

# *Crop Residue Management: A Sustainable Pathway to Mitigate Climate Change*

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## ABSTRACT

In India, crop leftover is one of the most underutilized agricultural resources or the plant biomass left behind after harvest. Crop residue burning (CRB) has become a serious agricultural and environmental problem greatly increasing greenhouse gas emissions, air pollution and soil degradation. The production of crop leftovers has significantly expanded with growing agricultural intensification especially in rice-wheat systems. This article examines the relationship between burning crop residue and climate change; emphasizes the effects it has on the environment and society and talks about sustainable crop residue management (CRM) techniques. Critical analysis is done on both *in-situ* and *ex-situ* management techniques including Happy Seeder technology, Pusa decomposer, biochar production and biomass usage. Recent research shows that sustainable crop residue management can increase crop yields, improve soil organic carbon, cut greenhouse gas emissions by up to 50% and create new revenue streams for farmers. In order to move from residue burning to sustainable practices for climate mitigation and agricultural sustainability, the paper highlights the necessity of combined governmental support, technical adoption and awareness.

## INTRODUCTION

Climate change stands as the most significant environmental challenge of the 21<sup>st</sup> century. The decade 2011-2020 was the warmest on record, atmospheric CO<sub>2</sub> has surpassed 420 parts per million and global mean temperatures have increased by about 1.1°C over pre-industrial levels (IPCC 2023). Nearly 75% of the world's greenhouse gas emissions come from the burning of fossil fuels and 18-24% come from agricultural operations which produce carbon dioxide from burning biomass, nitrous oxide from fertilizers and methane from cattle. Crop residue burning has emerged as a visible and manageable problem. The core of this problem in India is the Indo-Gangetic Plains (IGP) rice-wheat cropping system. This cropping system produces massive amounts of straw and stubble. Farmers have little time for alternative management because there is only a 10-20 day gap between rice harvest and wheat sowing. The quickest and least expensive option is burning. However, its effects include particulate matter and greenhouse gas emissions that hasten global warming. It necessitates immediate and systematic solutions for residue management.

### **Crop residue burning:**

Crop residues include straw, stubble, husks and roots left after harvesting the main crop. These residues improve soil organic matter, enhance nutrient cycling and support microbial activity. India is the world's second largest producer of crop residue after China. India produces 500-700 million tons annually (FAOSTAT 2022). The highest percentage comes from rice (about 34% or 170 million tonnes of straw, husk and roots) which is followed by wheat (22% or 110 million tonnes of straw and stubble), sugarcane (15%), maize (11%) and cotton (8%). An estimated 140 million tonnes of this amount are surplus residue or material that has no immediate

productive end use and is prone to burning. There is a lot of concentration in the regional distribution. Uttar Pradesh produces 115-120 million tonnes annually because of its large planted area, the most of any state. Because their rice-wheat systems produce enormous amounts of paddy straw in a harvest window, Punjab (50-55 Mt) and Haryana (25-30 Mt) are the most intense burning hotspots despite producing relatively less in absolute terms. A significant share of India's yearly residue fires is caused by Punjab and Haryana combined (ICAR/MNRE 2018-2022). Besides their importance, large amounts are frequently burned rather than being used efficiently.

### **Crop residue burning and climate change:**

Crop residues store atmospheric CO<sub>2</sub> as plant biomass which acts as temporary carbon sinks. This stored carbon is quickly released as a combination of greenhouse gasses when burned. Burning crop residues releases a lot of nitrous oxide, carbon dioxide and methane into the environment. India burns over 87 million tonnes of crop residues annually. According to IISER Bhopal, burning releases 141.15 million tonnes of CO<sub>2</sub> equivalent. India's total greenhouse gas emissions from burning crop residue increased by 75% between 2011-2020 from 19,340 Gg CO<sub>2</sub> equivalent annually to 33,834 Gg annually (Deshpande *et al.* 2023). A considerable amount of pollutants is released when one tonne of crop residue is burned. Roughly 1,460 kg of CO<sub>2</sub>, methane (CH<sub>4</sub>) which is 25 times more potent than CO<sub>2</sub>, nitrous oxide (N<sub>2</sub>O) nearly 300 times more potent than CO<sub>2</sub>, carbon monoxide (CO) and fine particulate matter (PM<sub>2.5</sub>) is released which causes seasonal air quality crises throughout northern India in October-November. The effects of residue burning extend beyond climate to soil health. Burning reduces the long-term fertility of the soil by destroying almost all of the nitrogen and

organic carbon on the surface. Along with releasing 1.5 million tons of particulate matter that cause significant respiratory problems throughout northern India, it also destroys the microbial communities and soil fauna that performs nutrient cycling.

