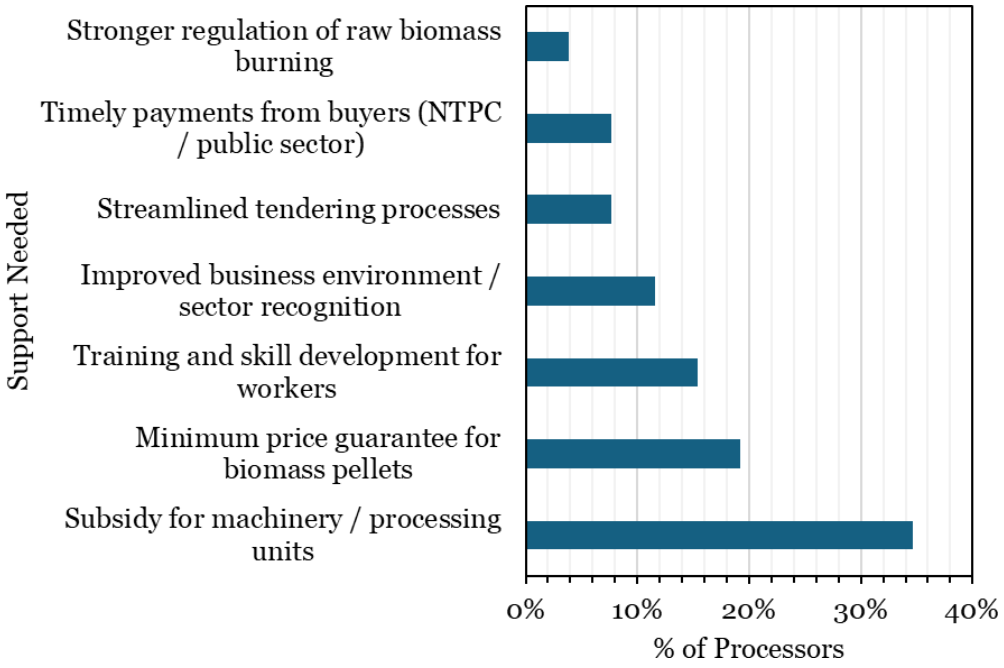


Figure 49: Support Needed by Processors

Despite these challenges, most respondents reported that NTPC demand has had a positive impact on their businesses. Approximately 65% of respondents indicated that their business performance had improved due to NTPC procurement, with 25% reporting that it had improved significantly. A smaller proportion (15%) reported no

significant change, while only one respondent indicated a negative impact. These findings show that while NTPC procurement processes may present operational challenges, the demand generated by NTPC remains an important driver for the biomass pellet processing market (Figure 49).

5.2.4. Transporters

The transporters surveyed in this study can be broadly categorized into two groups based on their roles in the biomass supply chain (Figure 50). The first group is involved in moving raw biomass from farms to aggregators and, from there, to processing units, where aggregators themselves often act as transporters. This group, comprising 10 respondents, primarily uses tractor-trolleys to transport biomass bales from farms to storage sites and onward to densification plants. The second group consists of 5 respondents responsible for transporting processed biomass (pellets or briquettes) from densification plants to end users such as power plants and industries, typically using heavy trucks for bulk transportation (Independent Transporters Between Processors and End Users).

5.2.4.1. Aggregators as Transporters

The aggregator as transporters indicates a relatively young to middle-aged workforce, with most respondents falling in the 35-44 age group, followed by those in the 25–34 and 45–55 categories. In terms of education, the majority have completed secondary schooling, while a smaller proportion have primary or higher secondary education, and only a few are graduates.

In the aggregation stage, tractors from brands such as John Deere, Swaraj, and New Holland are commonly used for transportation activities. The investment in a 65 HP tractor with trolley ranges from approximately ₹7.5 to ₹27 lakh, with most stakeholders owning their equipment and a few relying on rentals. Transporters typically use locally fabricated 1-2 tonne trolleys to move biomass over distances of 5-50 km. The cost per trip varies between ₹1,000 and ₹7,500, resulting in an average round-trip transportation cost of about ₹51.5 per tonne-km. The workforce mainly consists of locally hired drivers and helpers (laborers), engaged on a seasonal basis for 2-7 months, with around 15-30 workers employed during peak periods. These workers are largely unskilled and involved in activities such as loading, unloading, and handling biomass. Despite the operational intensity, all surveyed aggregator-

transporters reported that they do not face any significant transportation-related challenges.



Figure 50: Snapshots from Field: Engagement with Transporters

5.2.4.2. Independent Transporters Between Processors and End User

The independent transporters operating between processors and end users, such as power plants and industries, represent a relatively experienced group, with all respondents being male and falling within the 31-50 years age range. In terms of educational background, most have primary-level education, while one respondent has completed secondary education. Commonly used truck models include TATA 12- and 14-wheelers, TATA 3518, and Mahindra 2025. These transporters typically cover

long distances ranging from 325 to 600 km per trip, carrying 25-30 tonnes of pellets. The cost per trip ranges from ₹20,000 to ₹50,000, resulting in an average transportation cost of approximately ₹75.7 per tonne-km. Despite the organized nature of operations, key challenges highlighted include high fuel costs and inefficiencies in truck management at plant sites, which affect turnaround time.

The workforce in this segment is entirely male, comprising drivers and helpers. Helpers are compensated through a combination of fixed and variable payments, earning around ₹8,000 per month, along with ₹1,600 per trip and an additional ₹200 per trip for food. Drivers receive a higher wage package of approximately ₹27,500 per month, which includes a fixed component of ₹15,000, trip-based incentives, and food allowances for working days.

5.2.5. Power Plant Staff

The fifth and important stakeholder in this supply chain is the end users (thermal power plants and other industries) who procure pellets from processing plants. The thermal power plants are procuring a specific quality of pellets (non-torrefied) as per their utility. In this study, a detailed discussion was conducted with the NTPC staff to get important insights into the practical aspects of biomass co-firing across supply, operational, technical, and policy dimensions (Figure 51).

i. **Supply & Logistics Challenges:**
   - Seasonal availability of biomass remains a major concern, particularly during the monsoon period, leading to supply shortages.
   - Inconsistent quality of biomass, especially in terms of moisture content and composition, affects plant performance.
   - Limited storage infrastructure at plant sites restricts the ability to stock biomass for continuous operations.
   - High inflow of trucks during peak supply periods creates congestion at the plant, increasing unloading time and logistics inefficiencies.

ii. **Economic Aspects:**
   - The cost of biomass pellets is generally higher compared to coal, making co-firing economically less attractive without policy support.
   - Additional costs related to handling, storage, and testing of biomass further increase the overall expenditure.

- These incremental costs are often transferred through tariffs, impacting the end-user electricity price.



Figure 51: Snapshots from Field: Engagement with NTPC Staff

iii. **Operations, Workforce and Health:**

- Biomass co-firing requires additional manpower for handling, feeding, and managing biomass at plant sites.
- Workforce participation is predominantly male, with limited involvement of women in plant operations.
- Workers are exposed to significant dust levels during biomass handling, raising occupational health concerns.

iv. **Technical Observations:**

- Co-firing at around 5% blending ratio has minimal impact on ash-related performance and overall boiler operation and efficiency.
- Higher blending ratios may require modifications in handling systems and combustion management.
- Cattle dung, when used alone, is not suitable due to its high moisture content and relatively low calorific value, limiting its standalone applicability. However, a blended fuel comprising cattle dung and agricultural residues may be considered for co-firing, provided it meets the required quality and characterization criteria specified by the plant.

Box 3: Growth Without Gender Inclusion in the Biomass Sector

Despite women forming a significant share of the agricultural workforce, their participation in the biomass supply chain is minimal and largely invisible across all stages. Biomass activities, especially aggregation, transport, and processing, are dominated by men, with women contributing mainly to informal or household-level tasks. In processing units, women's involvement is limited and concentrated in low-skilled, support, or administrative roles, with negligible presence in technical operations. Social perceptions, heavy manual work, lack of facilities, and shift-based operations act as key barriers to women's inclusion. Mechanization and commercialization have reduced women's traditional roles in residue handling without creating equivalent income opportunities. Women retain some agency in livestock management and dung utilization, but this work remains unpaid and outside the formal biomass economy. Overall, the emerging biomass value chain is not gender-inclusive, highlighting a critical gap and opportunity for targeted interventions in skills, infrastructure, and inclusive employment practices.

v. **Policy & Future Outlook:**

- Annual co-firing levels are maintained at approximately 5% across plants in 2024-25.
- There is potential to scale up co-firing to around 30–40%, provided supply chain reliability and biomass quality improve.

- Stronger policy incentives and financial support mechanisms are needed to make biomass co-firing more viable.
- Government initiatives such as the SAMARTH Mission are supporting adoption through capacity building, training, and awareness programs among stakeholders

6. Cow Dung-Biomass Fuel Blends for Cofiring in Coal-fired Thermal Power Plants

India has the 2nd largest cow population in the world after Brazil, with about 145.12 million cows (female), according to the 20th Livestock Census-2019. On average, a single cow produces 9-15 kg of dung per day, which translates to an estimated ~1.3–2.17 million metric tonnes of cow dung being generated daily across the country, which adds up to ~476.7–794.5 million metric tonnes annually [12]. This makes cow dung one of the most abundant bioresources in India. Despite this massive availability, its organized use for energy production remains negligible. Only 15% of the cattle dung produced in the country is being utilized [13]. The primary challenge with cow dung lies in its composition. It has relatively high moisture content, while its gross calorific value is comparatively low, around ~3066 Kcal/kg [14]. These characteristics make its direct use as a solid fuel inefficient, and combustion often produces smoke and incomplete combustion. On the other hand, its abundance and renewability make it a highly attractive resource if processed or blended effectively.

In India, a large proportion of cow dung cakes is used for household cooking, which generates household air pollution. Household air pollution emits concentrated polycyclic aromatic hydrocarbons (PAHs), which significantly damage DNA. It results in severe respiratory illness [14]. It is reported that around 3.7 million global deaths occur each year due to household air pollution, which majorly (60%) affects the life expectancy of women [15]. Therefore, it is of utmost importance to find alternative uses for the large amount of cow dung produced in the county. One usage is the utilization of cow dung as a feedstock for the anaerobic digestion process, which produces biogas. The utilization of cow dung in this way is also very limited in the country (0.04% of the total dung generated in the country in 2024-25) [16]. It requires a large plant area and a huge investment, and the process takes a long time.

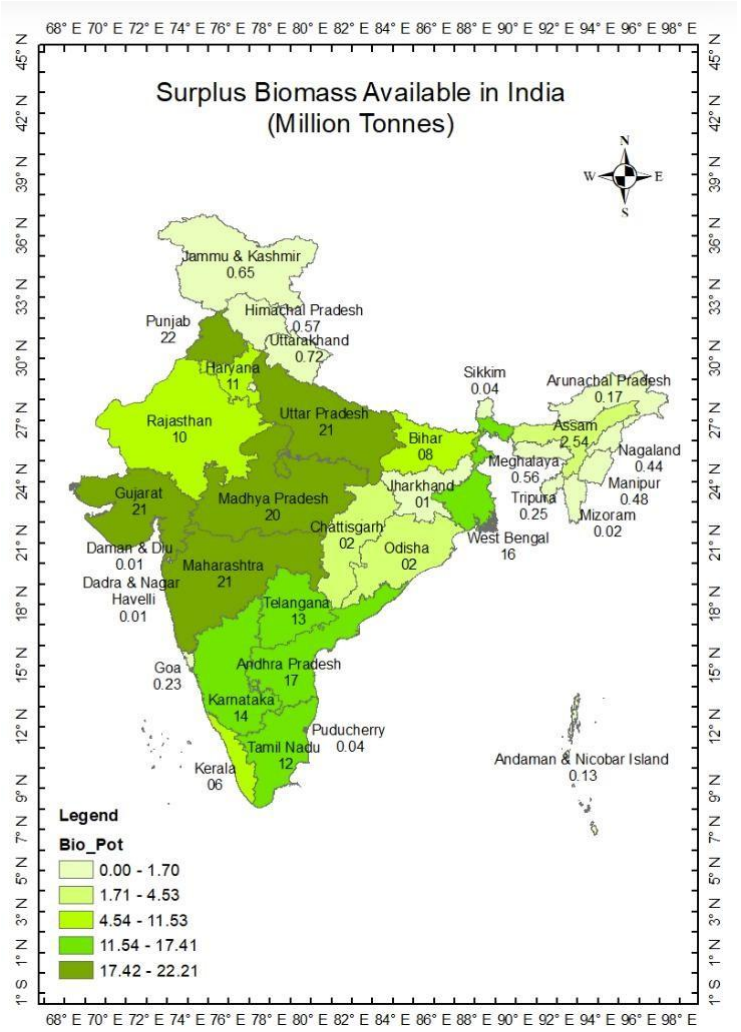


Figure 52: Surplus Biomass Atlas of India

To enhance its fuel potential, scientific attention has shifted to blending cow dung with agricultural residues, which addresses its shortcomings and improves energy efficiency [17, 18]. Agricultural residues generally have higher calorific values, lower ash content, and lower moisture compared to cow dung. When combined, the blend may achieve a balance between energy density and stability. Moreover, cow dung has good binding properties, which help make pellets and briquettes from agri-residue. The advantages of blending extend beyond technical improvements in fuel quality and the health benefits of the women. It also supports rural energy independence by converting locally available waste into usable energy. Farmers benefit from reduced dependence on fossil fuels and added income opportunities through biofuel production. Additionally, blending cow dung with residues promotes

a circular economy where livestock and agricultural byproducts are reintegrated into productive energy cycles.

