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Why Stubble Burning Persists in North India: Structural Constraints and Alternative Feasibility

Hezal Manocha
hezal.manocha11@gmail.com

ABSTRACT

Stubble burning remains a dominant residue management practice in North India despite well-documented environmental and public health consequences. Its persistence is closely tied to the economic and operational constraints faced by farmers, including rising labour costs, limited machinery access, and narrow sowing windows. Rather than treating burning as a matter of awareness or regulation alone, the analysis investigates whether alternative residue management pathways can realistically substitute burning within existing agrarian systems.

A comparison of two contrasting case-based pathways — EcoLeaf Press as a decentralized, community-oriented utilisation model and bioenergy-based systems as centralized, capital-intensive solutions — forms the core of the evaluation. Using a feasibility-based analytical framework, these alternatives are assessed across cost structures, temporal compatibility, logistical requirements, and institutional accessibility.

The comparison reveals that decentralized solutions enhance local accessibility but face labour dependence and scalability constraints, whereas centralized bioenergy pathways offer higher absorptive capacity while imposing significant coordination and capital demands. The continued reliance on burning thus reflects a structural mismatch between intervention design and farm-level realities, limiting sustained adoption and long-term environmental impact.

By developing and applying a feasibility-testing framework, this research extends existing discussions beyond technical potential, emphasizing the importance of aligning residue management strategies with the structural constraints that shape farmer decision-making.

Keywords: Stubble burning; North India; Crop residue management; Bioenergy; Decentralized solutions; Feasibility analysis.

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1. INTRODUCTION

The Indo-Gangetic Plain in India is widely recognized as a major air pollution hotspot, with post-harvest crop residue burning identified as a significant contributor to seasonal pollution spikes. Numerous studies have documented that stubble burning contributes substantially to fine **particulate matter** (PM2.5)(Gottipati et al., 2021),(Health Effects Institute, 2025) and other harmful emissions, driving Air Quality Index (AQI) deterioration across North India.(Gottipati et al., 2021; Jain & Pradhan, 2026) ***Notably, burning one tonne of paddy straw releases approximately 3 kg of particulate matter, 60 kg of carbon monoxide, 1,460 kg of carbon dioxide, 199 kg of ash, and 2 kg of sulphur dioxide, thereby degrading air quality and posing serious public health risks.*** (Health Effects Institute, 2025) Together, these figures underscore the magnitude of residue burning as a structural contributor to regional air pollution rather than an isolated or minor source.

Beyond atmospheric impacts, residue burning also leads to soil nutrient loss, deterioration of soil structure, and increased dependence on chemical fertilizers, which further undermines long-term agricultural sustainability. (Abdurrahman et al., 2020) Despite long-standing awareness of these environmental and health consequences, stubble burning remains widespread in North India. Its persistence cannot be understood solely in terms of environmental neglect, but must be situated within the material realities shaping farmer decision-making.

Non-burning residue management often requires additional expenditures on labour, machinery, and residue removal, which are difficult to afford under existing income conditions.(Gottipati et al., 2021), (Sanjay et al., 2021) At the same time, farmers face tight temporal pressures due to the narrow window between rice harvesting and wheat sowing, widespread use of combine harvesters that leave residue dispersed across fields, and limited availability of appropriate machinery during peak seasons. (Jain & Pradhan, 2026)

The continued prevalence of stubble burning therefore cannot be explained solely by its environmental or health consequences. Rather, it is embedded within the structural conditions that shape agricultural production and farmer decision-making. While policy discussions frequently emphasize bans, regulation, or awareness campaigns, they often overlook a more fundamental question: whether proposed alternatives are practically viable within existing farm-level realities.

To address this gap, the analysis evaluates crop residue management alternatives through a structured feasibility framework. It asks why stubble burning persists under farm-level economic and operational constraints, and to what extent decentralized and centralized alternatives can be feasibly assessed as substitutes. By comparing EcoLeaf Press and bioenergy systems as contrasting case-based pathways, the study examines whether these approaches can function within the temporal, economic, and institutional conditions shaping North India's evolving agrarian landscape.

2. METHODOLOGY

This study uses a literature- and case-based comparative methodology rather than primary field data collection. The analysis draws on the 23 sources listed in the reference section, comprising peer-reviewed research, government sources, and institutional reports addressing crop-residue burning, agricultural labour, machinery access, sowing-window constraints, residue logistics, and bioenergy. Sources were selected for their direct relevance to the structural constraints identified in the research question and to the feasibility of residue management alternatives. The study does not claim to provide a systematic review of every available technology.

