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Public-Private Partnerships for Crop residue valorisation and Circular Value Chain Development in India

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Abstract

India generates substantial quantities of agricultural waste and crop residues, yet a significant share of usable residue remains underutilised or is disposed of through open-field burning. The problem is especially severe in rice and wheat cultivating areas such as Punjab and Haryana, where the short interval between paddy harvesting and wheat sowing creates strong pressure for rapid field clearance. To address this issue, the present paper analyses how public-private partnerships can support crop residue-based circular economy models by improving residue aggregation, farmer participation, processing systems and output-market linkages. In this context, the paper examines the role of PPP governance in converting crop residue from a disposal burden into a productive circular value-chain resource. The study adopts a theory-synthesis approach supported by a structured thematic review of peer-reviewed literature, government reports, policy documents and institutional publications. The paper argues that crop residue burning is not merely a technological or pollution-control issue, but a governance and value-chain coordination problem shaped by weak feedstock aggregation, high logistics costs, uncertain output markets, limited farmer incentives and fragmented institutional responsibility. Based on this analysis, the paper develops a non-empirical framework linking circular economy principles, public-private partnership governance and crop residue value-chain development. It proposes four indicative models: village biogas clusters, district compost hubs, regional biomass-to-energy plants and agro-biorefinery complexes. The findings suggest that the viability of these models depends on reliable feedstock supply, fair risk allocation, assured offtake arrangements, farmer participation, timely payment systems and clear public coordination. The paper contributes to the existing literature by reframing crop residue valorisation as a circular value-chain governance issue and by offering a conceptual basis for future empirical research, policy design and farmer-inclusive residue management.

Keywords: Public-private partnerships; Crop residue; Circular economy; Residue valorisation; Value-chain governance

1. Introduction

Crop residue management is a major circular economy challenge for Indian agriculture. Agricultural waste includes crop residues, animal manure and agro-processing by-products; where crop residues refer to straw, stalks, stubble, husks and other post-harvest biomass. India generates about 350 million tonnes of agricultural waste annually, with potential to produce more than 18,000 MW of power. Recent review evidence also reports that agriculture contributes 13.72 percent of India's greenhouse gas emissions, compared with a global average of 11 percent, making residue management important for climate action and resource recovery^[1, 2].

The crop residue problem must be understood through the difference between generated residue, surplus residue and burned residue. Generated residue is the total biomass produced after crop harvesting. Surplus residue is the portion left after existing local uses such as fodder, bedding, mulching, composting, thatching, mushroom cultivation and domestic fuel. Burned residue is the portion actually disposed of through open-field burning. This distinction

matters because industrial valorisation should target only surplus residue, not residue that already serves useful local functions. Global crop residue increased from 3,803 million tonnes in 2003 to 5,011 million tonnes in 2013, showing the scale of the wider waste-management challenge^[3].

India's crop residue estimates vary across sources, but they point to the same policy concern. The National Policy for Management of Crop Residues reported about 500 million tonnes of crop residues generated annually, with the highest generation in Uttar Pradesh, Punjab and Maharashtra. It also reported that cereals contribute about 70 percent of residue and rice alone contributes about 34 percent^[4]. Lan *et al.* estimated that India generates nearly 500 million tonnes of crop residue each year and burns nearly 100 million tonnes.⁶ These figures show that residue burning is not a minor farm-level problem. It is a recurring value-chain failure in which biomass is produced, but timely collection and profitable use are not assured.

Paddy straw burning in Punjab and Haryana shows why the issue cannot be reduced to farmer behaviour alone. Farmers often burn paddy straw because the time between paddy

harvest and wheat sowing is short, and burning clears fields quickly at low immediate cost. However, satellite monitoring confirms that stubble burning remains a recurring post-harvest problem in Punjab and Haryana [5]. Lan *et al.* estimated that crop residue burning caused about 44,000 to 98,000 PM_{2.5} pollution exposure-related premature deaths annually during 2003-2019.⁶ Burning also causes nutrient losses and damages soil biological activity, which reduces the long-term value of land [4].

This paper argues that crop residue valorisation needs a governance-led value-chain approach. Technologies such as composting, anaerobic digestion, compressed biogas, biomass pellets, biochar, pyrolysis and biorefining can convert residues into useful products [2, 3, 24, 25]. Yet technology can work only when residue is mapped, collected, stored, processed and sold through reliable institutional arrangements. Public-private partnerships can support this coordination by combining public authority, private investment, farmer participation and assured output markets. The paper therefore addresses the gap between technical potential and practical implementation by developing a PPP-based framework for crop residue circular value-chain development.