Across India, the annual surplus biomass residue touches about 228.5 million metric tonnes (Table 8). Rice, wheat, and maize residues account for the largest share, contributing roughly 41.7, 33.4, and 15.2 million metric tonnes, respectively. States such as Punjab, Uttar Pradesh, Maharashtra, Gujarat, and Madhya Pradesh emerge as major contributors, each offering substantial residue volumes capable of supporting biomass power projects Figure 52 [19]. Sugarcane, arhar, bajra, rapeseed mustard, and groundnut residues together strengthen the region's diversified biomass base.

This section presents the detailed assessment of 15 innovative cow dung-biomass fuel blends prepared using the most abundantly available biomass residues in India, i.e., rice, wheat, and maize residues, for their cofiring potential in coal-fired thermal power plants. A total of 15 fuel blends were prepared by combining rice residue, wheat residue, and maize residue with cow dung. For each type of agricultural residue, five blends were prepared by varying cow dung content from 10% to 50% (in increments of 10%), yielding five different proportions per residue type. To underscore their suitability for use as boiler fuel in thermal power plants, an in-depth proximate analysis, evaluation of gross calorific value, ultimate analysis, and ash fusion temperature analysis are performed.

Table 8: Annual Surplus Biomass Residue Available in India [19]

Annual Surplus Biomass Residue (kt) in India									
States	**Rice**	**Wheat**	**Maize**	**Sugarcane**	**Arhar/Tur**	**Bajra**	**Rapeseed Mustard**	**Groundnut**	**Total***
Andaman & Nicobar	3.3	--	0.2	--	--	--	--	--	131.7
Andhra Pradesh	2571	--	2389	394	195	31	1.5	194	17093
Arunachal Pradesh	14	2.8	20.2	0.5	--	--	--	--	173.8
Assam	650.58	8.71	42.5	14.12	9.92	--	172.29	--	2541
Bihar	1106.7	2019.2	1860.6	570.6	65.1	2.3	87.2	0.3	7983.9
Chandigarh	0.1	0.9	--	--	--	--	--	--	1.11
Chhattisgarh	2189.5	53.6	86.9	1	68.4	0.1	20.7	19.2	2651.8
Dadra & Nagar Haveli, and Daman &Diu	7.06	0.11	0.45	0.66	3.14	0.3	--	--	12.16
Goa	26.78	--	--	0.51	--	--	--	1.3	231.4
Gujarat	111.4	981	116.1	155.7	671.3	460.1	327.7	344	21740.3
Haryana	3002.7	2002.4	11.5	92.9	18.5	383.3	759.2	1.6	10907.5
Himachal Pradesh	28.3	184.5	291.8	0.5	--	--	3.2	--	572.2

Jammu & Kashmir	147.2	208	244.2	--	--	3.1	28.1	--	652.3
Jharkhand	347.9	68.1	346.5	--	240.3	--	47.7	--	1201.8
Karnataka	750.2	62.3	1876.2	1524.5	1498.4	93.6	0.5	222.3	14048.5
Kerala	175.9	--	--	0.1	2.7	--	--	0.2	6042.1
Madhya Pradesh	1940.8	6311.1	2152.3	46.9	909.2	249.7	584.3	151.3	19928.3
Maharashtra	43.1	609.6	38.9	858.4	--	299	3	108.4	21493.8
Manipur	352.1	2	27.1	2.3	1	--	21.2	1.3	484.9
Meghalaya	25.7	0.3	19.1	--	3	--	8.4	--	561.3
Mizoram	11.3	--	4.4	0.6	0.6	--	0.4	--	22.9
Nagaland	203.5	1.8	63.9	5.3	9.4	0.3	24.5	0.5	438.3
Odisha	2007.3	0.1	66.5	0.5	--	--	2.3	22.9	2227.6
Puducherry	12.9	--	--	2.5	0.7	--	--	0.4	37.8
Punjab	18786.3	3092.6	202.6	91.5	8.4	--	40.7	1.1	22251
Rajasthan	108.2	4121.8	25.3	6.4	16.9	1709.3	--	239.1	10211
Sikkim	0.2	0.1	31.5	--	--	--	--	--	40
Tamil Nadu	3086.2	--	2124	256.9	178	134.6	0.1	--	12217.4
Telangana	1368.7	4.8	2350.4	45.9	202	9.7	2.5	103.4	13761.6
Tripura	228.8	0.1	4.3	0.5	4.8	--	3.7	0.5	254.9
Uttar Pradesh	1035.2	13038.8	35.7	2211.8	778.7	465.7	875.9	42.2	21600.7
Uttarakhand	158.3	327.9	18.3	73.9	5.5	--	10.2	0.5	723.3

West Bengal	1225.2	269.7	756	20.4	8.1	--	616.5	88.7	16277.3
Total*	**41726.9**	**33372.5**	**15206.7**	**6379.1**	**4899.2**	**3842.2**	**3641.8**	**1543.1**	**228516.9**

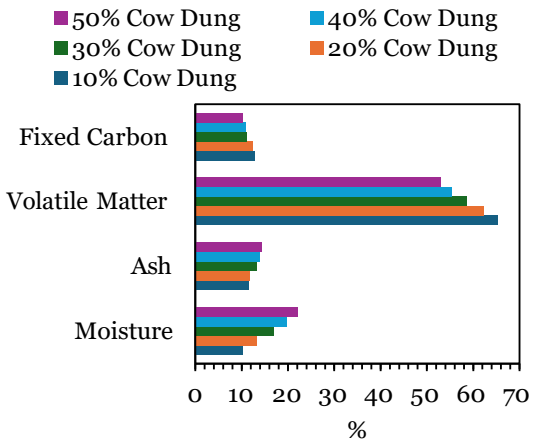
* Total includes a total of 38 crops.

6.1. Proximate Analysis and Gross Calorific Value

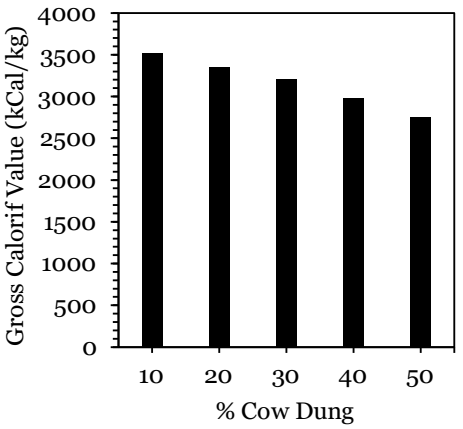
The proximate analysis of the prepared fuel blends is performed using the Thermo-gravimetric Analyzer (Make: Leco Corporation, USA, Model: Leco/701), while the evaluation of the gross calorific value is performed using the Bomb Calorimeter (Make: ARICO, India, Model: ARICO IP 1). The proximate analysis indicates the moisture, ash, volatile matter, and fixed carbon in the fuel blend.

Figure 53 represents the results of the proximate analysis and gross calorific values for the developed fuel blends. The various blends are prepared by mixing different proportions of cow dung (10-50%) in various agri-residues such as wheat, rice, and maize. The technical feasibility of the developed fuel blends for co-firing with coal in coal-fired power plants is evaluated based on the quality criteria established by NTPC Limited, India's largest coal-based power generation company. NTPC permits the use of biomass pellets for co-firing in its thermal power plants, subject to specific quality criteria. These include a gross calorific value (GCV) in the range of 2800–4000 kcal/kg and a moisture content below 14%. Figures 53 (a) and 53 (b) present the results of the proximate analysis and GCV evaluation of fuel blends composed of wheat residue and cow dung. The blend containing 10% cow dung in wheat residue exhibits a moisture content of 10.25%, while the blend with 20% cow dung in wheat residue shows a moisture content of 13.33%. The corresponding GCV values for these blends are 3515 kcal/kg and 3352 kcal/kg, respectively. Both blends satisfy NTPC's prescribed specifications for biomass co-firing, indicating their suitability as alternative fuel options in thermal power plants.

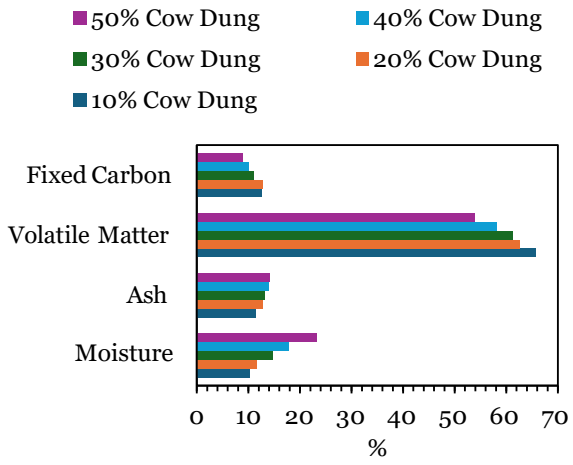
Figures 53(c) and 53(d) illustrate the results of the proximate analysis and gross calorific value (GCV) assessment for fuel blends prepared using rice residue and cow dung. It can be observed that the blends containing 10% and 20% cow dung in rice residue exhibit moisture contents of 10.18% and 11.67%, respectively. The corresponding GCV values are 3480 kcal/kg and 3341 kcal/kg. These results fall within the acceptable limits specified by NTPC, thereby confirming that the rice residue-cow dung blends are also suitable for co-firing applications in thermal power plants.



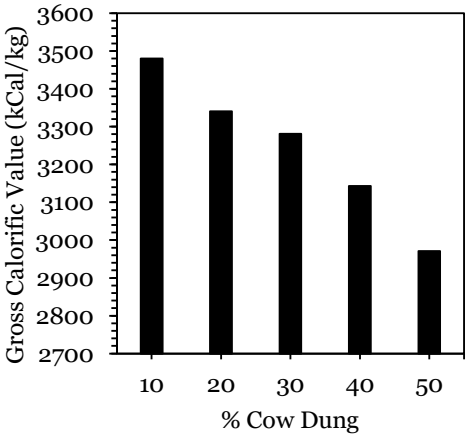
(a) Proximate analysis of wheat-cow dung fuel blend



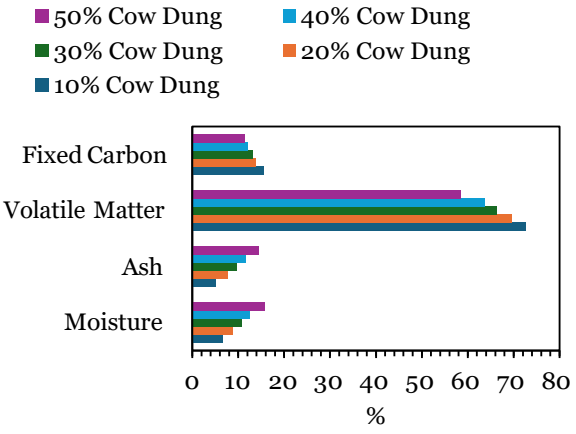
(b) Gross calorific value of wheat-cow dung fuel blend