The analysis focuses on two contrasting pathways already central to the paper's research question: centralized bioenergy systems and the decentralized EcoLeaf Press case. Bioenergy was selected as a contrasting system-level pathway because it represents a relatively capital- and infrastructure-intensive approach, while EcoLeaf Press represents a locally operated, lower-capital pathway. The two cases are therefore compared analytically rather than treated as an exhaustive list of alternatives.

Feasibility is assessed using five common dimensions: cost and capital requirements, operational complexity, time compatibility with the rice–wheat cycle, logistics and spatial coordination, and scale and institutional access. Evidence is interpreted comparatively: a pathway is considered more feasible where its requirements fit more closely with the economic and operational conditions described in Section 2. Because the analysis is case- and literature-based, the framework evaluates practical compatibility rather than measuring actual adoption rates or farmer preferences.

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3. UNDERSTANDING THE ROOT CAUSES OF STUBBLE BURNING

3.1 Economic Constraints: Labour and Machinery as Cost Amplifiers

Labour-based residue removal has become economically unviable under contemporary agrarian conditions in North India. Non-burning alternatives often require intensive manual labour within a **narrow post-harvest window** (Gottipati et al., 2021), making their feasibility highly sensitive to labour costs and availability.

Data from the Labour Bureau (*Rural Wages | Official Website of Labour Bureau, Ministry of Labour and Employment, Government of India*, n.d.) and the Periodic Labour Force Survey(*Ministry of Statistics and Program Implementation | Government Of India*, n.d.) indicate that average daily agricultural **wages**

increased from approximately ₹285 in 2014–15 to over ₹440 by 2024-25, representing a rise of nearly 50-60 percent within a decade. Even a few additional labour days per hectare now translate into noticeably higher clearing costs for farmers. When applied to residue management, this wage increase exposes farmers to greater financial risk for practices that do not directly generate revenue. (Nawaz et al., 2022)

At the same time, labour availability has declined due to structural shifts in rural employment**. Migration toward non-farm and urban sectors** has reduced the agricultural workforce, intensifying seasonal labour shortages during peak post-harvest periods. Periodic Labour Force Survey (*Ministry of Statistics and Program Implementation | Government Of India*, n.d.) data indicate that agriculture now accounts for less than 45 percent of total employment nationally. In Punjab, where mechanisation is already widespread, rural workers are increasingly shifting toward non-agricultural occupations (Singh & Pattanaik, 2025), making labour shortages particularly acute during harvest and sowing transitions. As a result, even farmers willing to pay higher wages face uncertainty in securing labour within the required timeframe (Nawaz et al., 2022; Thakur et al., 2025). Under these conditions, **manual residue removal becomes both costly and unreliable**, increasing the economic risk associated with non-burning practices. (Bhardwaj et al., 2021; Sokra et al., 2025)

Mechanisation further compounds these economic pressures. Combine harvesters are widely adopted because they reduce labour dependence and accelerate harvesting, but they leave large quantities of loose straw and standing stubble in fields (Bhardwaj et al., 2021). This mechanisation structurally increases residue volume and transforms residue clearance into a separate and costly operational stage.(Kemanth, Kurinji, Ramandeep Singh, and Sneha Maria Ignatious., 2024). Attachments such as **the Super Straw Management System (SMS) are promoted to mitigate residue accumulation, yet their use increases harvesting costs from approximately ₹1,200 per acre to ₹1,500 per acre due to higher fuel consumption**.(Keil et al., 2021; Sidhu et al., 2007) These mechanisation-induced residues require additional machinery and services for field clearance, introducing new layers of capital and rental costs for farmers.

Moreover, equipment such as **Happy Seeders , Super SMS units, and straw choppers** requires high upfront capital investment, placing ownership beyond the reach of many small and marginal farmers. (Manpreet-Singh et al., 2024) Even when government subsidies exist, most farmers rely on rental markets for machinery access. **Rental charges** during peak post-harvest periods typically range between ₹1,600 and ₹2,500 per acre, often exceeding standard hiring rates. These costs are further increased by fuel expenses, tractor compatibility requirements, and operator labour. Limited machine availability during the narrow sowing window adds uncertainty, making timely access difficult even for farmers willing to pay. Consequently, mechanisation reduces labour dependence but shifts the economic burden to post-harvest residue management, reinforcing the financial rationale for burning. (Kemanth, Kurinji, Ramandeep Singh, and Sneha Maria Ignatious., 2024; Sachan et al., 2023)

