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Crop Residue Valorization: Turning Stubble into Soil Health, Energy and Income

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India generates roughly 500 million tonnes of crop residue a year, and about 92–100 million tonnes of it is burnt in the field, destroying soil carbon and nitrogen, emitting greenhouse gases and black carbon, and polluting the air. Burning persists because the gap between paddy harvest and wheat sowing is short and labour, machinery and money are limited. This article argues that residues should be treated as resources, not waste, while recognizing that total, surplus and sustainably recoverable residue are different quantities. It reviews the effects of residue retention on soil health, the role of machinery such as the Super Straw Management System and the Happy Seeder, and the main valorization pathways: biological (composting, vermicomposting, mushroom cultivation, anaerobic digestion), thermochemical (biochar, gasification) and physicochemical (briquetting, pelletizing, second-generation ethanol). Drawing on 18 case studies, it highlights the need for life cycle assessment, product safety testing and attention to economic, market and knowledge barriers. It concludes that no single solution fits every location: residue should be retained where soil needs it, only the sustainable surplus should go to energy and industry, and options should be validated through multi-season trials before scaling up.

Keywords: crop residue, stubble burning, valorization, soil health, biochar, circular economy

The problem in the fields

Every year, Indian farms generate roughly 500 million tonnes of crop residue, and about 92–100 million tonnes of it is burnt in the field (Jain et al., 2014; Kaur et al., 2022). Rice straw is the main culprit in the north-west, with around 50 million tonnes burnt annually, while wheat straw is burnt mostly in April–May. Punjab, Haryana, Uttar Pradesh, Madhya Pradesh and Rajasthan together account for the bulk of the burning, and satellite records for 15 September to 30 November 2024 show that fires remain a widespread seasonal event across several states. The costs are easy to list. Burning destroys soil carbon and nitrogen, releases carbon dioxide, methane, nitrous oxide and black carbon, and fills the air with fine particles that cause smog and respiratory illness. It also cuts the nutrient recycling and microbial activity that keep soil productive. In short, a valuable biomass is converted into pollution.

Why farmers still burn

Burning persists not because farmers are careless but because the alternatives are hard. The gap between paddy harvest and wheat sowing is very short. Labour is scarce, machinery is limited at peak periods, holdings are small and costs are high. Where combine-harvested straw lies thick on the field, even the available machines struggle. Any solution must therefore start from these practical constraints rather than from appeals to behaviour.

Residues are resources

The central idea of valorization is simple: residues are resources, not waste. Straw, stalks, husks and cobs can protect soil, feed animals, produce energy or become industrial raw

material. In circular-economy terms, residue should re-enter the system as a product instead of ending up burnt or dumped, with simple options such as mulching and composting at one end and modern valorization at the other. Valorization does not, however, mean removing everything. Total residue, surplus residue and the sustainably recoverable fraction are different quantities. Existing uses such as fodder and bedding must be counted first, and enough residue must stay in the field to protect soil and carbon.

Residues also differ: rice straw is high in silica and ash, wheat straw is wanted as fodder, maize stover has several uses, and sugarcane trash is costly to collect while bagasse is already used at the mill.

What happens when residue stays in the soil

Retained residue reduces erosion and evaporation, moderates soil temperature and, with repeated additions, can build soil organic carbon. It feeds microbes that release and stabilize nutrients. There are catches. Straw has a wide carbon-to-nitrogen ratio, so microbes may temporarily lock up soil nitrogen, and a cooler seedbed, weeds or seeding difficulty can reduce yield. Retention does not always raise yield, and the benefits of conservation agriculture cannot be credited to residue alone (Turmel *et al.*, 2015). Nutrient budgets should also be kept honest, because residue does not fully replace fertilizer. For the rice–wheat belt, machinery makes retention practical. The Super Straw Management System spreads straw evenly behind the combine, and the Happy Seeder sows wheat directly through the residue, so burning is unnecessary. A 2025 survey of 400 wheat farmers in Punjab and Haryana showed that adoption depends on access to machines and affordable services, not on yield alone.