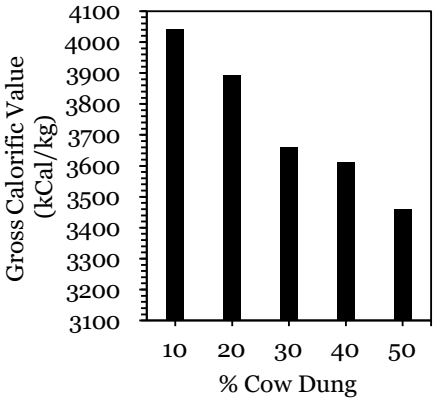
(c) Proximate analysis of rice-cow dung fuel blend



(d) Gross calorific value of rice-cow dung fuel blend

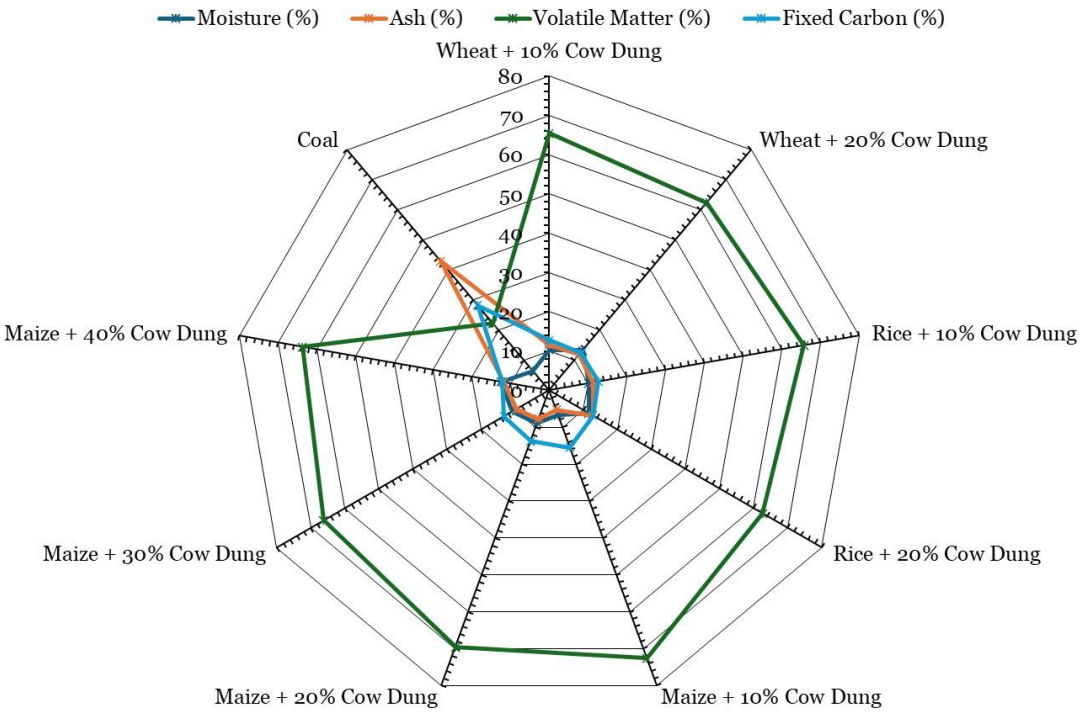


(e) Proximate analysis of maize-cow dung fuel blend

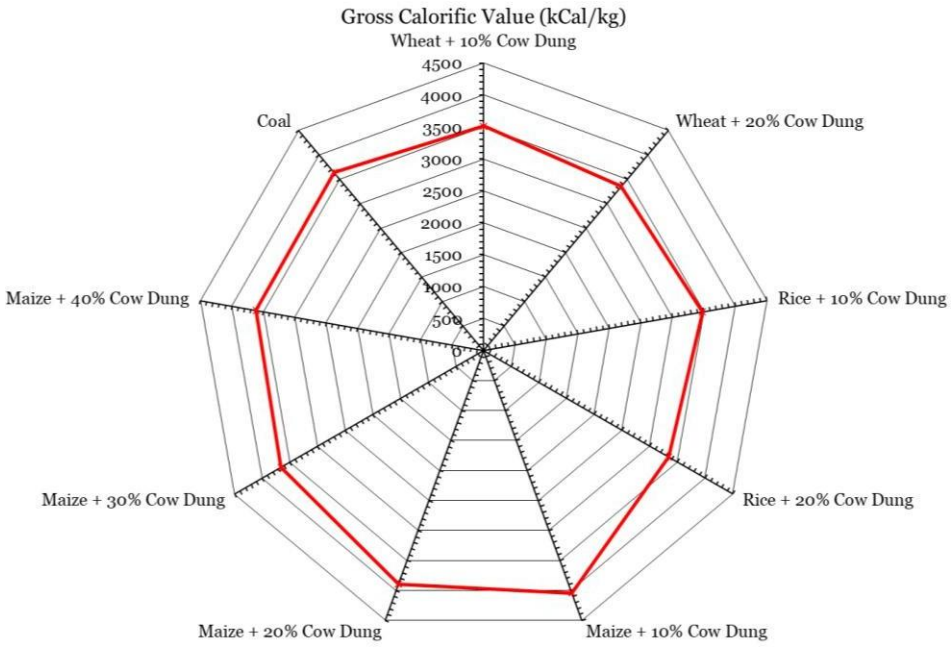


(f) Gross calorific value of maize-cow dung fuel blend

Figure 53: Proximate Analysis (a, c, e) and Gross Calorific Value (b, d, f) of the Developed Fuel Blends



(a)



(b)

Figure 54: Comparative Evaluation of the Developed Fuel Blend with Coal (a) Proximate Analysis (%) (b) Gross Calorific Value (kcal/kg)

In contrast to the other fuel blends, maize residue demonstrates a higher tolerance for blending with cow dung (as shown in Figures 53(e) and 53(f). The

moisture content of maize-cow dung blends is observed to be 6.73%, 8.9%, 10.8%, and 12.52% for 10%, 20%, 30%, and 40% cow dung incorporation, respectively. The corresponding gross calorific values (GCV) are 4042 kcal/kg, 3893 kcal/kg, 3660 kcal/kg, and 3612 kcal/kg. These values remain within the acceptable limits specified by NTPC, indicating that even at higher proportions of cow dung, maize-based blends are suitable for co-firing applications in thermal power plants. Figure 54 represents the comparative evaluation of the eight qualified fuel blends against thermal coal. It is evident from the figure that the developed fuel blends possess significantly lower ash content compared to coal, which can contribute to reduced loading on electrostatic precipitators (ESP) in power plants. Additionally, the fuel blends exhibit higher volatile matter content than coal. Elevated volatile matter enhances ignition characteristics and supports stable combustion; however, excessively high levels may alter flame behavior and combustion dynamics.

All the developed blends exhibit gross calorific values (GCV) that are comparable to coal. Notably, the maize-based blend with 10% cow dung shows a higher GCV (4042 kcal/kg) than coal, while blends containing 20-40% cow dung maintain values that are either similar to or exceed that of coal. This observation is particularly important, as biomass fuels often tend to lower the boiler's heat flux when co-fired with coal. In contrast, the maize-based blends demonstrate the ability to sustain, or even enhance, the energy input to the furnace, making them more effective for co-firing applications.

6.2. Ultimate Analysis

All qualified fuel blends are further examined through ultimate analysis to determine their elemental composition and to gain insights into their intrinsic properties compared to thermal coal. CHNS Analyzer (Vario Macro Cube) is used to determine the elemental composition of a material, specifically the percentage of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) present in fuel samples (Figure 55). The developed fuel blends exhibit a relatively higher hydrogen-to-carbon (H/C) ratio, which promotes faster flame propagation and improves combustion reactivity. In addition, co-firing these blends with coal has the potential to lower SO_2 emissions in power plants, contributing to a cleaner combustion process.

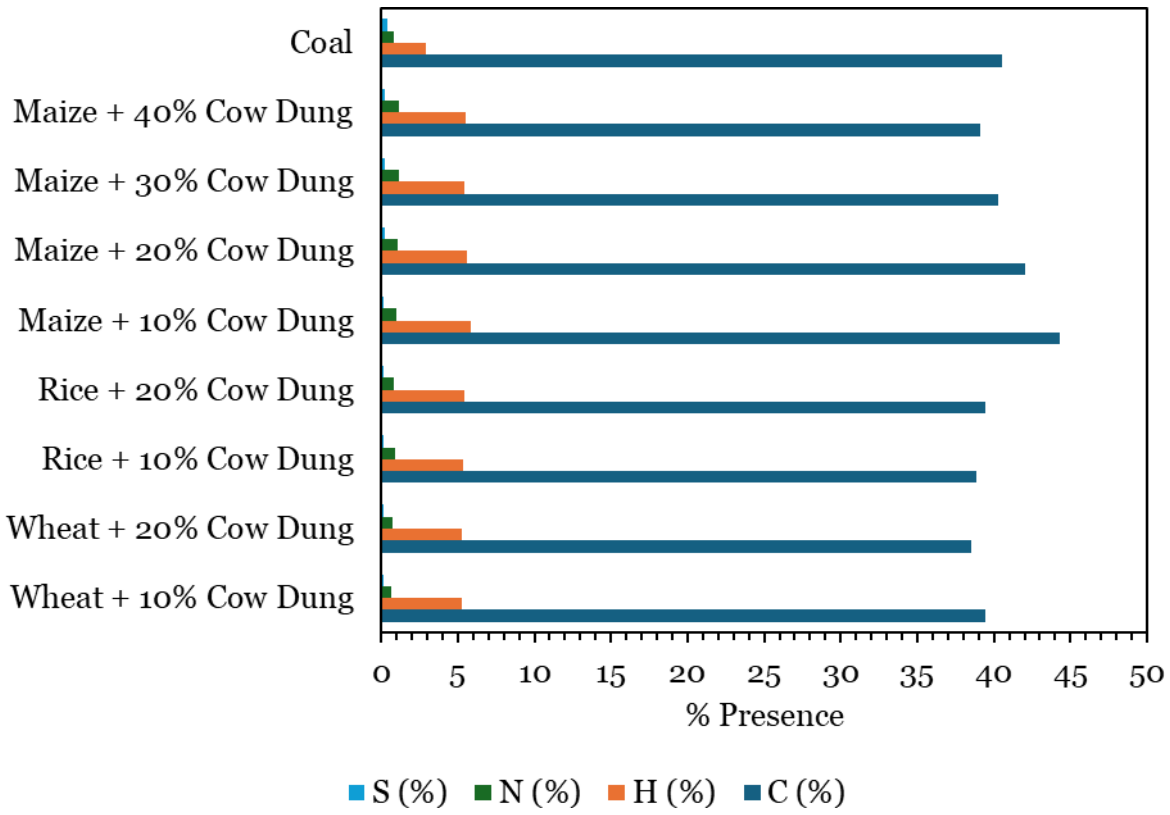


Figure 55: Ultimate Analysis of the Developed Fuel Blends and Their Comparative Evaluation with Coal

6.3. Ash Fusion Temperature Analysis

The Hesse EM301 Heating Microscope is used to further evaluate the ash fusion characteristics, including softening, deformation, melting, and flow (Figure 56). These characteristics are essential for evaluating slagging and fouling behavior of ash in boilers. Figure 4 shows the results of the ash fusion temperature analysis carried out for the developed fuel blends, along with a comparison to conventional thermal coal. The results indicate that biomass ash generally starts melting at a lower temperature (initial deformation temperature) than coal ash. However, during co-firing, biomass does not replace coal ash; instead, it mixes with it and effectively dilutes the overall ash composition.

At low co-firing ratios, the behavior of the combined ash is still largely controlled by coal, meaning the overall ash fusion temperature remains closer to that of coal rather than biomass. In a typical pulverized coal boiler, furnace gas temperatures range from about 1200 to 1500 °C, while wall temperatures lie between 900 and 1200 °C. Coal currently used in such systems is generally resistant to slagging due to its higher ash fusion temperature.

