CENTRE FOR A
People-centric Energy Transition

From Waste to Watts: Socioeconomic and Policy Pathways for Biomass Co-firing in Thermal Power Plants

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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

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Table of Content

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
MSW	Municipal Solid Waste
NGO	Non-governmental Organizations
PM	Particulate Matter
RDF	Refused-derived Fuels
SAMARTH	Sustainable Agrarian Mission on Use of Agri-Residue in Thermal Power Plants
SMAM	Sub-Mission on Agricultural Mechanization
TPP	Thermal Power Plant

1. Background and Policy Context

Solid fuel blending in coal-fired thermal power plants involves mixing coal with alternative fuels, such as biomass and waste-derived fuels. This practice reduces stubble-burning, greenhouse gas (GHG) emissions, and improves energy security by diversifying the fuel mix. Therefore, the Indian government has mandated blending solid biofuels with coal in thermal power plants. Across India, the annual surplus biomass residue touches about 228.5 million metric tonnes [1]. Rice, wheat, and maize residues account for the largest share, contributing roughly 41.7, 33.4, and 15.2 million metric tonnes, respectively (Figure 1). 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.

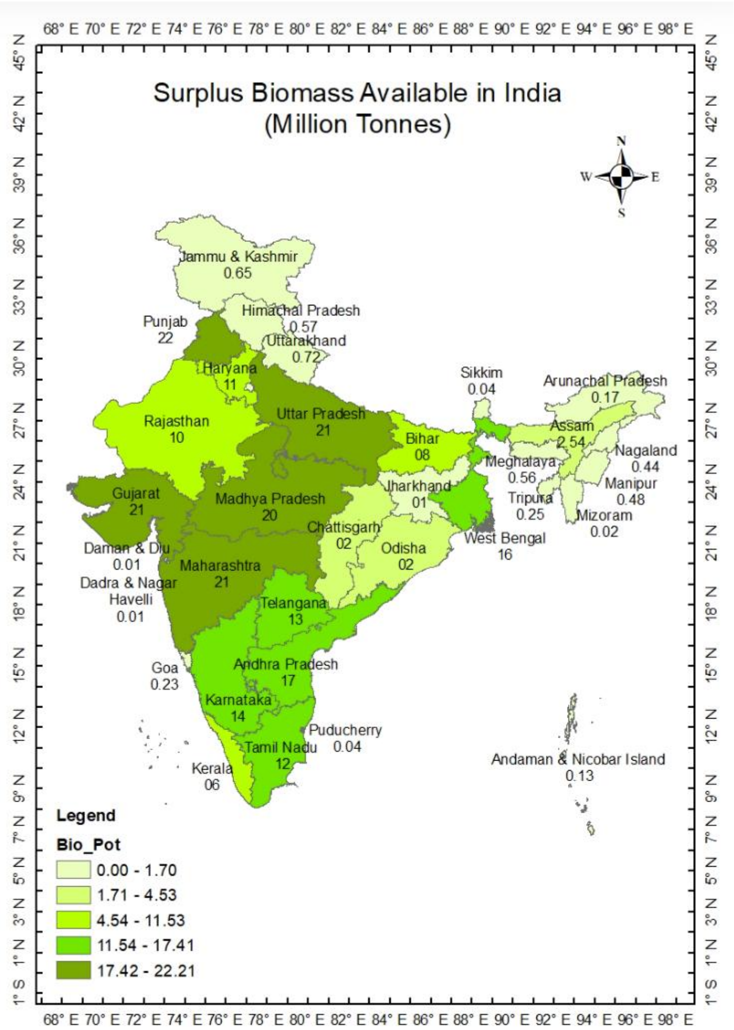


Figure 1: Surplus Biomass Atlas of India [1]

The biomass supply chain transforms agricultural waste into pellets/briquettes through four interconnected stages: collection at farms, aggregation and storage, processing through densification plants, and final delivery to power plants, as shown in Figure 2.