3.2 Operational Constraints: Narrow Sowing Windows and Time Pressure

Beyond economic costs, operational constraints strongly shape residue management decisions. The rice–wheat cropping system imposes a **narrow sowing window** (Saifuddin et al., 2025) that systematically favours rapid residue clearance methods. Rice is typically harvested between late September and early October, while wheat must be sown by mid-October to early November to avoid yield losses. This leaves farmers with only two to three weeks to clear residue, prepare fields, and complete sowing. (Saifuddin et al., 2025)

Within this compressed timeframe, most non-burning alternatives require additional coordination, including suitable soil moisture conditions, timely access to machinery, and trained operators. Any delay at one stage directly affects subsequent operations, increasing the risk of missing the optimal sowing window. Weather uncertainty further compresses this operational margin, reducing flexibility for experimentation with slower residue management practices. (Shah et al., 2021) Under such time pressure, methods that allow immediate field clearing become operationally dominant, regardless of environmental considerations.

3.3 Converging Economic and Operational Constraints

Taken together, rising labour costs, declining labour availability, high machinery costs, and narrow sowing windows create a set of interlinked constraints that strongly shape how farmers manage crop residue. Compared to labour-intensive or machinery-dependent alternatives, stubble burning is fast, requires no upfront expenditure, and can be completed within a very short time frame. When labour is expensive, machines are difficult to access, and the time between crop cycles is limited, most non-burning options become costly and uncertain. In this context, burning is less a deliberate environmental trade-off and more a practical response to pressure, allowing farmers to clear fields quickly and avoid delays that could threaten the next crop cycle.

These converging constraints suggest that traditional residue management practices have become increasingly difficult to sustain, and that addressing stubble burning requires identifying alternatives that can operate within existing economic and operational realities. This makes it necessary to evaluate whether proposed solutions can realistically function under these constraints, which the next section explores through alternative residue utilisation pathways.

3.4 Why Burning Emerges as the Default Residue Management Strategy

Compared to labour-intensive or machinery-dependent alternatives, stubble burning offers farmers a low-cost and rapid method of field clearance under highly constrained conditions. Rising labour wages, limited and uncertain access to residue management machinery, and narrow inter-crop sowing windows collectively increase the perceived risk of non-burning practices. Under these conditions, burning functions less as a preference and more as a risk-management strategy that ensures timely sowing with predictable outcomes. This convergence of economic and operational constraints highlights why burning persists as the default practice, thereby motivating the evaluation of alternative residue management pathways that can function within these same constraints.

4. EXPLORING ALTERNATIVES TO OPEN-FIELD STUBBLE BURNING

Many policy and research discussions on stubble burning in North India focus on identifying alternative uses of crop residue instead of open-field burning. (Gottipati et al., 2021) However, these alternatives are often assessed under idealised conditions and without systematic evaluation of whether they can operate under the structural limitations faced by farmers after harvest. This paper adopts a feasibility-based analytical lens, treating residue utilisation pathways as socio-technical systems shaped by labour availability, machinery costs, time constraints, scale requirements, and access barriers.

Two pathways bioenergy-based residue utilisation and EcoLeaf Press are examined as contrasting but analytically comparable approaches to converting rice stubble into productive outputs. **Bioenergy represents a centralised, capital- and infrastructure-intensive pathway**, **while EcoLeaf Press represents a decentralised, labour-intensive, low-capital pathway.** Both pathways are evaluated using common criteria, cost, operational complexity, time requirements, scale, and access to assess their practical applicability under farm-level constraints rather than their theoretical or environmental potential.

4.1 Bioenergy as a centralised residue utilisation pathway

Bioenergy (Porichha et al., 2021) is widely promoted as a large-scale alternative to open-field burning because it converts rice straw into usable energy products such as biogas, ethanol, electricity, pellets, and briquettes. However, this pathway is structurally shaped by high costs, complex operations, time mismatches, and scale requirements, which limit its feasibility at the farm level.

i. **Cost as a Feasibility Constraint**

Bioenergy creates potential income for farmers, but the cost structure limits its practicality. Farm-gate prices for paddy straw are typically around ₹500–₹1,000 per tonne (Yadav & Yadav, 2025), but the delivered cost rises sharply once baling, densification, and transport are included. Studies estimate total biomass supply and processing costs for pellets or briquettes at approximately ₹4,700–₹5,200 per tonne, reflecting the high expense of handling bulky straw.(*Is Ex-Situ Crop Residue Management a Scalable Solution to Stubble Burning?*, 2023)
This gap means that farmers capture only a small share of the final value, while most costs are borne by aggregators and energy firms, making farmer-level participation economically weak.

ii) **Operational complexity as a structural barrier.**

Bioenergy requires multiple coordinated steps: residue collection, baling, transport, storage, and centralized processing. Rice straw's low bulk density makes baling or palletisation necessary before transport, increasing machinery and labour needs. Such systems depend on organized supply chains, skilled operators, and fuel-intensive logistics.
This makes bioenergy operationally dependent on intermediaries rather than individual farmers. (*Bioenergy*, n.d.)

iii) Time mismatch between farming cycles and bioenergy supply chains.