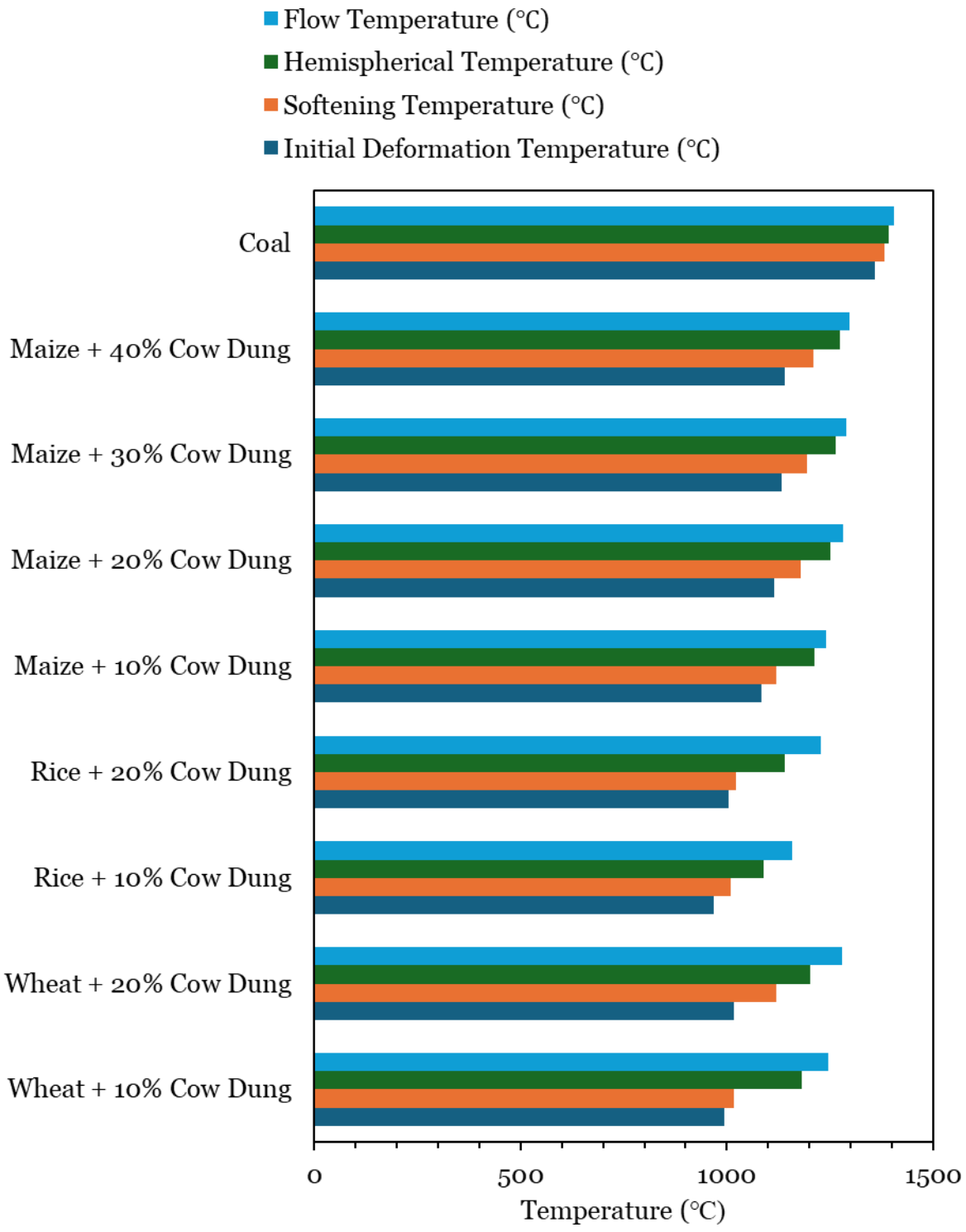


Figure 56: Ash Fusion Temperature Analysis of the Developed Fuel Blends and Their Comparative Evaluation with Coal

Slagging issues begin when the initial deformation temperature of ash falls below the wall temperature, and the risk becomes severe if the softening or hemispherical temperature drops below the furnace temperature. Since biomass ash

tends to have lower fusion temperatures, increasing its proportion in co-firing can reduce the overall ash fusion temperature of the mixture. This creates a higher risk of slag formation inside the boiler. Therefore, maintaining an appropriate co-firing limit is essential to ensure safe and efficient plant operation.

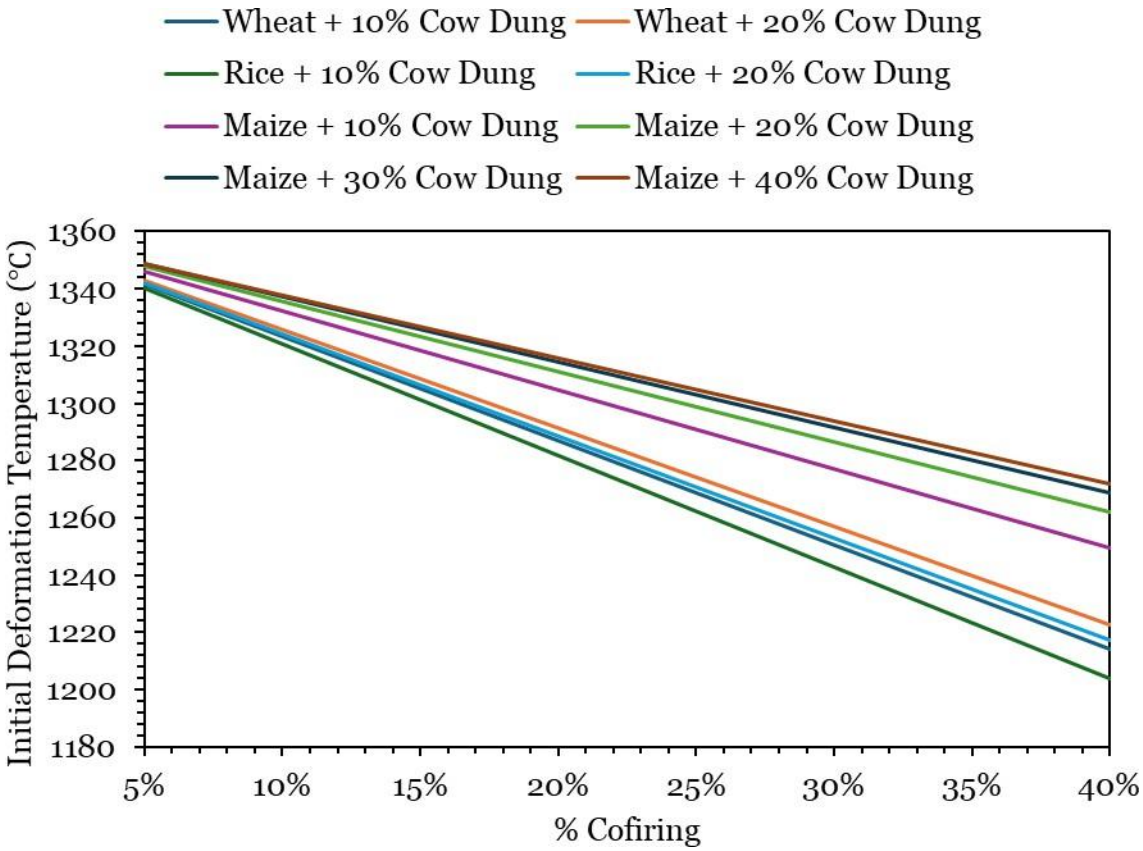


Figure 57: Estimation of the Initial Deformation Temperature of the Mixtures of Coal with Various Proportions of the Developed Fuel Blends

The study by Hu et al. has shown that at lower co-firing ratios, the ash initial deformation temperature of coal-biomass blends tends to decrease in a nearly linear manner with an increase in biomass proportion [20]. Building on this observation, further analysis was conducted to estimate the initial deformation temperature (IDT) of coal when mixed with the developed fuel blends in proportions ranging from 10% to 40%. As illustrated in Figure 57, the results suggest that the developed fuel blends can be co-fired with coal at levels up to 40% in thermal power plants without significant risks of slagging or fouling. However, it is important to note that these results are based on predictive analysis. To validate these observations under real

operating conditions, detailed experimental studies using actual coal-developed fuel blend mixtures are required.

7. Global Experiences and Regulatory Drivers of Biomass Co-Firing

Biomass co-firing has emerged as a transitional strategy to reduce coal dependency in both developed and developing economies. This section presents experiences from various countries worldwide that have adopted biomass cofiring in their coal-fired thermal power plants. A thorough discussion on their key regulatory drivers for promoting biomass cofiring practices is also included here.

7.1. North America

North America has abundant fossil fuel resources, and 40% of its electricity comes from natural gas, followed by 17 % from nuclear. Biofuel contributed 1 % of the total electricity produced in 2023 [21]. In North America, biomass co-firing deployment has been shaped by federal tax incentives, state and provincial-level renewable policies, and local biomass availability. As a result, biomass co-firing has developed unevenly, with activity concentrated in forestry-rich regions and at plants equipped with fuel-flexible boiler technologies.

7.1.1. United States of America

In 2023, 42.4% and 23%, respectively, of total electricity generated in the United States came from natural gas and renewable energy sources [22]. Electricity generated from coal accounted for 15.8% of total electricity generated in 2023. Of the total renewable energy generation, biomass and waste accounted for 1.3% of the electricity generated this year. Under its updated climate framework, the United States has committed to achieving a 50–52% reduction in greenhouse gas emissions by 2030 (compared to 2005 levels) and a 100% clean electricity grid by 2035 [23]. Within this strategy, coal-fired generation is expected to decline rapidly, driven by plant retirements and competition from low-cost natural gas and renewables. Co-firing has primarily been used to reduce emissions from existing coal assets in specific regions where biomass supply is abundant, and coal retirement timelines are extended.

At the central level, the Inflation Reduction Act (IRA) of 2022 is a key federal policy driver that extends and enhances Production Tax Credits (PTC) and Investment Tax Credits (ITC) for renewable electricity generation, including biomass power technologies [24]. In parallel, state-level Renewable Portfolio Standards (RPS) continue to play a critical role. Several US states recognise biomass as a qualifying renewable resource, allowing electricity generated from biomass or biomass co-firing to earn Renewable Energy Certificates (RECs) [25]. This fragmented but flexible policy landscape has resulted in regionally concentrated co-firing activity, rather than a nationally coordinated programme.

The most common method is direct co-firing in coal and fluidised bed boilers because it doesn't require much investment [26]. Biomass is used in small amounts (≤10%), and a few dedicated biomass plants are also established. The limited use of biomass is due to the low cost of natural gas and the focus on shutting down coal plants. It is making it harder for biomass to compete, even though plenty of wood and forest waste are available. Primarily, fluidised bed boilers are used in existing coal-based thermal power plants. It is reported that coal-fired boilers experience technical issues, such as fouling and slagging, when cofiring biomass.

7.2. South America

South America has one of the cleanest electricity generation mixes globally, dominated by hydropower, with growing contributions from wind, solar, and bioenergy [27]. Despite this relatively low-carbon profile, thermal power plants-primarily coal, oil, and gas-based-continue to play an important role in ensuring system reliability during hydrological variability, drought periods, and peak demand conditions. Within this context, biomass co-firing has emerged as a complementary and transitional decarbonisation option, particularly in countries with strong agricultural and forestry sectors. The region's comparative advantage lies in its abundant biomass resource base, including agricultural residues, forestry by-products, and agro-industrial waste streams. Biomass co-firing in South America is therefore driven less by coal phase-out imperatives and more by resource efficiency, waste management, rural economic development, and incremental emissions reduction from existing thermal assets.

South American nations have aligned their climate agendas with the Paris Agreement, collectively pursuing net-zero or carbon neutrality goals by 2050 through

the integration of bioenergy into their Nationally Determined Contributions (NDCs). These commitments prioritise low-cost mitigation pathways that utilise existing infrastructure, often supported by emerging market-based instruments like carbon pricing and credit mechanisms. Within this regional framework, biomass co-firing serves as a strategic supporting mechanism, designed to complement, rather than replace, established energy pillars such as hydropower, variable renewables, and the mature biofuels sector.

7.2.1. Brazil

Brazil stands out globally for having one of the cleanest electricity mixes, with renewables overwhelmingly shaping its energy profile. In 2023, Brazil's total electricity generation was 702 billion units, of which nearly 89% was from renewable energy sources. Electricity generated from coal accounted for 1.2% of total electricity in 2023. Biomass and waste contributed 58 BU, accounting for roughly 8.2% of Brazil's total power generation [22]. Brazil has committed to reducing net greenhouse gas emissions by 59-67% below 2005 levels by 2035 and to achieving long-term climate neutrality by 2050 [28]. Biomass co-firing in Brazil is positioned not as a core decarbonisation pillar, but as a complementary pathway to enhance resource efficiency, reduce emissions from existing thermal assets, and monetise agricultural and industrial residues.