2. Literature Review

2.1 Circular economy and residue valorisation

Circular economy theory explains why crop residue should be treated as a resource rather than waste. Pearce and Turner linked economic activity with environmental limits, while Stahel emphasised value creation through longer material use.^{7,8} The Ellen MacArthur Foundation later described circular economy as a system that designs out waste and retains material value.⁹ Geissdoerfer *et al.*, Kirchherr *et al.* and Korhonen *et al.* further show that circular economy requires system design, not only recycling [10, 11, 12].

In agriculture, circularity means that residue should first support local sustainable uses and then move into higher-value conversion pathways where surplus remains. Composting, bioenergy, anaerobic digestion, biochar, gasification and biorefining can reduce waste and produce useful outputs [2, 23, 24, 25]. However, circular economy theory does not fully explain who should organise scattered residue flows, pay farmers, manage storage or guarantee product markets. This paper fills that management gap by connecting circular economy principles with PPP governance.

2.2 PPP governance and value-chain coordination

PPP governance theory focuses on risk allocation, contract design, incentives and accountability. Engel *et al.* argue that PPPs work better when risks are assigned to the actor best able to manage them [13]. Iossa and Martimort show that bundled construction and operation can improve long-term asset quality because the private operator remains responsible for performance [14]. Roehrich *et al.* also found that contract completeness and governance clarity are central to PPP performance [15].

Crop residue PPPs are difficult because feedstock supply is seasonal, scattered and affected by weather, crop choice, harvesting method and farmer decisions. Shrestha *et al.* stress that risk transfer should be realistic, while Warsen *et al.* show that successful PPPs need both contractual clarity

and relational trust [16,17]. Engel *et al.* further warn that PPP efficiency depends on governance mechanisms that reduce opportunistic renegotiation over the project life cycle [18]. These lessons are directly relevant to residue projects, where weak feedstock guarantees or uncertain output prices can make private investment unattractive.

2.3 Crop residue value chains and bioenergy potential

Crop residue value chains differ by crop, region and local use. Paddy straw in Punjab and Haryana differs from wheat straw, sugarcane trash, cotton stalk and maize residue because each has different moisture, bulk, seasonality, local demand and collection cost. Recent review evidence reports that around 180 million tonnes of surplus crop residues may be generated annually in India, and nearly 80 percent of surplus residue is linked to rice straw, sugarcane bagasse, cotton stalk and wheat straw [2]. This concentration supports region-specific models rather than one national template.

Bioenergy and biogas studies show both opportunity and risk. Breitenmoser *et al.* found that anaerobic digestion projects often face problems when planners overestimate biomass quantity and quality [19]. Singh and Kalamdhad show that agricultural residue-based biogas can contribute to energy generation when feedstock is secured.²⁰ Ravindra *et al.* document the air-pollution burden of residue burning, while Chaudhary *et al.* and Bandgar *et al.* identify supply, logistics and pricing constraints in biomass and CBG systems [21, 22, 23]. This literature shows that crop residue circularity is not only a conversion issue. It is also a chain-design issue involving farmers, aggregators, technology operators, public agencies and buyers.

2.4 Research gap

Existing research has examined residue burning, crop residue policy, composting, anaerobic digestion, bioenergy potential, biochar, pyrolysis and circular economy practices. However, much of the literature remains technology-centred or policy-centred. Recent review evidence notes that techno-economic, socio-cultural, institutional and governance barriers still limit sustainable agricultural waste management in India [2]. This gap is important from a management perspective because crop residue valorisation is not only a technical conversion activity. It also requires coordination among farmers, aggregators, private operators, public agencies, financial institutions and output buyers. Therefore, a management-oriented framework is needed to explain how PPP design can connect feedstock aggregation, farmer incentives, risk allocation, processing technology, offtake security and institutional accountability into one workable circular value chain. This paper addresses this gap by developing a PPP typology, a value-chain governance framework and testable propositions for crop residue valorisation in India.

3. Objectives of the study

1. To analyse the role of public-private partnerships in promoting crop residue-based circular economy models in India.
2. To explain how circular economy principles and PPP governance mechanisms interact in crop residue value-chain development.
3. To develop a conceptual PPP typology, risk-allocation

framework and future research propositions for crop residue valorisation in India.