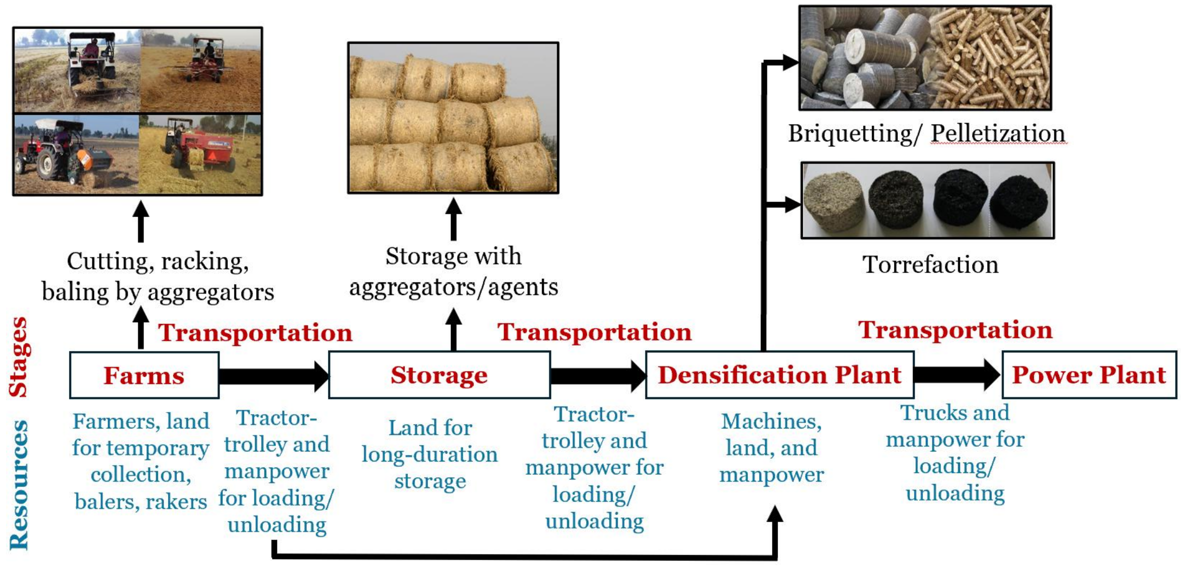


Figure 2: Biomass supply chain

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 [2].

The National Bio-Energy Program (2021-2026) encourages biomass co-firing and the development of biomass supply chains [3]. 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 [4]. 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 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 crore (per project) of CFA for Biomass (non-bagasse) cogeneration projects, with Rs. 40 lakhs/MW (on installed capacity). To tackle crop residue burning and rising pollution, the Haryana government, with central support, launched the Crop Residue Management (CRM) scheme in 2018-19. Farmers were initially offered ₹1,000 per acre to avoid burning, which has been increased to ₹1,200 per acre for 2024-25 under in-situ and ex-situ management. Additionally, the government provides up to 50% subsidy on machinery like balers, choppers, rakers, and seeders under the SMAM (Sub-Mission on Agricultural Mechanization) scheme [5, 6].

NTPC, India's largest power producer, 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 [7]. Recently, they achieved a 20% co-firing of torrefied biomass at their Tanda plant in Uttar Pradesh [7].

2. Problem Statement and Objectives

Socio-economic impacts are important to understand how technological interventions affect people. 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 [8, 9]. 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 objectives of the present study are as follows:

i. Assess socioeconomic and health impacts of biomass co-firing, focusing on rural livelihoods, gender inclusion, and air quality.
ii. Evaluate the feasibility of cow dung-biomass blends by assessing their technical performance, while exploring their potential contribution to sustainable energy generation and rural economic development.
iii. Review global co-firing practices to inform policy and strategy in India.
iv. Propose actionable, socially inclusive, and community-centred policy recommendations.