A major evolution in Brazil's bioenergy governance came with the launch of RenovaBio, a national biofuel policy that introduces Decarbonisation Credits (CBIOs), one tradable credit for each metric ton of CO_2 equivalent emission reduction, linked to certified lifecycle greenhouse gas (GHG) emission reductions. RenovaBio aims to reduce the carbon intensity of fuels sold in Brazil by around 10% by 2030. While primarily targeted at transport fuels, RenovaBio has important spillover effects for the power sector by strengthening biomass certification, traceability, and sustainability assurance, which are increasingly relevant for biomass co-firing projects. A key feature of RenovaBio is its risk-based approach to land use change (LUC) and indirect land use change (ILUC). The programme enforces strict eligibility criteria of the prohibition of biomass sourcing from recently deforested land and mandatory traceability [29].

Brazil's approach to biomass co-firing is defined by project-specific experimentation rather than national mandates, focusing on regional integration where thermal plants are located near stable feedstock sources. Utilising a technology-

diverse framework, the country primarily employs direct co-firing in pulverised coal (PC) and Circulating Fluidised Bed (CFB) boilers, with the latter preferred for its ability to handle the high moisture and variable ash content of local agricultural residues. While pilot projects like Porto do Pecém have tested advanced indirect co-firing via gasification, the sector remains centred on domestic feedstocks such as sugarcane bagasse, rice husks, and woody biomass [30].

7.3. Australia

Australia's power generation mix is heavily reliant on coal-fired power generation. In 2023, Australia's power generation was 47.5% from coal, followed by 35.6% from renewable energy sources. Here, biomass and waste contributed only 1.1% of the total electricity generation mix [22]. It targets 62-70 % reduction in GHG below 2005 levels by 2035 [31]. Australia's renewable energy transition has been shaped by a combination of federal mechanisms, such as the Renewable Energy Target, and increasingly ambitious state-level clean energy and emissions-reduction policies. Although there is no biomass- or co-firing-specific national policy, biomass is recognised within broader renewable energy and waste-to-energy frameworks, and several states have introduced policies that indirectly enable co-firing trials by supporting renewable integration. Australia's biomass types were closely linked to its forestry and agricultural residues. Biomass co-firing adoption in Australia remains limited, with activity focused on feasibility studies, pilot assessments, and short-term trials, with no large-scale, long-term commercial co-firing programmes currently in operation. Deployment has focused primarily on direct co-firing at pulverised coal boilers, typically at low biomass shares below 5%, reflecting cautious operational strategies and a desire to minimise capital expenditure.

7.4. Africa

Africa's power generation mix is dominated by fossil fuels. Natural gas is the critical component in the power generation mix. In 2023, Africa's 42% power generation was from natural gas, and 25% power generation output from coal, while 2,431 GWh of power generation was through biofuel, which is 0.2% of total power generation in 2023 [32]. Africa has more than 1,900 TWh of underutilised biomass resources, including agricultural residues, agro-industrial waste, and forestry by-products [33]. Therefore, biomass co-firing is emerging here. Across the African continent, national energy and

climate strategies are increasingly recognising bioenergy as part of the clean energy transition, even though explicit biomass co-firing policies remain limited. Instead, co-firing is implicitly supported through broader renewable energy targets, power-sector decarbonisation strategies, and industrial waste-to-energy frameworks (IEA, 2023).

Africa's country has committed to reducing emissions and transitioning toward a cleaner energy mix under its Integrated Resource Plan (IRP) and updated NDC (IEA, 2024). Across Africa, biomass co-firing deployment remains small-scale and pilot-driven, with no large commercial programmes currently in operation. Typical biomass blending levels are low, generally in the range of 1–10 %, reflecting early-stage trials and conservative operational strategies. Direct co-firing is the predominant approach due to its lower capital requirements. Africa's biomass resource potential is substantial and largely derived from sugarcane bagasse, rice straw and husk, forestry residues, and agro-processing waste [30]. However, biomass supply chains remain fragmented and informal, limiting scalability and reliability. Key constraints include weak logistics networks, inconsistent fuel quality, and the lack of aggregation and preprocessing infrastructure. Addressing these challenges is essential for biomass co-firing to progress beyond pilot applications. Emerging solutions across the continent increasingly focus on capacity building, institutional strengthening, and innovative financing mechanisms.

7.5. Europe

Europe has a highly diversified power generation mix, with countries in the European region having varying mixes of fossil fuels, renewables, and nuclear energy. In 2023, the majority of the electricity was generated by renewable energy resources (44.3%), followed by 16.7% by natural gas and 11.6% by coal. Biomass contributed 4.8% of the total energy generation in 2023 [34]. Under the European Climate strategies and targets, the EU has set a goal to cut its net greenhouse gas emissions by at least 55 % by 2030 compared to 1990, and to achieve climate neutrality by 2050 [35]. To achieve these targets, the EU has reinforced various regulations such as the Industrial Emissions Directive and the Renewable Energy Directives. The EU member states have translated those target objectives into their national policies. Those national policies are implemented in the following ways:

- Support Schemes: Implementation of renewables obligations and feed-in schemes.
- Banded Support: Specific financial backing for "co-firing" (burning biomass alongside coal) and full plant conversions.
- Targeted Incentives: Subsidies aimed specifically at Combined Heat and Power (CHP) and biomass projects.

In addition to direct subsidies, the EU Emissions Trading System (ETS) and national carbon taxes have introduced a clear "emissions-price signal." By making carbon emissions more expensive, these policies have improved the economic viability of the entire biomass value chain compared to fossil fuels. These various layers of policy-combining EU directives, carbon trading (ETS), and national subsidies like Renewable Obligation Certificates (ROCs), Contracts for Difference (CFDs), or the Renewable Heat Incentive (RHI) work together toward a single goal. Collectively, they provide the financial security and regulatory clarity needed to convince businesses to invest in biomass co-firing and full power plant conversions. The majority of biomass cofiring and fully biomass converted plants are located in the United Kingdom (UK), Germany, and Italy, with notable activity also in Denmark, the Netherlands, and Finland.

7.5.1. United Kingdom

In 2023, the UK's total electricity generation was 268 BU, of which 50% was generated from renewable energy sources (1.3% from coal). In renewable energy generation, biomass and waste accounted for 34 BU (12.6% of total electricity generation). The UK's power plants that utilise biomass for electricity generation are either fully dependent on biomass or use a significant share of biomass alongside coal. The UK government has a Nationally Determined Contribution (NDC) target to reduce its greenhouse gas emissions by at least 81% by 2035 (base year 1990) and achieve net-zero emissions by 2050. Renewable Obligation (RO) and the current Contracts for Difference (CFD) schemes are the UK government's mechanisms for supporting the renewable energy sector [36]. The United Kingdom introduced the Renewables Obligation (RO) in 2002 to stimulate renewable electricity generation by awarding one tradable certificate for each megawatt-hour of eligible power produced. As technology costs and maturity diverged, the scheme adopted a banded structure in 2009, providing higher support for costlier or less developed options such as offshore wind and biomass, while mature technologies received lower support. Biomass co-firing and

conversion plants were differentiated by the proportion of biomass used, resulting in varied incentive levels. The RO closed to new entrants in 2017 and was largely replaced by the Contracts for Difference (CFD) scheme (which supports renewable generators by guaranteeing a fixed “strike price” for electricity; if market prices fall below this level, generators receive a top-up, and if prices rise above it, they pay back the difference), while existing accredited biomass plants continue to receive RO support under grandfathering provisions [37]. Most UK power plants have adopted biomass cofiring in their pulverized coal boilers, using a direct cofiring approach. The preferred biofuel for this purpose is wood pellets [30]. Cofiring is no longer a growing part of the UK's electricity mix. The UK is moving away from biomass co-firing toward dedicated biomass-based power generation, in line with its commitment to phase out coal-fired electricity generation.

7.5.2. Germany

Electricity generation from coal accounted for around 26% of total electricity generated in 2023, whereas electricity from renewable energy sources accounted for 54.5%, including 10.3% from biomass and waste [22]. Germany aims to cut emissions by at least 65 % by 2030, and 88 % by 2040 (base year 1990), and to reach net GHG neutrality by 2045 [38]. In Germany, the Renewable Energy Sources Act was enacted in 2000. In this act, renewable electricity had priority dispatch over conventional sources, and a specified feed-in-tariff was given to certain renewable energy generation technologies for investment, guaranteed for 20 years. There is no specific policy related to biomass and co-firing in Germany.

In Germany, biomass co-firing was generally involved in pulverised coal boiler-based power plants with a 5-20% share and was implemented using the direct co-firing method. Most biomass co-firing plants use sewage sludge, forest residues, and waste wood [39].

7.5.3. Italy

Italy generated 44.7% of its total electricity in 2023 using renewable energy resources (including 6.2% from biomass and waste), followed by 43.5% using natural gas and 7.4% using coal [22]. Italy is obligated to contribute to the EU's 2030 climate target of a 55% reduction in net GHG emissions compared to 1990 levels and carbon neutrality by 2050. In 2010, the National Renewable Energy Action Plan (NREAP) was

primarily a policy tool developed within the framework of the EU, which was adopted by Italy [40]. There is no existing policy specific to biomass cofiring. Most power stations that cofire biomass in pulverised coal boilers use a direct cofiring approach, with wood pellets serving as the main biomass fuel. In these plants, the biomass share typically falls within the range of 5–15%.

7.6. Asia

Asia is among the group of diversified fuel-to-energy producers. This is due to its diversified portfolio of primary energy production, including both fossil fuels and non-fossil fuels. Approximately 57% of Asia's electricity came from coal in 2023. Here, 2.2% of the total generated electricity came from biomass and waste [41]. Biomass co-firing in Asia is emerging as a practical pathway to decarbonise the region's extensive coal fleet, driven by national climate commitments and the growing need to utilise abundant agricultural and forestry residues.

7.6.1. Japan

In 2023, Japan's total electricity generation was 955 BU, while 244.6 BU (25.5%) was from renewable energy (6.4% from biomass and waste). Moreover, 29.4% the electricity generated by coal this year. Under revised national climate plans, Japan aims to achieve a 46% reduction in emissions by 2030 (base year 2013) and carbon neutrality by 2050. The Green Transformation (GX) policy framework guides Japan's thermal power phase-out by 2030. Within the (GX) policy framework, biomass co-firing is increasingly positioned as a short-term efficiency and decarbonisation tool, supporting coal phase-out strategies rather than extending coal plant lifetimes. Japan's future low-carbon power strategy is expected to prioritise a combination of renewable expansion, ammonia and hydrogen co-firing, and the potential development of Bioenergy with Carbon Capture and Storage (BECCS) [42]. Biomass co-firing in Japan is predominantly implemented through a direct co-firing approach in 1-15% cofiring ratios in the existing coal-based thermal power plants. The boiler configuration is largely based on pulverised coal steam boilers, reflecting Japan's existing thermal power infrastructure. Japan's heavy reliance on imported wood pellets and Palm Kernel Shells (PKS) from Indonesia and Malaysia has facilitated a rapid scale-up of biomass co-firing, yet this dependence on foreign feedstocks creates significant strategic vulnerabilities.

7.6.2. China

China has the world's largest coal-fired power fleet, and coal continues to dominate its electricity generation mix (59.3% of total electricity generation in 2023). Renewables contributed 31.5% (including 2.2% from biomass and waste) of the total electricity generation this year [22]. China has committed to progressively decarbonising its power sector as part of its broader climate strategy, which includes peaking carbon emissions before 2030 and advancing towards long-term carbon neutrality by 2060 [43]. Biomass co-firing in China is primarily guided by national planning instruments and sector-specific action plans rather than a standalone biomass policy. A major catalyst for the growth of biomass cofiring arrived in 2010 when the National Development and Reform Commission (NDRC) introduced a Feed-in Tariff (FiT) of 0.75 CNY/kWh, nearly doubling coal-fired rates and securing the financial viability of biomass supply chains. Subsequent policies, such as the 12th and 13th Five-Year Plans (2012-2016), refined the industry by promoting resource-specific deployment, distributed energy systems, and stricter environmental safeguards for emissions and ash handling [44]. Most recently, the 2021 Construction Work Plan reaffirmed this long-term commitment by allocating 2.5 billion RMB in subsidies, cementing biomass's role in China's national low-carbon transition and its ongoing integration into the power grid [45]. The National Action Plan for Low-Carbon Transformation of Coal Power (2024-2027), issued by the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA), explicitly identifies biomass co-firing as one of three recognised retrofit pathways for coal-fired power plants, alongside efficiency upgrades and fuel switching [46]. Under the 14th Five-Year Plan (2021-2025), China has set a quantitative target of up to 50 million tonnes per year of biomass co-fired by 2025, signalling strong policy intent to scale deployment. At the provincial level, additional incentives have been introduced to accelerate uptake. For example, Guangdong Province provides an extra feed-in tariff of RMB 0.25/kWh for eligible dedicated biomass power generation, indirectly supporting biomass supply chains relevant to co-firing applications.