4. Research Methodology

This study follows a conceptual theory-synthesis design supported by a structured thematic review of secondary sources of data. Peer-reviewed literature was searched through major academic databases including Scopus, Web of Science and Google Scholar and government and institutional sources were collected from official platforms such as the Press Information Bureau, Ministry of Agriculture and Farmers Welfare, PNGRB, NRSC-ISRO, IEA and FAO. Recent studies from 2020-2026 were prioritised to capture current debates on crop residue management, compressed biogas, agricultural waste

valorisation and PPP-based implementation. Earlier seminal theory and policy sources were retained only where they provided conceptual grounding or essential policy context. The selected sources were screened for relevance, credibility and publication traceability, and then coded under six themes: residue scale, surplus-use distinction, conversion pathway, PPP risk allocation, output market and institutional coordination. These themes were integrated to develop the PPP typology, conceptual framework, risk-allocation matrix and research propositions. Current official sources were retained where they provided recent programme status, including GOBARDhan coverage, Crop Residue Management support and CBG commissioning data.

Table 1: Review Protocol for the Present Study

Element	Details
Review type	Conceptual theory synthesis supported by structured thematic review
Academic databases	Scopus, Web of Science and Google Scholar,
Government and institutional sources	PIB, Ministry of Agriculture and Farmers Welfare, PNGRB, NRSC-ISRO, IEA and FAO
Keywords	Crop residue, paddy straw, PPP, circular economy, CBG, biomass pellet, SATAT, GOBARDhan, anaerobic digestion, residue valorisation
Time frame	Recent academic and technical literature from 2020-2026 was prioritised. Earlier seminal theory sources and key policy documents were retained selectively where necessary for conceptual grounding and policy context.
Inclusion criteria	Sources directly relevant to crop residue management, circular economy, PPP governance, Indian bioenergy systems and residue policy
Exclusion criteria	Untraceable sources, unmatched publication details, non-relevant technical studies and sources lacking institutional credibility
Coding categories	Residue scale, surplus-use distinction, conversion pathway, PPP risk allocation, output market and institutional coordination
Output	PPP typology, framework, risk-allocation matrix and propositions

Source: Followed literature synthesis approach based on Jaakkola’s framework [27].

5. Findings and Discussion

5.1 Crop residue is a regional value-chain problem

The review indicates that India’s crop residue challenge is substantial in scale, but uneven in its regional and crop-wise distribution. Official estimates report nearly 500 million tonnes of annual crop residue generation, with Uttar Pradesh, Punjab and Maharashtra among the major residue-generating states. Cereals constitute the largest source of residues, accounting for about 70 percent of total crop residues, while rice alone contributes nearly 34 percent [4]. This concentration shows that the residue problem is strongly associated with cereal-based farming systems, particularly regions where high residue volumes coincide with short post-harvest field-clearance windows. Lan *et al.* further estimate that nearly 100 million tonnes of crop residue are burned annually in India, creating significant air-quality and public-health concerns [6]. Although available estimates vary due to differences in crop year, residue-to-product ratios, local utilisation patterns and measurement approaches, they lead to a common interpretation that: the central policy and management challenge is not the generation of residue itself, but the weak conversion of surplus residue into organised, traceable and economically viable value chains. The regional distribution of crop residues has direct implications for selecting the relevant PPP design. Dense paddy-straw regions require rapid aggregation, baling, storage and assured industrial utilisation because residues

must be removed within a short post-harvest window. Sugarcane-based clusters may be better suited to mill-linked or biorefinery-based models, while mixed farming regions may support smaller decentralised options such as biogas and composting. Punjab’s 2023 action plan illustrates this need for region-specific strategies. The state estimated nearly 20 million tonnes of paddy straw generation, with about 11.5 million tonnes targeted for in-situ management and 4.67 million tonnes for ex-situ routes such as briquetting, bioethanol, biomass power, compressed biogas and cardboard production [28]. These figures indicate that crop residue management cannot depend on a single technology or uniform model. Instead, PPP design must be aligned with local residue density, crop type, collection window, storage capacity, processing technology and output-market demand.

5.2 Policy support is rising, but market integration remains weak

India has created several policy routes for crop residue valorisation. The National Policy for Management of Crop Residues promotes in-situ management, diversified uses of residue and PPP-based uses such as power generation, bioethanol, packaging material, paper, board, biogas, composting and mushroom cultivation [4]. The National Policy on Biofuels-2018 recognises advanced biofuels, including bio-CNG, while NITI Aayog has discussed ethanol and biofuel pathways as part of clean energy

transition [30, 31]. These policies show that crop residue is already recognised as a productive input, not merely as waste.