3. Methodology

In the present work, a new framework, "**BLEND (Balancing Lives, Emissions, and National Development)**", is developed and utilized. The BLEND framework is a seven-stage (Figure 3), an indicator-based methodology. The framework utilizes a comprehensive set of indicators across technical, economic, social, and environmental domains to ensure a holistic evaluation.

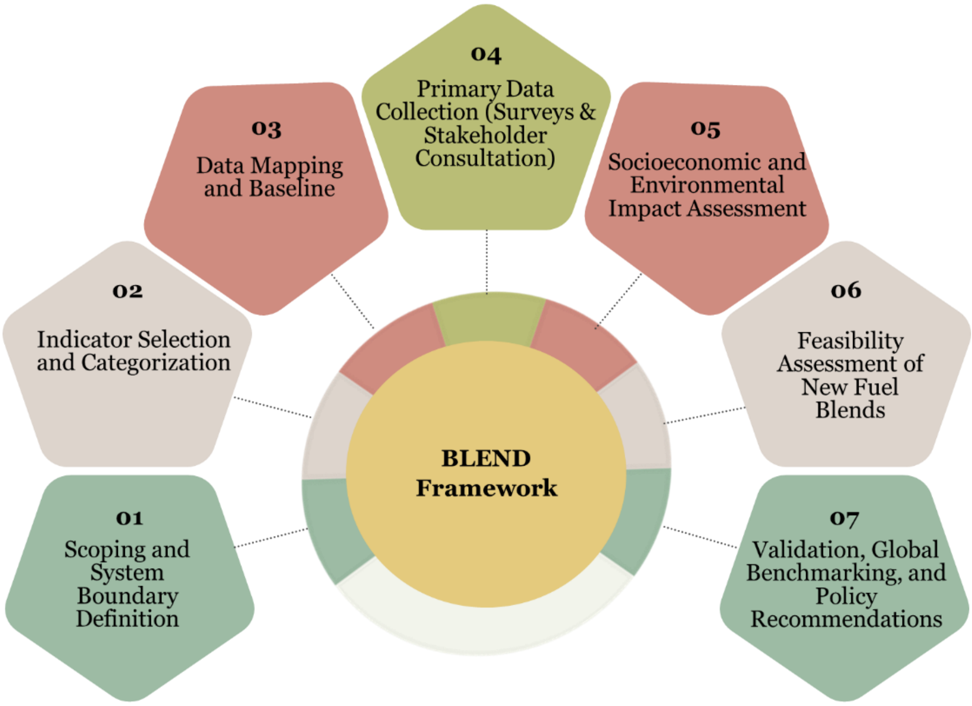


Figure 3: Various stages of the BLEND Framework

Primary data was collected using a mixed-methods approach across the biomass supply chain through purposive, multi-stakeholder sampling in key agricultural districts of Haryana (Karnal, Panipat, and Sonipat). The study covered 21 villages and surveyed 100 farmers, 20 aggregators, 20 processors, 15 transporters, and NTPC Dadri plant staff. Data was collected using CAPI-based surveys, with quality ensured through enumerator training, field monitoring, data cleaning, consistency checks, and statistical validation.

4. Key Findings

The following section presents key findings structured around the study objectives. It highlights stakeholder-level impacts, evaluates the feasibility of cow dung-biomass blends, and draws policy-relevant lessons from global co-firing experiences.

4.1. The Human Side of Biomass Cofiring in Thermal Power Plants: A Socioeconomic Impact Assessment

This section discusses the impact of large-scale biomass cofiring in thermal power plants on all stakeholders in the supply chain.