Residue is produced within a short post-harvest window, but bioenergy plants require continuous feedstock throughout the year. Delays in collection during the narrow harvest window disrupt supply chains and increase field-level time pressure. Research on biomass logistics highlights seasonal supply variability as a key bottleneck in bioenergy systems.

iv) Scale and access as institutional constraints.

Bioenergy systems require large capital investments in balers, transport fleets, storage infrastructure, and processing plants, often costing several crores at industrial scale. As a result, access is mediated through private firms, cooperatives, or government-supported aggregators. Small and marginal farmers have limited direct control over participation and depend on external market linkages. (*Bioenergy*, n.d.)

Taken together, bioenergy represents a centralised, capital-intensive, and logistics-dependent residue management pathway. While environmentally promising, its feasibility at the farm level is constrained by high supply-chain costs, operational complexity, time mismatches with cropping cycles, and scale-dependent access. As a system-level intervention, bioenergy contrasts sharply with decentralised, locally implementable alternatives such as Eco Leaf Press, making their comparison essential for assessing practical feasibility in farmer-led residue management.

4.2 EcoLeaf Press as a Decentralised Residue Utilisation Pathway (Case-Based System Analysis)

EcoLeaf Press is examined in this paper as a decentralised, small-scale residue utilisation pathway that converts rice stubble into paper products. The case is used to assess whether a low-capital, locally operated residue-use model can function under the same economic and operational constraints that shape farmer decision-making in North India. The initiative has undergone limited pilot-level testing and remains at an early developmental stage, making it suitable for feasibility assessment without overstating its current scale. Rather than presenting EcoLeaf Press as a definitive solution, it is analysed as a comparative system to evaluate viability relative to large-scale bioenergy pathways.

i. **Cost Structure and Capital Feasibility**

At a manual or semi-manual scale, EcoLeaf Press involves relatively low direct material costs. Rice stubble is locally available after harvest and typically priced at approximately ₹0.50–₹1.00 per kilogram, while chemical and biological processing inputs such as caustic soda and plant-based additives contribute limited variable costs. The estimated per-sheet production cost of handmade paper is approximately ₹1.50–₹2.00.

However, scaling beyond manual production requires capital investment in pulping, screening, and pressing equipment, estimated at roughly ₹2–₹8 lakh for small-scale units. While these costs are substantially lower than those associated with industrial bioenergy infrastructure, labour remains a recurring and significant expense.

ii. **Operational Complexity and Labour Dependence**

Operationally, EcoLeaf Press involves sequential steps of residue collection, fibre processing, pulping, sheet formation, and drying. Unlike bioenergy pathways, the process does not rely on advanced machinery, centralised processing facilities, or complex supply-chain coordination. Most stages can be carried out manually or with basic equipment, reducing dependence on skilled technical operators and large machine fleets.

However, EcoLeaf Press is highly dependent on sustained human labour across multiple production stages. The system requires continuous manual input for collection, processing, and sheet formation, making it operationally simple but labour-intensive. This contrasts with bioenergy systems, which are technologically complex and capital-intensive but involve comparatively lower labour engagement at the farm level once supply chains are established.

iii. **Time Dynamics and Post-Harvest Feasibility**

The EcoLeaf Press process is time-intensive at the manual scale, with the production of approximately 100 sheets requiring a full working day, including drying time. Unlike mechanised residue removal or bioenergy collection chains, EcoLeaf Press does not enable immediate field clearance during the narrow sowing window. Therefore, while it may offer supplementary residue utilisation, EcoLeaf Press cannot fully substitute burning during peak sowing periods.

However, residue can be collected and processed over an extended period rather than within the post-harvest sowing window, reducing immediate time pressure on farmers. This temporal flexibility distinguishes it from mechanised alternatives but limits its capacity to manage large residue volumes rapidly.

iv. **Scale and Access Constraints**

EcoLeaf Press operates most feasibly at small or community scales, requiring no centralized biomass markets, large transport networks, or industrial processing plants. Production can occur close to residue generation sites, improving physical access and reducing logistics costs.
Nevertheless, daily output remains limited, and dependence on manual labour constrains scalability. Unlike bioenergy, which is structurally designed for industrial scale, EcoLeaf Press prioritizes decentralised feasibility over volume efficiency.