Recent official data show progress but also expose implementation gaps. The 2026 PIB backgrounder reports that GOBARDhan covered 51.4 percent of Indian districts and had 979 operational biogas plants by 14 January 2026 [1]. The same source reports that, from 2018-19 to 2025-26, INR 3,926.16 crore was released under the Crop Residue Management initiative to Punjab, Haryana, Uttar Pradesh, NCT of Delhi and ICAR; more than 42,000 Custom Hiring Centres were established; and more than 3.24 lakh machines were supplied [1]. These numbers show public investment, but not stable ex-situ residue markets.

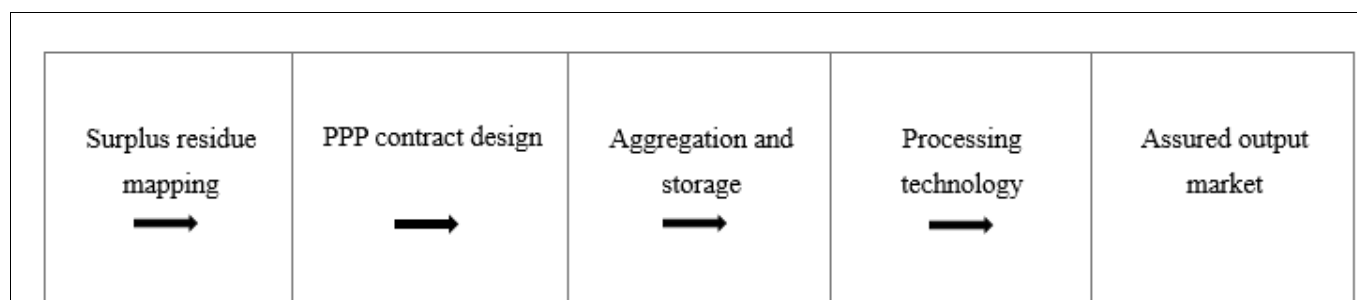
The CBG (Compressed Biogas) pathway illustrates the gap between policy ambition and market readiness. A PNGRB programme presentation reported a target of 5,000 CBG plants under SATAT (Sustainable Alternative Towards Affordable Transportation) by 2030. As of April 2026, 207 CBG plants were commissioned, but only 17 were connected through pipelines. The same presentation reported about 1,086 letters of intent by oil marketing companies and a minimum price guarantee of INR 46 per kilogram plus applicable taxes until 31 March 2029 [26]. This means that offtake policy exists, but infrastructure and market linkage remain incomplete. For PPP design, this is important because a plant cannot be commercially viable if feedstock supply, pipeline access, buyer contracts and price clarity are weak.

5.3 PPP (Public Private Partnership) design must connect feedstock, processing and offtake

The proposed framework conceptualises crop residue management as an integrated circular value chain rather than a set of isolated technological interventions. The value

chain begins with field-level identification and mapping of surplus residues and extends to the conversion and utilisation of outputs such as compressed biogas (CBG), compost, pellets, biochar, bio-oil and bioenergy. Circular economy theory provides the resource-use rationale by emphasising the continued productive use of crop residues instead of their disposal or burning [10, 11, 12, 34]. PPP governance theory explains how risks, responsibilities, investment obligations and incentives can be allocated among public agencies, private firms and community-level institutions [13, 14, 16]. Transition management further supports the framework by explaining how local pilot initiatives can be scaled into wider institutional and market change when learning, coordination and policy support are sustained over time [35].

The framework operates at three interlinked levels. At the transaction level, PPP contracts must clearly define feedstock quantity, quality standards, pricing mechanisms, collection schedules, storage responsibilities, payment terms and output offtake arrangements. These contractual provisions are essential because crop residue supply is seasonal, spatially dispersed and quality-sensitive. At the organisational level, institutions such as farmer producer organisations (FPOs), gram panchayats, cooperatives, municipalities, state agencies and agro-processing firms are required to coordinate farmer participation, residue aggregation, storage operations and technology deployment. At the governance level, the role of the state remains central in providing land access, permits, viability gap support, quality standards, monitoring systems and single-window coordination. The framework therefore suggests that crop residue burning can be reduced only when the organised value chain becomes more reliable, timely and economically attractive than open-field burning.