4.1.1. Farmers

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%). The key findings of the survey conducted with the farmers are as follows:

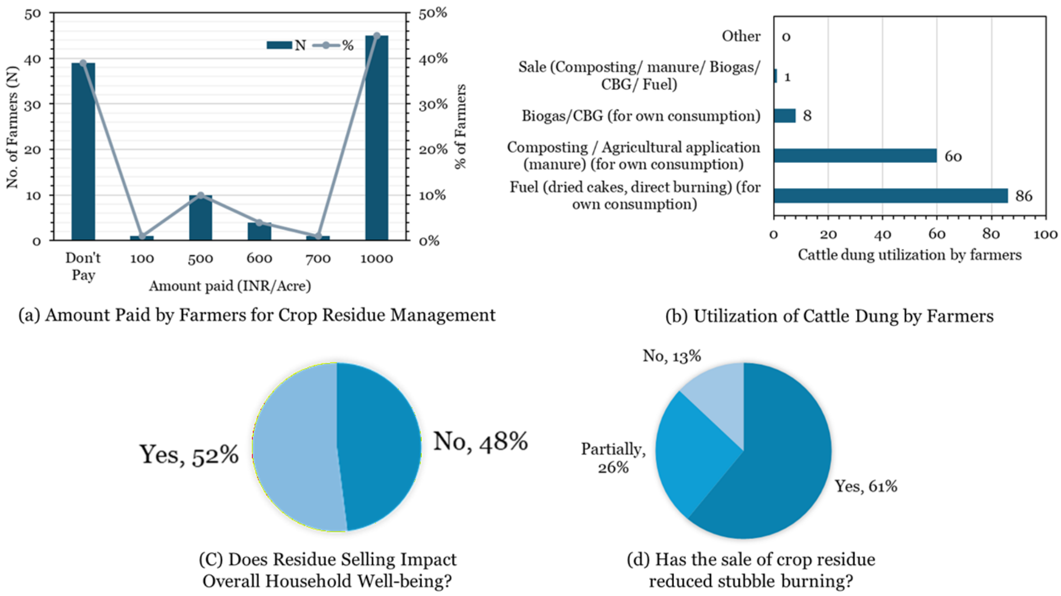


Figure 4: Impact on Farmers

i. 61% of farmers reported paying for crop residue management or field cleaning due to the limited on-time availability of the aggregators (Figure 4(a)). 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.

ii. 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%). 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 neighbours for free, though many would prefer to receive payment for it (Figure 4(b)).

iii. 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 4(c)). Overall, the findings indicate that while crop residue management has improved well-being for some households, the economic benefits are uneven and often indirect. In many cases, improvements are more closely linked to reduced health risks or supplementary monetary benefits (reduction in field preparation expenses) than to substantial changes in household earnings.

iv. 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 (Figure 4(d)). The finding is consistent with recent evidence showing a significant decline in stubble burning incidents in Haryana [10].

v. 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.

vi. Most farmers are not currently participating in formal crop residue markets. Farmers highlighted that their preferred selling channels would include aggregators, direct sales to power plants or industry, or government-supported procurement systems. The results also show limited awareness of the biomass industry among farmers.

vii. Farmers highlighted the need for a locally available residue collection centre that can provide services when required.

viii. 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.

4.1.2. Aggregators

Aggregators, locally referred to as balers, play a central role in the crop residue management supply chain. A total of 20 aggregators were surveyed across three districts of Haryana: Karnal, Panipat, and Sonipat. Nearly half of the respondents were from Karnal (45%), followed by Panipat (40%), and Sonipat (15%). For most respondents, biomass aggregation is not the primary source of income. Over half (55%) reported that it contributes only 0-10% of their total earnings. The key findings of the survey conducted with the aggregators are as follows:

i. On average, each aggregator reported procuring around 1,027 tonnes of crop residue annually. Paddy residue is the most commonly collected biomass (reported by 83% of respondents), followed by wheat (42%) and sugarcane residue (33%). While most aggregators procure residue locally, many reported traveling long distances (60 km) during peak season.
ii. 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.
iii. 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.
iv. Because of limited storage capacity and inconsistent supply, most small aggregators do not enter into formal contracts with end users. This gap has created space for agents and larger stockists, who invest in bulk procurement and storage of crop residue. These intermediaries can enter into contracts with large buyers, such as bio-CNG plants, refineries, and distilleries, and often secure better prices due to assured supply.
v. 90% of the aggregators have their own aggregation machinery, including baling machines, tractors with trolleys, cutters, and racks. 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).