The typical biomass co-firing share ranges between 5% and 15%. Higher co-firing ratios are being explored through pilot projects and parallel combustion systems [46]. China utilises a technology-agnostic strategy for biomass co-firing, primarily employing direct co-firing for its cost-efficiency, alongside indirect gasification and

parallel combustion systems that integrate into existing steam cycles. These configurations are versatile enough to be implemented across various infrastructures, ranging from high-efficiency ultra-supercritical and supercritical pulverised coal (PC) boilers to circulating fluidised bed (CFB) boilers. Notably, CFB technology is favoured for its superior fuel flexibility, allowing plants to effectively process heterogeneous and high-alkali biomass feedstocks that might otherwise challenge standard combustion systems.

By leveraging its vast agricultural and industrial residue base, China's biomass co-firing program utilises a diverse array of feedstocks, including straw, rice husks, wood pellets, refuse-derived fuel (RDF), and sludge, to maximise regional resource availability without competing with food production. While this strategy successfully integrates waste streams like peanut shells, torrefied biomass, and palm kernel shells, the wide variety of materials introduces technical complexities. Specifically, power plant operators must manage significant variations in fuel quality consistency, as well as heightened corrosion risks and unpredictable ash behaviour within the boilers.

7.6.3. Indonesia

In 2023, Indonesia's power sector generated a total of 383 BU, including 64.2% electricity generated using coal and 18% generated using renewable energy sources. The biomass and waste contributed approximately 6.7% of the total energy generated this year [22]. Indonesia's updated NDC commits to reducing greenhouse gas emissions by 31% unconditionally and 43% conditionally (depending on international support) by 2030 [47]. Within this framework, the power sector plays a central role due to its heavy reliance on coal. Biomass co-firing is positioned as a near-term decarbonisation pathway for coal-fired power plants, while enabling the utilisation of abundant domestic biomass residues. The Presidential Regulation No. 22 of 2017 (RUEN-General National Energy Plan) mandates renewable energy uptake and obligates electricity providers to procure power from biomass-based generation facilities. Presidential Regulation No. 112 of 2022 guarantees that electricity purchases from dedicated biomass power plants will be made at the highest benchmark tariff, significantly improving project bankability [48]. The formal target under current regulations is to achieve up to 10% biomass share in co-firing by 2025, although actual blending levels remain lower at most plants.

Indonesia operates one of the world's most extensive co-firing pilot portfolios, targeting 114 coal power plants for implementation to achieve rapid, low-cost emissions reductions. Currently in an early operational phase, the program primarily utilises direct co-firing with modest biomass blends of 1-5%, focusing on subcritical, supercritical, and circulating fluidised bed boilers that require minimal retrofitting [49]. By leveraging existing fuel handling systems to process local residues, such as rice husks, sawdust, palm kernel shells (PKS), and refuse-derived fuel (RDF), the state utility has prioritised immediate scalability over high-share conversion.

7.6.4. Thailand

Thailand relies heavily on fossil fuels-especially natural gas and oil, to meet its rising energy needs. In 2023, natural gas alone produced about 65.8% of the country's electricity, out of a total of 196 BU generated that year; renewable energy accounted for 35 BU (17.8%). Within the renewable energy mix category, biomass and waste contributed 20 BU, which represented approximately 10.2% of the country's total electricity generation [22]. Thailand has committed to achieving carbon neutrality by 2050 and net-zero greenhouse gas emissions by 2065 [50]. Within this framework, biomass co-firing is positioned as a short- to medium-term transitional solution, enabling emission reductions from existing coal plants.

Thailand's biomass co-firing efforts are primarily driven by its national decarbonisation strategy and the strategic role of the Electricity Generating Authority of Thailand (EGAT) in piloting low-carbon transition options for existing thermal assets. Thailand has adopted a cautious, pilot-led approach, focusing on technical validation and supply-chain feasibility rather than rapid scale-up. Biomass co-firing is supported under broader renewable energy and climate policies embedded within Thailand's Power Development Plan (PDP) and long-term energy transition framework [51]. Here, the adopted cofiring % is 2-5% with plans to scale up to 15% [52]. To minimise retrofit costs and operational disruptions in ageing assets, Thailand adopted a direct co-firing approach using pelletized or milled biomass [53]. Thailand primarily utilised wood pellets, including both standard and torrefied types. Although agricultural residues were available, their use was constrained by issues with quality, moisture, and logistics. This led to a partial dependence on imported pellets because domestic manufacturing capacity was not yet sufficient for utility-scale needs. Table 1 summarizes the current status of biomass cofiring across the globe.

Table 9: Status of Biomass Cofiring Across the Globe [26]

Country	Major Policies	GHG Reduction Target	Typical Biomass Share	Co-firing Approach	Boiler Configuration	Main Biomass Feedstocks	Remarks
Australia	Renewable Energy Target	62-70 % below 2005 levels by 2035	≤5%	Direct	Pulverised coal boilers	Agri-residue	Adoption of cofiring is limited, with activity focused on feasibility studies, pilot assessments, and short-term trials only
Brazil	RenovaBio	59-67% below 2005 levels by 2035, and to achieve long-term climate neutrality by 2050	≤10% (energy basis)	Direct	Pulverised coal and circulating fluidised bed boilers	Sugarcane bagasse, rice husks, and woody biomass	Brazil's approach to co-firing is defined by project-specific experimentation, focusing on thermal plants

							that are located near stable feedstock sources.
China	National Action Plan for Low-Carbon Transformation of Coal Power (2024-2027), Enterprise Income Tax Incentives (2007), Feed-in Tariff (FiT), Five-Year Plans	Carbon neutrality by 2060	5-15%	Direct and Indirect	Pulverised coal (PC) boilers, circulating fluidised bed (CFB) boilers	Straw, rice husks, wood pellets, refuse-derived fuel (RDF), and like peanut shells, torrefied biomass, and palm kernel shells, sludge	Implementation of biomass-specific targets and schemes.
Denmark	Renewable Energy Act and Public Service	20% reduction from 2005 levels by 2020	5–100% (up to full biomass	Direct and indirect	Pulverized coal combustion and fluidized bed combustion	Straw, waste wood, chips, and pellets	High import dependence remains a concern.

	Obligation (PSO)		in parallel units)				
Germany	Renewable Energy Sources Act (EEG) and Electricity Feed-In Act	88 % by 2040 (base year 1990), and to reach net GHG neutrality by 2045	5–20% (energy basis)	Direct	Pulverized coal boiler	Straw, sewage sludge, waste biomass, organic residues	Policy direction now favors using waste-based biomass over dedicated energy crops.
Indonesia	Presidential Regulations for the promotion of renewable energy and biomass (RUEN General National Energy Plan)	By 31% unconditionally and 43% conditionally (depending on international support) by 2030	1-5%	Direct	Pulverised coal boilers, circulating fluidised bed boilers	Rice husks, sawdust, palm kernel shells (PKS), and refuse-derived fuel	World's most extensive co-firing pilot portfolios, targeting 114 coal power plants, dedicated biomass cofiring targets.
Italy	National Renewable	55% reduction to 1990 levels by 2030 and	5-15%	Direct	Pulverised coal boilers	Wood pellets	Limited adoption of biomass

	Energy Action Plan (NREAP)	carbon neutrality by 2050					
Japan	Green Transformation (GX) policy framework	46% reduction in emissions by 2030 (base year 2013) and carbon neutrality by 2050	1-15% (mass basis)	Direct	Pulverized coal combustion and fluidized bed combustion	Wood pellets and palm kernel shells	Cofiring is positioned as a short-term decarbonisation tool, supporting coal phase-out strategies rather than extending coal plant lifetimes.
Netherlands	National Energy Accord	30% from 1990 levels by 2030	5–34% of fuel input	Direct and indirect blending	Pulverized coal combustion and fluidized bed combustion	Imported wood pellets, palm kernel shells, cocoa, and wood waste	Declining subsidies and high import costs are limiting growth; long-term operation may shift fully to

							biomass-based units.
Thailand	Thailand's Power Development Plan (PDP)	Carbon neutrality by 2050 and net-zero greenhouse gas emissions by 2065	2-5%	Direct	Pulverised coal boilers	Torrefied and torrefied wood pellets	Adopted a cautious, pilot-led approach, focusing on technical validation and supply-chain feasibility rather than rapid scale-up.
United Kingdom	Renewable Obligation (banded certificates) and the current Contracts for Difference (CFD) schemes	81% by 2035 (base year 1990) and achieve net-zero emissions by 2050	Dedicated biomass plants	Direct	Pulverized coal combustion	Wood pellets, miscanthus, short-rotation coppice, olive/palm residues	Moving away from biomass co-firing toward dedicated biomass-based power generation, in line with its commitment to

							phase out coal-fired electricity generation.
United States	Inflation Reduction Act 2022, Renewable Energy Certificates	50–52% reduction by 2030 (compared to 2005 levels) and a 100% clean electricity grid by 2035	≤10% (energy basis)	Direct	Pulverized coal and fluidized bed	Sawdust, wood pellets, chips, and other forest waste	The limited use of biomass is due to the low cost of natural gas and the focus on shutting down coal plants.

8. Conclusions and Recommendations

Biomass co-firing emerges as a promising pathway for cleaner energy generation while delivering tangible, though uneven, socio-economic benefits across the value chain. At the farm level, the transition has contributed to a visible decline in stubble burning, with a large majority of farmers reporting associated health improvements, alongside emerging income opportunities. However, participation remains constrained by structural challenges: a significant proportion of farmers continue to bear the cost of residue management, limited access to timely government incentives, low awareness of biomass markets, and the absence of assured pricing mechanisms such as a minimum support price. The continued reliance on informal uses of crop residue, coupled with time constraints between cropping cycles and the lack of locally accessible collection infrastructure, further limits market integration. At the same time, monetizing cow dung presents an opportunity to reduce its traditional use as cooking fuel, thereby lowering household air pollution and improving women's health outcomes. Across the downstream value chain, aggregators, processors, and transporters are benefiting from growing institutional demand, yet operational inefficiencies persist, including inadequate storage infrastructure, seasonal supply disruptions (particularly during monsoons), feedstock variability, and payment delays. The workforce is largely composed of unskilled and semi-skilled labor, while women's participation remains minimal and largely confined to administrative roles. Occupational health concerns, especially dust exposure in processing units, continue to pose risks, highlighting the need for improved safety measures. From a broader systems perspective, the biomass sector aligns strongly with the vision of energy self-reliance, as it is largely supported by domestically manufactured machinery and localized supply chains, unlike other renewable technologies such as solar and wind with higher import dependence. Technically, biomass and cow dung blends meet co-firing requirements, with evidence supporting safe and efficient co-firing at substantial blending ratios without significant operational risks, while also creating opportunities to enhance rural incomes and reduce household air pollution.