Source: Based on authors' own synthesis of the available literature [10, 13, 35].

Fig 1: Proposed PPP-Enabled Crop Residue Circular Value-Chain Framework

Table 2: Proposed PPP Typology for Crop Residue-Based Circular Economy in India

PPP model	Anchoring entity	Primary technology	Best-fit context	Critical public support
Village biogas cluster	FPO and gram panchayat	Anaerobic digestion	Villages with mixed organic residues and decentralised feedstock	Land, training, local mobilisation and digestate-market support
District compost hub	District municipality and private operator	Aerobic composting	Peri-urban districts and farming belts with organised organic residue flows	Certification, buyer linkage and partial offtake
Regional biomass-to-energy plant	State energy agency and private operator	Pelletisation, biomass power or CBG	Punjab, Haryana and other dense residue belts	Feedstock mapping, logistics support, storage hubs and offtake assurance
Agro-biorefinery complex	Agro-processor, sugar mill or research institution	Pyrolysis, extraction or integrated biorefining	Agro-processing clusters and sugarcane belts	Permits, R&D support, quality standards and market linkage

Source: Authors' own proposed framework based on the synthesis of available literature [2, 4, 13, 16, 19, 23].

Table 2 shows that crop residue-based PPPs require context-specific design rather than a uniform institutional model. Village biogas clusters are suited to decentralised residue settings where FPOs and gram panchayats can support local aggregation and use of digestate. District compost hubs fit areas with organised organic residue flows and nearby agricultural or peri-urban markets. Regional biomass-to-energy plants are more appropriate for dense residue belts where large-scale feedstock aggregation, storage and assured offtake are necessary. Agro-biorefinery complexes are better aligned with agro-processing and sugarcane clusters where advanced conversion technologies, research support and market linkages are available. The typology therefore suggests that effective PPP design must align feedstock availability, processing scale, institutional capacity and public support mechanisms.

The analysis further indicates that crop residue valorisation technologies can generate economic and environmental value only when they are embedded within a functioning value chain. CBG, composting, pelletisation, biochar and biomass energy provide different conversion pathways, but each depends on timely residue collection, assured feedstock supply, viable transport arrangements, farmer participation and stable output markets. Therefore, PPP design must address the full chain of residue movement, processing and offtake rather than focusing only on technology installation. Public agencies are required to support coordination, standards, land access and viability support, while private actors should contribute in investments, increasing processing capacity and developing market linkages.

5.4 Risk allocation is the central condition for PPP viability

Risk allocation is the most important managerial issue in

crop residue PPPs. Public agencies are better placed to manage land, permits, policy incentives, convergence with schemes and interdepartmental coordination. Private firms are better placed to manage technology operation, processing efficiency and product marketing. FPOs, panchayats and cooperatives are better placed to mobilise farmers, organise local collection and reduce transaction costs. If these roles are unclear, the project may fail even when the technology is sound.

Feedstock supply risk is the most serious risk because residue projects depend on regular quantity, correct moisture level and low contamination. Output-market risk is also critical because CBG, pellets, compost and biochar require buyers with reliable payment. Technology risk arises when plant design does not match actual residue quality. Breitenmoser *et al.* show that anaerobic digestion projects face problems when biomass flows are assumed rather than verified ^[19]. Wang *et al.* further show that minimum revenue guarantees can improve investor confidence when carefully designed ^[36]. These findings support the need for realistic feedstock mapping and offtake assurance before project commissioning.

Structural barriers further explain why the problem persists. Indian agriculture is dominated by small and marginal holdings, which makes direct farm-to-plant collection costly and difficult ^[37]. Wider agricultural waste literature also identifies weak collection infrastructure, low awareness, technology access gaps, economic constraints and limited training as major barriers ^[2, 3, 24]. Composting provides a clear example: it can improve soil health and recycle nutrients, but adoption remains limited when processing time, space requirement, market demand and certification are weak. Thus, a compost hub needs a business model, not only a composting pit.