vi. Most of the machinery used in biomass aggregation is indigenous, which is encouraging for promoting local manufacturing and reducing dependence on imports (**Error! Reference source not found.**).

vii. Aggregators reported using their own vehicles for both procurement and sale of biomass, and none reported facing transportation-related challenges.

viii. Biomass aggregation activities are largely dependent on a seasonal workforce, primarily consisting of unskilled or semi-skilled male labourers with low levels of formal education, who are typically hired for 2 to 7 months during the peak aggregation season. 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.

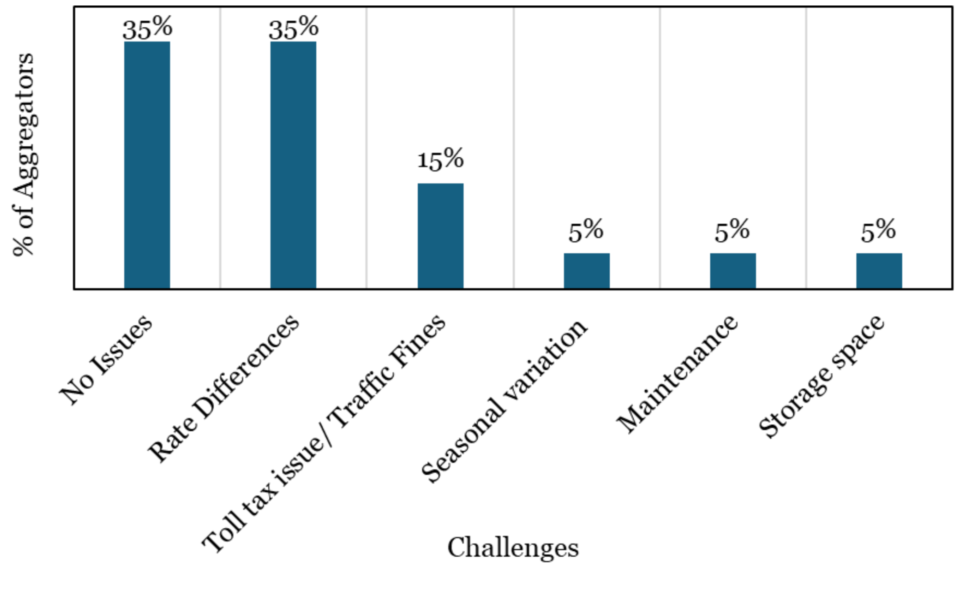


Figure 5: Challenges of Aggregators

ix. All aggregators reported observing a reduction in stubble burning, noting that fewer farmers are burning crop residue. This results in better local air quality, improves respiratory health, and reduces medical expenses.