A global review indicates that biomass co-firing practices across regions are generally characterized by low to moderate blending ratios, predominantly through direct co-firing in pulverized coal boilers, supported by policy-driven incentives and region-specific feedstock utilization strategies. These experiences underscore the

importance of stable policy support, robust supply chains, and phased implementation for scaling up co-firing initiatives. Building on these findings, the following section outlines targeted and actionable policy recommendations.

i. **Region-Specific Co-firing Targets**: Biomass co-firing targets can be tailored based on the availability of biomass. Plants located near areas with abundant surplus biomass could adopt higher blending levels (15–20%), while targets for other regions could increase gradually, taking into account the year-round availability of biomass, seasonal variations, and logistical considerations.

ii. **Promoting Long-Term, Capacity-Based Agreements with Biomass Suppliers**: Long-term agreements of 5–10 years between power producers and biomass pellet suppliers could be promoted to enhance price stability and provide greater investment security throughout the supply chain. Contracts could be structured based on the capacity of individual biomass supplier plants rather than applying uniform terms to all suppliers, ensuring a fair and efficient allocation of resources

iii. **Doubling Farmers' Income by Enhancing Participation in Biomass Supply Chains:** A village-level biomass aggregation system, integrated with farmer-producer organizations (FPOs) and supported by awareness programs, could be developed to improve farmer participation and increase residue collection efficiency. A biomass floor price mechanism (MSP) could be introduced to provide stable additional income streams, supporting the goal of ***Doubling Farmers' Income*** while ensuring a reliable supply to power producers.

iv. **Promoting Women's Participation in Biomass Supply Chains through Skill India:** Women's participation in biomass supply chains could be strengthened through targeted skill development under the ***Skill India Mission***, with training programs facilitated by ***National Skill Training Institutes***. Access to gender-inclusive financing and support for women-led biomass enterprises can further expand livelihood opportunities and enhance supply chain efficiency.

v. **Strengthening Biomass Storage through Farmers Producers Organization's Infrastructure:** Reliable biomass supply, especially during the monsoon season, could be supported through decentralized, weather-

resilient storage systems by leveraging existing FPO warehouse infrastructure and standardized storage practices. Additionally, dedicated biomass storage facilities at plant sites could be developed to maintain sufficient pellet reserves, ensuring uninterrupted co-firing operations in power plants.

vi. **Promoting Cow Dung-Biomass Fuel Blends for Co-Firing:** Co-firing with cow dung-biomass blends can be implemented using 10-20% cow dung in rice and wheat residues and 10-40% cow dung in maize residues, allowing up to 40% co-firing with coal without causing fouling, slagging, or operational issues. This approach also provides opportunities to increase farmer income and reduce household air pollution from traditional cow dung use.

vii. **Streamlining Biomass Procurement and Logistics Management:** Administrative barriers in biomass procurement could be reduced through simplified procedures and mandatory time-bound payment systems, while improved handling practices and rationalized quality parameters (such as GCV, moisture content, and fines) could help balance plant performance with supply chain feasibility. Additionally, AI/ML-enabled, app-based truck scheduling and queue management systems could optimize biomass delivery coordination, reduce congestion and waiting times at plant sites.

viii. **Strengthening Occupational Health and Dust Exposure Management Across the Biomass Supply Chain:** High levels of dust exposure at biomass processing units and plant handling sites pose significant health risks to shredding workers, pellet handlers, and transport personnel. This can be addressed by providing appropriate personal protective equipment, such as masks, and implementing regular health monitoring programs. Additionally, targeted training on safe handling practices can help reduce exposure, improve worker well-being, and enhance overall productivity across the supply chain.

ix. **Linking Biomass Co-Firing with Carbon Credit Trading Scheme (CCTS):** A carbon credit framework for biomass co-firing can be integrated into India's emerging Carbon Credit Trading Scheme (CCTS), enabling power plants to generate tradable carbon certificates from verified emission reductions. These credits can support hard-to-abate sectors in meeting domestic emission intensity targets.

x. **Promoting Biomass for Energy Security and Reducing Critical Mineral Dependency:** Biomass utilization across power plants and industries could be promoted as a strategic pathway to enhance energy security and self-reliance. Unlike certain renewable energy technologies (Solar Photovoltaic technology) that rely heavily on imported critical minerals, biomass leverages domestically available resources and technologies, reducing import dependency. This approach can strengthen local manufacturing ecosystems, diversify fuel sources, and support a reliable and resilient energy supply.

9. Future Scope

Future research can be directed toward three key areas to strengthen and scale the present work. First, an expanded assessment covering states such as Punjab, Gujarat, Uttar Pradesh, Madhya Pradesh, and Rajasthan can be undertaken using the BLEND framework to evaluate socioeconomic and environmental impacts, enabling the development of national-level policy recommendations. Second, a similar framework-based approach can be applied to systematically assess the municipal solid waste (MSW) supply chain, providing deeper insights into its integration with thermal power plants. Third, detailed technical investigations involving characterization of developed fuel blends, along with ash fusion behavior studies through blending with coal in varying proportions, can be conducted to evaluate real-time feasibility, combustion performance, and operational compatibility in thermal power plants. These efforts can ultimately contribute to formulating evidence-based policy recommendations and facilitating the large-scale adoption of biomass and MSW co-firing in India's thermal power sector.

10. References

[1] "Unlocking India's bioenergy potential." https://www.iea.org/commentaries/unlocking-indias-bioenergy-potential.

[2] "National Bio-Energy Programme, Ministry of New and Renewable Energy." https://mnre.gov.in/en/bio-energy-overview/.

[3] "Biomass Programme, Ministry of New and Renewable Energy." https://mnre.gov.in/en/bio-mass/ (accessed Apr. 17, 2026).

[4] "SAMARTH Mission." https://samarth.powermin.gov.in/.

[5] "Management of Crop Residue, Press Information Bureau." https://www.pib.gov.in/PressReleseDetailm.aspx?PRID=2068477&reg=3&lang=2 (accessed Apr. 17, 2026).

[6] "Sub-Mission on Agricultural Mechanization (SMAM), Haryana." https://agriharyana.gov.in/MechCRMScheme (accessed Apr. 17, 2026).

[7] "Mitigate crop residue burning, Parliament Question." https://www.pib.gov.in/PressReleasePage.aspx?PRID=2240644&reg=3&lang=2 (accessed Apr. 17, 2026).

[8] "NTPC Annual Report."

[9] W. Mo, K. Du, Y. Sun, M. Guo, C. Zhou, M. You, J. Xu, L. Jiang, Y. Wang, S. Su, S. Hu, and J. Xiang, "Technical-economic-environmental analysis of biomass direct and indirect co-firing in pulverized coal boiler in China," *Journal of Cleaner Production*, vol. 426, Nov. 2023, doi: 10.1016/j.jclepro.2023.139119.

[10] Y. Xu, K. Yang, J. Zhou, and G. Zhao, "Coal-biomass co-firing power generation technology: Current status, challenges and policy implications," *Sustainability (Switzerland)*, vol. 12, no. 9, May 2020, doi: 10.3390/su12093692.

[11] "Haryana sees drop in farm fires, but still breathes hazardou .. Read more at: http://timesofindia.indiatimes.com/articleshow/125281080.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst." https://timesofindia.indiatimes.com/city/chandigarh/haryana-sees-drop-in-farm-fires-but-still-breathes-hazardous-air/articleshow/125281080.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst (accessed Apr. 23, 2026).

[12] M. R. Shaibur, H. Husain, and S. H. Arpon, "Utilization of cow dung residues of biogas plant for sustainable development of a rural community," *Current Research in Environmental Sustainability*, vol. 3, p. 100026, 2021, doi: 10.1016/j.crsust.2021.100026.

[13] S. Rodrigues, “The Indian Cow Dung: A potential billion-dollar gold mine in organic fertiliser market.” https://incubees.com/the-indian-cow-dung-a-potential-billion-dollar-gold-mine-in-organic-fertiliser-market/ (accessed Mar. 02, 2026).

[14] P. C. Roy, A. Datta, and N. Chakraborty, “Assessment of cow dung as a supplementary fuel in a downdraft biomass gasifier,” *Renewable Energy*, vol. 35, no. 2, pp. 379–386, Feb. 2010, doi: 10.1016/j.renene.2009.03.022.

[15] A. Gill-Wiehl, I. Ray, and D. Kammen, “Is clean cooking affordable? A review,” *Renewable and Sustainable Energy Reviews*, vol. 151, no. July, p. 111537, 2021, doi: 10.1016/j.rser.2021.111537.

[16] “Lok Sabha Question No. 2774, Biogas Plants in India.” Accessed: Mar. 03, 2026. [Online]. Available: https://sansad.in/ls/hi/questions/questions-and-answers.

[17] G. Anwar, Z. Iqbal, H. Ullah, W. Zulfiqar, M. M. Gulzar, and E. A. Al-Ammar, “Strain modulated physical properties of double perovskite Rb2InGaCl6 for the possible energy applications,” *Physica B: Condensed Matter*, vol. 701, no. January, p. 416975, 2025, doi: 10.1016/j.physb.2025.416975.

[18] M. Wzorek, R. Junga, E. Yilmaz, and P. Niemiec, “Combustion behavior and mechanical properties of pellets derived from blends of animal manure and lignocellulosic biomass,” *Journal of Environmental Management*, vol. 290, no. March, 2021, doi: 10.1016/j.jenvman.2021.112487.

[19] “National Biomass Atlas of India, Sardar Swaran Singh National Institute Of Bio-Energy.” https://nibe.res.in/english/biomass-atlas.php (accessed Mar. 03, 2026).

[20] Y. Hu, B. Peng, S. Cao, Z. Hou, S. Wang, and Z. Ge, “Multistage Reaction Characteristics and Ash Mineral Evolution in Coal–Biomass Co-Combustion Process,” *Energies*, vol. 18, no. 18, Sep. 2025, doi: 10.3390/en18185023.

[21] “Energy system of North America.” https://www.iea.org/regions/north-america (accessed Jan. 27, 2026).

[22] “U. S. Energy Information Administration.” https://www.eia.gov/international/data/world/electricity/electricity-generation (accessed Jan. 28, 2026).

[23] “The United States of America NDC to Reduce GRH Emissions.” Accessed: Jan. 28, 2026. [Online]. Available: https://unfccc.int/.

[24] “INFLATION REDUCTION ACT OF 2022.” https://www.energy.gov/edf/inflation-reduction-act-2022#:~:text=The%20President’s%20Inflation%20Reduction%20Act,net%2Dzero%20economy%20by%202050. (accessed Jan. 28, 2026).

[25] N. Rader and S. Hempling, “The Renewables Portfolio Standard: A Practical Guide,” 2001. Accessed: Jan. 28, 2026. [Online]. Available: www.energy.gov.

[26] M. S. Roni, S. Chowdhury, S. Mamun, M. Marufuzzaman, W. Lein, and S. Johnson, “Biomass co-firing technology with policies, challenges, and opportunities: A global review,” *Renewable and Sustainable Energy Reviews*, vol. 78. Elsevier Ltd, pp. 1089–1101, 2017, doi: 10.1016/j.rser.2017.05.023.

[27] T. International Renewable Energy Agency, *Regional energy transition outlook: South America*. 2025.

[28] “BRAZIL’S NDC National determination to contribute and transform.” Accessed: Jan. 28, 2026. [Online]. Available: https://climateactiontracker.org/countries/brazil/2035-ndc/#:~:text=Brazil%20submitted%20its%202035%20NDC,international%20transfer%20of%20mitigation%20results.

[29] “Implementation of bioenergy in Brazil_RENOVA_Brazil.” Accessed: Jan. 28, 2026. [Online]. Available: https://www.iea.org/energy-system/renewables/bioenergy.

[30] M. S. Roni, S. Chowdhury, S. Mamun, M. Marufuzzaman, W. Lein, and S. Johnson, “Biomass co-firing technology with policies, challenges, and opportunities: A global review,” *Renewable and Sustainable Energy Reviews*, vol. 78, no. May, pp. 1089–1101, 2017, doi: 10.1016/j.rser.2017.05.023.

[31] “International climate action for Australia.” https://www.dcceew.gov.au/climate-change/international-climate-action (accessed Jan. 30, 2026).

[32] “Energy Mix of Africa by IEA.” https://www.iea.org/regions/africa/electricity (accessed Jan. 28, 2026).

[33] T. N. O. Mensah, A. S. Oyewo, D. Bogdanov, A. Aghahosseini, and C. Breyer, “Pathway for a fully renewable power sector of Africa by 2050: Emphasising on flexible generation from biomass,” *Renewable Energy*, vol. 234, Nov. 2024, doi: 10.1016/j.renene.2024.121198.

[34] “Electricity and heat statistics Statistics Explained.” Accessed: Jan. 30, 2026. [Online]. Available: https://ec.europa.eu/eurostat/.

[35] “Climate Targets of European Union.” https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2030-climate-targets_en (accessed Jan. 28, 2026).

[36] “Renewables Obligation: Guidance for Generators.” https://www.ofgem.gov.uk/guidance/renewables-obligation-guidance-generators (accessed Jan. 28, 2026).

[37] "Contracts for Difference." https://www.gov.uk/government/collections/contracts-for-difference (accessed Jan. 28, 2026).

[38] "Germany's greenhouse gas emissions and energy transition targets." https://www.cleanenergywire.org/factsheets/germanys-greenhouse-gas-emissions-and-climate-targets#:~:text=Germany's%20national%20climate%20targets,aims%20for%20net%2Dnegative%20emissions (accessed Jan. 28, 2026).