Taken together, EcoLeaf Press represents a decentralised, labour-intensive, and low-capital residue utilisation pathway. In contrast to bioenergy's centralised and capital-intensive structure, EcoLeaf Press offers greater local accessibility and temporal flexibility, but remains constrained by limited scalability and labour efficiency. This structural divergence highlights the trade-offs between decentralised behavioural alternatives and system-level technological interventions under the economic, operational, and temporal constraints faced by farmers.

5. COMPARATIVE FEASIBILITY OF RESIDUE MANAGEMENT PATHWAYS UNDER FARM-LEVEL CONSTRAINTS

Centralised bioenergy systems and decentralised residue-utilisation models represent fundamentally different approaches to managing agricultural residue. Bioenergy pathways seek scale and efficiency through industrial processing and coordinated supply chains, whereas decentralised initiatives such as EcoLeaf Press prioritise local processing, lower capital thresholds, and contextual adaptability. These contrasting structural logics imply different trade-offs across cost, labour dependence, time dynamics, and operational flexibility. To understand whether any pathway can realistically displace open-field burning, it is necessary to examine how these models perform under the farm level realities that shape farmer decision-making.

Table 1 compares centralised bioenergy pathways and the decentralised EcoLeaf Press model across key feasibility constraints, including labour and capital costs, logistics and spatial coordination, temporal pressures, and scale and access.

Constraint Dimension	Bioenergy-Based Pathways (Centralised)	EcoLeaf Press (Decentralised)
Labour Costs and Economic Feasibility	Lower farm labour reliance; high logistics costs limit returns.	Labour-intensive processing; rising wages reduce economic viability.
Machinery and Capital Requirements	High capital machinery; strong institutional and external dependence.	Low-cost equipment; labour-intensive with small-scale coordination burden.
Logistics and Spatial Coordination	Centralised aggregation; transport-heavy with institutional coordination dependence.	Localised operation; limited residue absorption capacity per site.
Temporal Pressure and Sowing Window Constraints	Time-sensitive collection; delays disrupt supply and coordination.	Flexible processing timeline; cannot ensure rapid field clearance.
Scale and Absorptive Capacity	Large-scale absorption; limited farmer control and participation.	Small-scale accessible; labour limits throughput and scalability.

The comparison demonstrates that centralised bioenergy systems are constrained by capital, coordination, and logistics intensity, while decentralised models face labour, time, and scale limitations, leaving neither pathway fully capable of independently replacing burning.

6. LIMITATIONS

Several limitations qualify the findings. First, the study relies on secondary literature and case-based estimates rather than primary farmer surveys, field measurements, or controlled trials. The analysis therefore cannot establish actual adoption behaviour, willingness to pay, or causal effects on burning practices. Second, the EcoLeaf Press case remains at an early developmental and pilot scale, so its reported costs, output, and operational requirements should not be interpreted as evidence of commercial viability at regional scale. Third, some EcoLeaf Press cost and output figures are indicative case estimates rather than independently validated benchmarks. Finally, the comparison includes two contrasting pathways and is not an exhaustive assessment of all residue-management technologies. Future research should test the framework through farmer-level surveys, field trials, independently verified cost accounting, and pilot-scale comparisons across different districts.

7. CONCLUSION AND FUTURE PERSPECTIVES:

Stubble burning in the Indo-Gangetic Plain has long been recognized as a major environmental and public health challenge, yet its persistence cannot be fully explained by a lack of awareness or regulatory gaps alone. As highlighted in the introduction, farmers operate under binding economic and operational constraints, including rising labour costs, mechanisation-induced residue accumulation, and narrow sowing windows. This paper demonstrates that burning persists not as an environmental trade-off but as a structurally rational response to these constraints. By comparing decentralized and centralized residue management pathways, the study shows that proposed alternatives often fail to align with the realities of farm-level decision-making.

The comparative analysis reveals that decentralized solutions such as EcoLeaf Press enhance local accessibility and reduce capital barriers but remain constrained by labour dependence and limited scalability. In contrast, centralized bioenergy-based pathways offer large-scale absorptive capacity but impose high capital, logistical, and institutional coordination requirements that reduce farmer-level autonomy and value capture. These findings underscore that technological potential alone is insufficient to displace burning; feasibility under real-world constraints is the critical determinant of adoption.

Beyond North India, this study advances a constraint-based feasibility framework for evaluating agricultural interventions. By prioritising operational compatibility over technical potential, it offers a lens applicable to other agrarian contexts where behavioural outcomes are shaped by structural constraints. The findings underscore the need for residue management strategies that align with farmers' economic, temporal, and institutional realities.

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