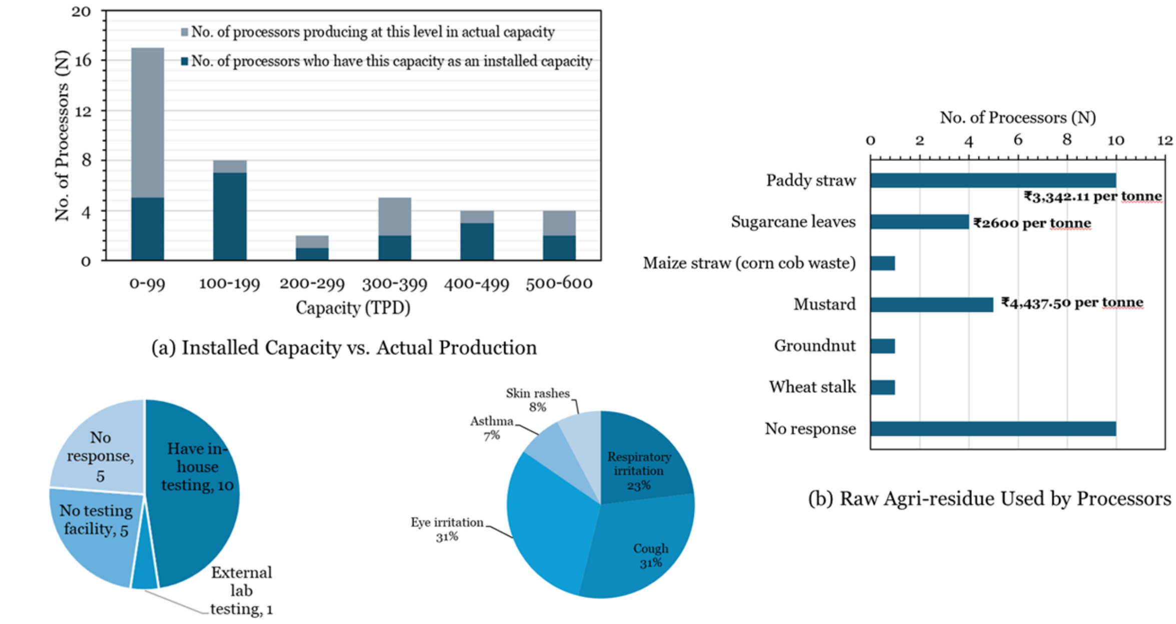
x. Most aggregators reported relatively few operational challenges in maintaining the biomass supply chain, with 35% indicating no major issues. However, an equal proportion (35%) highlighted price differences in the market as a key challenge. Other concerns included toll taxes or traffic fines (15%),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

4.1.3. Processors

The third stakeholder in this supply chain is the processor, who owns processing plants that make pellets and/or briquettes from crop residue. The respondents represented companies operating across multiple states in North India, with the highest concentration from Haryana and Rajasthan. Of the 20 processors interviewed, 16 reported supplying to the NTPC Dadri plant, 2 to the NTPC Jhajjar plant, and the remaining 2 to both plants. The key findings of the survey conducted with the processors are as follows:

i. A comparison between installed capacity and actual production levels indicates 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 (Figure 6(a)) This gap between installed and operational capacity is attributed to factors such as irregular feedstock supply, high logistical constraints, and market uncertainties.

ii. Most 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 6(b)). These are commonly procured from aggregators (balers) and, in some cases, from farmers. 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. The average cost reported by processors for paddy straw, mustard residue, and sugarcane leaves is ₹3,342 per tonne, ₹4,437 per tonne, and ₹2,600 per tonne, respectively. Disruptions in feedstock availability during the monsoon result in reduced production and consequent financial losses.



(a) Installed Capacity vs. Actual Production

(b) Raw Agri-residue Used by Processors

(c) Testing Capacity Among Processors

(d) Health issues faced by the Workers

Figure 6: Responses from Processors

iii. 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 6(c)). 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.

iv. Overall, the data suggest that the selling 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 average production cost across respondents is approximately ₹2,150 per tonne.

v. 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 (₹75 lakhs-2.85 crore). 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. The widespread use of indigenous machinery indicates strong potential for achieving self-reliance in biomass processing technologies.

vi. The responses indicate that biomass processing units employ a mixed workforce consisting of skilled technical staff, semi-skilled operators, and largely unskilled labourers. Small units typically employ 12-18 workers, medium units 20-30, and large units 40-50. It is important to note that Women's participation is limited and mainly confined to administrative roles.

vii. While 85% of processors report a decline in local stubble burning, workers continue to face significant dust exposure, leading to persistent health concerns (Figure 6(d)). 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. 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. The most commonly reported measures (7 respondents) include the provision of protective masks and safety training.