[39] A. Lüschen and R. Madlener, "Economic viability of biomass cofiring in new hard-coal power plants in Germany," *Biomass and Bioenergy*, vol. 57, pp. 33–47, Oct. 2013, doi: 10.1016/j.biombioe.2012.11.017.

[40] N. Scarlat, J. F. Dallemand, V. Motola, and F. Monforti-Ferrario, "Bioenergy production and use in Italy: Recent developments, perspectives and potential," *Renewable Energy*, vol. 57, pp. 448–461, Sep. 2013, doi: 10.1016/j.renene.2013.01.014.

[41] "Energy Statistics of Asia Pacific by International Energy Agency (IEA)." https://www.iea.org/regions/asia-pacific/renewables (accessed Jan. 28, 2026).

[42] "GX (Green Transformation) Basic Policy and Roadmap." https://japan.influencemap.org/policy/GX-Green-Transformation-5477 (accessed Jan. 28, 2026).

[43] J. He, Z. Li, X. Zhang, *et al.*, "Towards carbon neutrality: A study on China's long-term low-carbon transition pathways and strategies," *Environmental Science and Ecotechnology*, vol. 9, Jan. 2022, doi: 10.1016/j.ese.2021.100134.

[44] H. Guo, J. Cui, and J. Li, "Biomass power generation in China: Status, policies and recommendations," *Energy Reports*, vol. 8, pp. 687–696, Nov. 2022, doi: 10.1016/j.egyr.2022.08.072.

[45] "National Development and Reform Commission, Ministry of Finance, National Energy Administration: 2021 Biomass Power Generation Project Construction Work Program." https://www.iea.org/policies/14306-national-development-and-reform-commission-ministry-of-finance-national-energy-administration-2021-biomass-power-generation-project-construction-work-program (accessed Jan. 28, 2026).

[46] S. Wang, H. Yin, and C. Yin, "'Promoting biomass co-firing in coal power plants'--The new policy will reshape the landscape of bioenergy industry in China," *Energy Strategy Reviews*, vol. 59. Elsevier Ltd, May 01, 2025, doi: 10.1016/j.esr.2025.101714.

[47] "Second Nationally Determined Contribution Republic of Indonesia." Accessed: Jan. 28, 2026. [Online]. Available: www.unfccc.in.

[48] "Co-firing with biomass in Indonesia: Debunking Emission Reduction Claims." https://environmentalpaper.org/2023/11/co-firing-with-biomass-in-indonesia-debunking-emission-reduction-claims/ (accessed Jan. 28, 2026).

[49] "Putra Adhiguna, Energy Analyst Indonesia's Biomass Cofiring Bet Beware of the Implementation Risks," 2021. Accessed: Jan. 28, 2026. [Online]. Available: https://ieefa.org/resources/indonesias-biomass-cofiring-bet-beware-implementation-risks.

[50] "Thailand's Long-Term Low Greenhouse Gas Emission Development Strategy (Revised version)." https://unfccc.int/documents/622276 (accessed Jan. 28, 2026).

[51] "Thailand: Turning Point for a Net-Zero Power Grid," 2025.

[52] I. Energy Agency, "Thailand's Clean Electricity Transition How accelerated deployment of renewables can help achieve Thailand's climate targets." [Online]. Available: www.iea.org.

[53] "Biomass-and-Coal-Co-combustion-ASEAN-Phase-2," Accessed: Jan. 28, 2026. [Online]. Available: www.eria.org.

11. Annexures

Table A1: Coal-based power capacity of NTPC and its joint ventures (JVs)

Particulars	Capacity (MW)	No of Stations
NTPC - Coal Standalone Capacity	53850	27
NTPC JV+Subs Coal capacity (Without Captive)	7080	7
NTPC JV+Subs Coal capacity (Captive)	604	3
NTPC JV+Subs Coal Total capacity	7684	10
NTPC Coal group without captive	61534	34
NTPC Coal group with captive	62138	37

Table A2: Key characteristics of NTPC's thermal power plants

Types of Plants	P (MPa)	T (℃)	Overall Efficiency (%)	Capacity of a Unit of BTG (MW)
Subcritical	<22.6	540	35-38 (500 MW), 32-35 (200 MW)	200, 500
Super-Critical	>22.6	540-580	39-41	660, 800
Ultra-supercritical	>25	>600	41-42	800

Table A3: Cofiring at NTPCs' thermal power plants and joint ventures

Stations/ Years	2019-20	2020-21	2021-22	2022-23	2023-24	2024-25		2025-26 (Till June 30, 2025)	
	Received Quantity (MT)	Received Quantity (MT)	Received Quantity (MT)	Received Quantity (MT)	Received Quantity (MT)	Received Quantity (MT)	% Cofiring	Received Quantity (MT)	% Cofiring
Jhajjar			263	8,451	96,536	2,27,392	3.73%	99,489	6.13%
Dadri	3,903	9,733	6,382	574	36,596	2,74,677	3.84%	86,277	4.57%
Khargone			4,197	4,403	20,586	54,615	1.04%	42,170	2.63%
Mouda		7,738	13,317	2,578	4,981	71,129	0.72%	54,706	1.81%
Gadarwara			343	1,936	6,804	32,731	0.56%	22,474	1.26%
Tanda		177	2,138	1,490	197	28,213	0.39%	23,826	1.01%
Solapur		977	2,083			7,502	0.15%	6,496	0.50%
Sipat			206	3,646		5,880	0.04%	13,853	0.33%
Unchahar		4,723	4,609	154			0.00%	6,715	0.31%
Korba						449	0.00%	10,374	0.24%
Vindhyachal						852	0.01%	13,284	0.19%
Rihand							0.04%	2,910	0.07%
Singrauli							0.00%	2,071	0.07%

Lara			374	138		23	0.00%	1,423	0.06%
NSPCL ROURKELLA							0.00%	352	0.01%
Simhadri		137	3,950	480			0.00%		
NSPCL Bhilai							0.00%	8,536	
Farakka			77				0.00%		
Kudgi		904	1,009				0.00%		
Kahalgaon			4	6			0.00%		

Table A4: Upcoming NTPC's power plants to adopt biomass co-firing

Station	Initiation in Financial Years		
	2025-26	2026-27	2027-28
Bongaigaon	✓		
Barauni	✓		
Barh	✓		
North Kanpura	✓		
Nabinagar	✓		
Darlipalli	✓		
Talcher	✓		
Ramagundam	✓		
Telangana	✓		
Kanti	✓		
Meja	✓		
NSPCL			
Vallur		✓	
Patratu		✓	
Jhabua			✓

Table A5: Characterization of biomass accepted for cofiring at NTPC's thermal power plants

Parameters	Values
Base Materials	Agro-residue Pellets
Shape and Size	$D \leq 25\ mm$, $L \leq 35\ mm$
GCV (kCal/kg)	2800-4000
Moisture(%)	≪14
Fines of $L \leq 3\ mm$ (%)	≪5

Table A6: Agro-residues approved for co-firing by the Ministry of Power (Also accepted by NTPC)

- Agro-residue such as stubble/straw/stalk/husk, which are surplus and not being used as animal fodder. This includes agro-residue obtained from crops

like Paddy, Soya, Arhar, Gwar, Cotton, Gram, Jawar, Bajra, Moong, Mustard, Sesame, Til, Maize, Sunflower, Jute, Coffee, etc., as well as Groundnut Shell, Coconut Shell, Castor Seed Shell, etc.

- Bamboo and its by-products (Bamboo Chips, Cuttings, Bamboo Dust, etc.)
- Horticulture waste such as dry leaves and trimmings obtained from the maintenance & pruning of trees and plants.
- Pinecone/Needle, Elephant Grass, Sarkanda, etc.

Table A7: Benchmark cost of biomass

Fuel Type	Benchmark excluding GST and transport (₹/1000 kcal)
Torrefied Pellet (GCV: 3400-5000 kcal/kg, Moisture: <14%)	₹2.58 (NCR only)
Non-Torrefied Pellet (GCV: 2800-3400 kcal/kg, Moisture: <14%)	₹2.32 (NCR) / ₹2.27 (Northern) / ₹2.24 (Western)

Table A8: Reduction in Combustion-Related Emissions at NTPC Dadri under Different Biomass Co-Firing Scenarios

% Cofiring	CO_2 (kt)	CH_4 (kt)	N_2O (kt)	GHG Potential ($ktCO_2e$)	SO_2 (kt)
1	15.08	-0.01	-0.01	13.31	0.05
2	30.16	-0.02	-0.01	26.62	0.10
3	45.24	-0.03	-0.02	39.93	0.16
4	60.31	-0.04	-0.02	53.25	0.21
5	75.39	-0.05	-0.03	66.56	0.26
6	90.47	-0.06	-0.03	79.87	0.31
7	105.55	-0.07	-0.04	93.18	0.36
8	120.63	-0.08	-0.04	106.49	0.41
9	135.71	-0.09	-0.05	119.80	0.47
10	150.79	-0.10	-0.05	133.11	0.52

11	165.86	-0.11	-0.06	146.42	0.57
12	180.94	-0.12	-0.06	159.74	0.62
13	196.02	-0.13	-0.07	173.05	0.67
14	211.10	-0.14	-0.07	186.36	0.73
15	226.18	-0.15	-0.08	199.67	0.78
16	241.26	-0.16	-0.08	212.98	0.83
17	256.34	-0.17	-0.09	226.29	0.88
18	271.42	-0.18	-0.09	239.60	0.93
19	286.49	-0.19	-0.10	252.91	0.98
20	301.57	-0.20	-0.10	266.23	1.04

Table A9: Reduction in Combustion-Related Emissions at NTPC Jhajjar under Different Biomass Co-Firing Scenarios

% Cofiring	CO_2 (kt)	CH_4 (kt)	N_2O (kt)	GHG Potential ($ktCO_2e$)	SO_2 (kt)
1	11.45	-0.01	0.00	10.10	0.04
2	22.89	-0.01	-0.01	20.21	0.08
3	34.34	-0.02	-0.01	30.31	0.12
4	45.79	-0.03	-0.02	40.42	0.16
5	57.23	-0.04	-0.02	50.52	0.20
6	68.68	-0.04	-0.02	60.63	0.24
7	80.12	-0.05	-0.03	70.73	0.28
8	91.57	-0.06	-0.03	80.84	0.31
9	103.02	-0.07	-0.03	90.94	0.35
10	114.46	-0.07	-0.04	101.05	0.39
11	125.91	-0.08	-0.04	111.15	0.43
12	137.36	-0.09	-0.05	121.26	0.47
13	148.80	-0.10	-0.05	131.36	0.51

14	160.25	-0.10	-0.05	141.47	0.55
15	171.69	-0.11	-0.06	151.57	0.59
16	183.14	-0.12	-0.06	161.68	0.63
17	194.59	-0.13	-0.06	171.78	0.67
18	206.03	-0.13	-0.07	181.88	0.71
19	217.48	-0.14	-0.07	191.99	0.75
20	228.93	-0.15	-0.08	202.09	0.79

Table A10: Emission Factors Utilized in The Emission Calculations

Emission Inventory IPCC 2006					
Fuel type	**Emission factor by greenhouse gases (kg of greenhouse gas per TJ)**			**Emission Factor in kg CO_2*/TJ**	**Emission Factor in ton CO_2e/MJ**
	CO_2	**CH_4**	**N_2O**		
Coal (Bituminous and Sub-bituminous)	96,100	1	1.5	96,586	0.0966
Biomass (Rice straw)	83,840	9.03	5.59	85,763	0.0858

* The CO_2 equivalence is calculated based on the greenhouse effect potential of CH_4 and N_2O which is 21 and 310 times more than CO_2.

Table A11: % Sulfur Considered in the Analysis

% Sulphur	
Coal	**Biomass (Rice Husk)**
0.45	0.06

Table A12: Efficiency Considered in The Analysis

Efficiency (%)	
Flue Gas Desulfurization (FGD)	90.6
Electrostatic Precipitator (ESP)*	99

- High efficiency of ESP leads to negligible emissions of Particulate Matter (PM).



ASHOKA
UNIVERSITY

Campus Location
Plot No. 2, Rajiv Gandhi Education City,aNational Capital Region P.O. Rai, Sonepat Haryana-131029

Delhi Office
Ashoka University Office, 222, Second floor, Okhla Industrial Estate, Phase III, New Delhi-110020