Table 3: Risk Allocation and Design Safeguards for Crop Residue PPPs

Risk or barrier	Main effect	Best-placed actor	Design safeguard
Feedstock supply risk	Plant underutilisation and higher unit cost	FPO, panchayat, aggregator and operator	Catchment mapping, supply contracts, baling hubs and payment schedule
Output price uncertainty	Private revenue risk	Public agency and private buyer	Power, CBG, compost or pellet offtake before commissioning
Transport and storage cost	Residue becomes uneconomical	State, district agency and operator	Viability support, local depots, covered storage and route planning
Quality variation	Lower processing efficiency	Operator and local aggregator	Moisture standards, sorting protocol and quality-based payment
Institutional fragmentation	Delayed permits, subsidy and monitoring	District nodal authority or state bioenergy board	Single-window approval and shared dashboard
Farmer disinterest	Continued burning	FPO, panchayat and private operator	Transparent per-tonne payment, quick settlement and grievance system

Source: Based on authors' own synthesis from the available literature ^[2, 4, 13, 16, 19, 36]

5.5 Propositions, implications and interpretation

The proposed framework generates four propositions for future empirical testing. These propositions identify the key managerial and governance conditions that may influence the success of crop residue-based PPPs. Since the study is conceptual, the propositions are not treated as empirically verified findings. Instead, they provide a basis for future field-based research on how feedstock aggregation, offtake assurance, institutional coordination and farmer payment certainty affect PPP viability and farmer participation.

- **P1:** Feedstock aggregation risk reduces the commercial

viability of crop residue PPPs unless it is mitigated through FPO-led, cooperative-led or panchayat-supported collection systems.

- **P2:** Assured offtake arrangements increase private participation by reducing output-market uncertainty.
- **P3:** District-level nodal coordination improves project performance by reducing fragmented accountability across agriculture, energy, pollution-control and rural-development agencies.
- **P4:** Farmer payment certainty increases participation in ex-situ residue value chains by making collection more

attractive than open-field burning.

Together, these propositions indicate that crop residue PPPs should be evaluated not only through technology performance, but also through supply-chain reliability, contract design, farmer incentives, market assurance and institutional coordination. They provide a basis for future empirical studies to test how governance mechanisms affect project viability and farmer participation.

The implications suggest that crop residue PPPs should be designed as integrated supply-chain projects rather than isolated technology or equipment interventions. Effective contracts must define feedstock catchment, farmer payment, collection schedules, storage, quality standards, transport support, offtake arrangements and grievance mechanisms. Public agencies should support residue mapping, land access, permits, viability support, aggregation infrastructure and district coordination, while private actors should focus on technology operation, processing efficiency, product marketing and quality control. Inclusive participation of FPOs, rural enterprises and women's self-help groups can further strengthen aggregation, local service delivery, compost marketing and livelihood outcomes^[38].

6. Conclusion

Crop residue burning in India should be viewed as a value-chain and governance problem, along with its environmental implications. Although large volumes of crop residues are generated annually, weak systems for collection, aggregation, storage, processing and market linkage make burning a convenient short-term option for many farmers.

This paper examined how PPPs can support crop residue-based circular economy models in India. It suggests that technologies such as CBG, composting, pellets, biochar and biomass energy offer possible pathways for crop residue valorisation. However, their practical relevance depends on the development of reliable feedstock supply, farmer incentives, assured offtake, clear risk allocation and effective public coordination.

The paper proposed a non-empirical framework linking circular economy principles, PPP governance and residue value-chain development. It identified four indicative models: village biogas clusters, district compost hubs, regional biomass-to-energy plants and agro-biorefinery complexes. These models should be selected according to residue density, crop pattern, technology suitability, transport cost, market demand and institutional capacity.

The study contributes to the existing literature by reframing the crop residue valorisation as a governance-led circular value-chain issue. Since the framework is theoretical and not empirically tested, future research should validate it through field studies, project-level data and comparative analysis of operational PPP models.

7. Limitations and future research

The study is limited by its reliance on secondary sources of data and does not include primary evidence from farmers, firms, aggregators or public officials. Official reports may also underrepresent local implementation issues such as payment delays, contract enforcement, residue quality variation and plant-level financial constraints. The proposed PPP typology is therefore indicative and should be adapted

to regional crop patterns, residue density, institutional capacity and market conditions. The paper focuses specifically on crop residue and does not examine all agricultural waste streams or estimate project-level profitability, life-cycle impacts or technology-specific cost-benefit ratios.

Future research should empirically test the framework through field case studies, farmer surveys, stakeholder interviews and comparative analysis of successful and failed PPP projects in residue-intensive states such as Punjab, Haryana, Uttar Pradesh and Maharashtra. Methods such as techno-economic analysis, life-cycle assessment, GIS-based residue mapping, remote-sensing validation, adoption studies and financial modelling can help assess which PPP models are financially viable, environmentally sound and acceptable to farmers^[21].

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