viii. Processors face multiple challenges in biomass processing, including low procurement prices that do not match rising raw material costs, payment delays of 2-3 months, affecting cash flow. Strict quality norms of the power plants increase risks of rejection and intensify competition based on calorific value and blending ratios. Operational inefficiencies arise from logistics issues such as long truck waiting times and administrative hurdles in e-tendering and payments. Additionally, seasonal competition for raw materials leads to price fluctuations. Technical challenges include high moisture content during monsoon and winter, and inconsistent feedstock quality across sources. Despite these challenges, most respondents reported that power plants' demand has created a positive impact on their businesses.

4.1.4. Transporters

Transporters in the biomass supply chain comprise two groups: aggregators acting as transporters, who move raw biomass from farms to nearby storage sites and onward to processing units using tractor-trolleys, and independent transporters between processors and end users, who deliver pellets/briquettes to power plants and industries using heavy trucks. Aggregators do not face significant transportation-related challenges, whereas independent transporters encounter issues such as high fuel costs and inefficiencies in truck management at plant sites, affecting turnaround time. The workforce in this segment is entirely male, consisting of drivers and helpers.

4.1.5. Power Plant Staff

The fifth stakeholders in this supply chain are the end users (thermal power plants and other industries), who procure pellets from processing plants. The NTPC's thermal power plants are procuring pellets (non-torrefied) of a specific quality as per their utility. In this study, a detailed discussion was conducted with NTPC's staff. The key findings are as follows:

i. Seasonal variation in biomass availability, inconsistent quality, limited storage, and truck congestion at plant sites create major supply and logistics challenges.
ii. Biomass pellets are costlier than coal, with added handling, storage, and testing costs increasing overall expenses.
iii. Co-firing operations require additional manpower, with a predominantly male workforce and notable dust exposure raising health concerns.
iv. Low blending ratios (~5%) have minimal impact on plant performance, while higher ratios may need system modifications.
v. Cattle dung alone is unsuitable due to high moisture and low calorific value but can be used in blends with agricultural residues if quality standards are met.

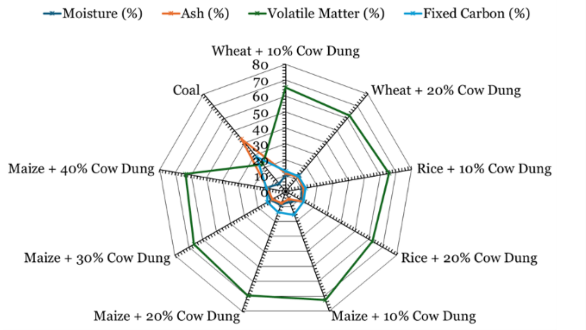
4.2. Adding Another Dimension: Cow Dung in Cofiring

India generates 476.7-794.5 million metric tonnes of cow dung annually, which largely remains underutilized. This makes cow dung one of the most abundant bioresources in India. High moisture and low calorific value make its direct use as a solid fuel inefficient. 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 (Figure 4), which generates household air pollution. It results in severe respiratory illness [11]. 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) [12]. It requires a large plant area and a huge investment, and the process takes a long time. The blending of cow dung with biomass to develop new fuel blends for cofiring in thermal power plants will not only provide health benefits to women but also create additional income for farmers. Additionally, blending cow dung with residues promotes a circular economy where livestock and agricultural byproducts are reintegrated into productive energy cycles.