Pathways for using residue

Valorization routes fall into three families: biological (composting, vermicomposting, mushroom cultivation, anaerobic digestion), thermochemical (pyrolysis, gasification, torrefaction) and physicochemical (briquetting, pelletizing, hydrolysis, extraction). Composting and vermicomposting recycle nutrients but need balanced feedstock, moisture and aeration, and quality checks for maturity, pathogens and contaminants. Mushroom cultivation gives a second use, since spent substrate can be composted. Biochar, made by heating biomass with little oxygen, stores carbon for a long time, but its quality depends on feedstock and temperature, and it must be tested for PAHs, heavy metals and salinity. **Compost and biochar are complementary, not interchangeable:** compost acts quickly, biochar acts persistently. On the energy side, anaerobic digestion yields biogas and digestate, although lignin-rich straw needs pretreatment or co-digestion. Briquettes and pellets ease transport, gasification produces syngas, and second-generation ethanol uses enzymes to release sugars.

Each faces costs: drying, baling, transport, enzymes, skilled operation and emission control. Beyond fuels, residues can become boards, packaging, silica, natural pigments, bio-adsorbents and fertilizers.

Evidence from the case studies

The seminar reviewed 18 case studies. At Panipat, Haryana, a second-generation ethanol plant was designed to use 200,000 tonnes of rice straw a year to make 30 million litres of ethanol, with projected savings of about 300,000 tonnes of CO₂-equivalent annually; these are announced design targets, not verified results. In South Africa, bagasse fermented to ethanol (Jugwanth *et al.*, 2020) reached 5.82 g/L in the best of 17 experimental runs but only 0.12 g/L in the weakest, a reminder that conditions interact and laboratory yields are not plant yields. In the United States, corn stover pre-digested for seven days before co-digestion with cattle manure gave 518.58 mL of methane per gram of volatile solids, against 189 for manure alone. Other studies point to unexpected uses. Rice straw added to gypsum at 5% by weight produced partition-wall blocks with a compressive strength of 2.2 MPa, well above the 0.5 MPa needed for non-load-bearing walls. Magnetic rice-husk biochar removed chromium (VI)

from water, and pineapple-peel nanocellulose strengthened packaging film. A two-stage digestion of fruit and vegetable waste lowered the C:N ratio from about 27–34 to about 11, producing a usable biofertilizer. One finding deserves special attention: biochar cost about ₹42–45 per kg in India, with three-quarters or more of the cost coming from electricity for drying and pyrolysis. Cheap feedstock does not make cheap biochar.

Economics, life cycle and safety

A technology may not pay the farmer yet still benefit society, so private costs and social benefits should be weighed separately, with attention to distance, moisture, labour, fuel prices and utilization. Life cycle assessment should check the whole pathway from field to final product, state its baseline and uncertainty, and avoid double-counting. Net emissions should be reported in CO₂-equivalents following standard inventory guidance (Intergovernmental Panel on Climate Change [IPCC], 2006), and biogenic carbon dioxide is not automatically climate-neutral. Safeguards matter too: biochar, compost and digestate need testing, and biomass burning for energy needs particulate control.

Policy, barriers and the way forward

India now has satellite monitoring of residue management, a central machinery subsidy scheme for Punjab, Haryana, Uttar Pradesh and Delhi, and a 2022 mission asking thermal plants to co-fire 5–7% biomass pellets with coal. Even so, farmers face financial, market and knowledge barriers: high investment, volatile prices, storage losses and fear of yield penalties. Custom hiring, demonstrations, aggregation, contracts and training can help, and tools such as remote sensing, GIS and AI can map biomass and schedule machinery if validated on the ground.

Five research gaps stand out: village-scale biomass balances, long-term trials of soil carbon, yield, water and microbes, integrated life cycle and economic analysis, product safety and socio-economics, and validated mapping and reporting. The seminar proposes a five-step framework of mapping, characterization, experiments, assessment and sustainability testing.

Conclusion

Crop residues are both a resource and a soil-health asset, and no single fix works everywhere. Retain residue where soil needs it, mechanize for timely sowing, send only the sustainable surplus to energy and industry, test amendments before use, and validate with multi-season trials and life cycle assessment before scaling up. The goal is to valorize the right residue in the right place.

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