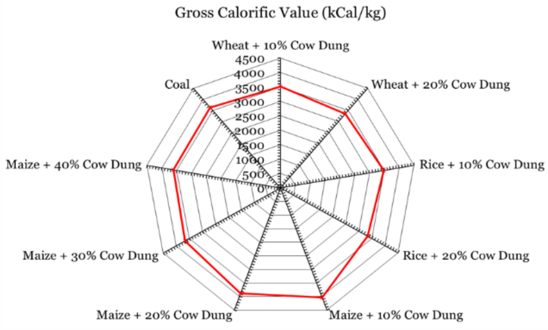
Across India, the annual surplus biomass residue touches about 228.5 million metric tonnes. Rice, wheat, and maize residues account for the largest share, contributing roughly 41.7, 33.4, and 15.2 million metric tonnes, respectively [1]. Therefore, in this study, 15 innovative cow dung-biomass (rice, wheat, and maize residues) blends are tested for their cofiring potential in coal-fired thermal power plants. The technical feasibility of the developed fuel blends for co-firing was evaluated in accordance with the guidelines of SAMARTH, which specify key quality criteria, including a gross calorific value (GCV) of 2800-4000 kcal/kg and a moisture content below 14%.

Proximate analysis indicates that fuel blends containing 10-20% cow dung with rice and wheat residues, as well as blends containing 10-40% cow dung with maize residue, satisfy these criteria (Figure 7). 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 behaviour 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. However, a comprehensive evaluation of ash chemistry, slagging and fouling indices, grindability, and long-duration combustion behaviour is essential to assess operational risks under real plant conditions.



(a)



(b)

Figure 7: Comparative Evaluation of the Developed Fuel Blend with Coal (a) Proximate Analysis (%) (b) Gross Calorific Value (kcal/kg)

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

Biomass co-firing has been adopted across countries as a transitional decarbonization strategy. The key observations are as follows:

i. Most countries operate within a low to moderate biomass blending range (typically 5-15%), indicating that co-firing is generally implemented without major boiler modifications, especially in pulverized coal systems.

ii. Countries promoting biomass co-firing have typically relied on a mix of regulatory and financial policy instruments to enable adoption. These include renewable energy targets or obligations that mandate a share of clean energy in the power mix, carbon reduction or net-zero commitments that encourage utilities to lower emissions from coal-based generation, and market-based mechanisms such as feed-in tariffs, renewable energy certificates, and contracts for difference to improve project viability.

iii. Developed nations increasingly treat co-firing as a short-term or transitional solution, often moving toward full biomass conversion or coal phase-out. Countries with abundant alternative energy options (e.g., natural gas or renewables) show limited long-term commitment to co-firing (e.g., the USA and Japan), prioritizing a direct transition away from coal.

iv. Emerging economies focus on co-firing as a scalable near-term mitigation option, aligned with energy security and agricultural waste utilization.

v. Feedstock selection is highly region-specific, driven by local availability, ranging from agricultural residues to industrial by-products and wood pellets.

vi. In many cases, co-firing deployment is constrained not by technology but by supply chain limitations, including collection, processing, and logistics of biomass feedstocks.

vii. Overall, global experience suggests that biomass co-firing is most effective when supported by clear regulatory targets, stable incentives, and robust biomass supply ecosystems, rather than as a standalone technical intervention.

5. Conclusions and Policy 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 labour, 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 Farmer Producer Organization (FPO) 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. This approach also provides opportunities to increase farmer income and reduce household air pollution from traditional cow dung use.

vii. **Streamlining Biomass Procurement and Quality Management:** Administrative barriers could be reduced through simplified procurement procedures and mandatory time-bound payment systems. Simultaneously, improved handling practices could be promoted to minimize penalties for processors from improper biomass management at the plant, while quality parameters such as GCV and moisture content could be rationalized to balance plant performance with supply chain feasibility for power producers.

viii. **Optimizing Truck Logistics and Queue Management at Plant Sites Using Artificial Intelligence:** Inefficiencies in truck movement could be addressed through AI/ML-enabled, app-based queue management and scheduling systems, allowing real-time coordination of biomass deliveries and reducing congestion at plant sites. This approach can improve unloading efficiency, minimize waiting times, and enhance overall supply chain reliability.

ix. **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.

x. **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.

xi. **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.

6. Endnotes

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