#### **Reasons behind crop residue burning:**

Open field burning is the most prevalent method of residue management in India mainly because of the reasons:

- **Time constraints:** Due to rice-wheat cropping system farmers are left with only 10-20 days gap between rice harvest and wheat sowing as field preparation after rice harvesting is time consuming so instead of residue management farmers go for residue burning as it remains the cheapest and quickest way to prepare fields for wheat sowing.
- **Mechanized harvesting:** Combine harvesters produce a significant residue burden that prevents direct seeding of the following crop by leaving 30-35 cm of standing stubble. Ultimately, burning turns into the quickest way to clear the field.
- **High machinery costs:** Rotavators, Happy Seeders and Super Seeders are residue management tools that demand a large initial investment. Large farmers can afford them but small holder farmers which constitutes about 85% of India's agriculture cannot afford.
- **Labor scarcity:** Transporting and removing straws by hand requires a lot of labour. Burning has become cheap option due to the decrease in peak-season labour availability caused by migration from rural to non-farm jobs.
- **Limited market connections:** The high silica concentration of paddy straw is not preferred as animal feed. In the absence of

accessible markets for straw as a raw material for energy or industrial feedstock, disposal costs surpass any possible revenue. These factors demonstrate that market expansion, legislative incentives and capacity building are just as important as technology solutions.

***In-situ* crop residue management:** Methods that manage the residues in the field either by keeping them on surface or by incorporating in the soil are included in *in-situ* crop residue management practices.

**Surface Retention and Mulching:** It serves as a key component of conservation agriculture i.e. applying straw as mulch on the surface. It slows down the evaporation of soil moisture, inhibits the growth of weeds, stops erosion and adds organic matter as it breaks down. Mulching increases water use efficiency while preventing greenhouse gas emissions from burning.

**Zero Till drill Seeding:** Direct drilling of seeds into standing stubbles using a zero-till ferti-seed drill that is originally developed at G.B. Pant University of Agriculture and Technology, Pantnagar in 1991. It permits wheat sowing without removing or burning rice residue. This only works well with partial residue covers not with heavy residue loads.

**Happy Seeder Technology:** Happy seeder was developed by Punjab Agricultural University (PAU), Ludhiana is a tractor-driven device that simultaneously cuts, lifts and sows seeds into standing rice stubble. Happy Seeder adopters in Punjab, Haryana increased wheat grain yields by 9.7%, decreased greenhouse gas emissions by 38.3% (from 1,750-1,080 kg CO<sub>2</sub>-eq/ha), sequestered 85.9% more carbon, enhanced soil organic carbon by 30.9%, retained 64.3% more nitrogen per hectare and used 68.7% less diesel (Gorain *et al.* 2025). The benefits of combining Happy Seeder wheat with zero-till direct-seeded rice is

confirmed by long-term conservation agriculture research (Chaudhary *et al.* 2025). These systems improved grain yields and energy efficiency and reducing the potential for global warming by up to 50% when compared to conventional puddled transplanted rice with conventional tillage.

**Super Straw Management System (Super SMS):** The Super SMS is an attachment installed on a combine harvester that cuts and evenly distributes paddy straw throughout the field. It is well adapted to the IGP's intensive rice-wheat belt which produces 45-55 million tonnes of residue a year and it prepares the field for Happy Seeder without burning.

**Pusa Decomposer:** A microbial consortium developed in 2019 by the Indian Agricultural Research Institute's (IARI) Microbiology Division, it consists of four fungal species *Trichoderma asperellum*, *T. harzianum*, *T. viride*, and *T. longibrachiatum* which accelerates the *in-situ* breakdown of paddy straw. One hectare can be treated with a liquid mixture made from just four capsules which costs Rs. 20 per kit. It reduces major air pollutants by about 80%, increases soil organic carbon by 5-15%, improves subsequent wheat yields by 5-10% and achieves 70-80% decomposition of residue within 20-25 days which takes 45-60 days for natural decomposition (Yasmin *et al.* 2025).

**Ex-situ crop residue management:** It involves the removal of crop residues from the field for various purposes such as fuel, fodder or compost without burning them.

**Composting:** Organic manures that enhances soil fertility and structure is produced by composting rice and wheat straw with cow dung and kitchen waste. Composting reduces dependence on synthetic fertilizers, stores carbon and stops methane from being released during the anaerobic breakdown of unmanaged manure.

**Mushroom cultivation:** Oyster (*Pleurotus ostreatus*), paddy straw mushroom (*Volvariella volvacea*) and white button mushroom (*Agaricus bisporus*) are edible mushrooms that may be successfully grown on rice and wheat straws. Mushroom cultivation converts low-value residue into a high value, protein rich product with a brief 14-day incubation period for *V. volvacea*, providing additional income for farmers and also prevents residue burning.

**Biochar production:** Biochar is a carbon rich material produced by slow pyrolysis at 400-500°C in low or absence of oxygen. It enhances water filtration, fertility and carbon storage and acts as a soil amendment. India's 512 million tonnes of gross agricultural wastes may yield about 212 million tonnes of biochar, which could offset 376 million tonnes of CO<sub>2</sub>-equivalent and significantly contribute to the country's climate goals (Anand *et al.* 2022).

**Bioenergy generation:** Anaerobic digestion of paddy straw can yield biogas for use in homes and power plants. In 2017, the PAU, Ludhiana built a 20 year long batch-type biogas plant that could handle 1.6 tonnes of paddy straw every batch and produce gas for three months per cycle. A circular bioeconomy can be achieved by using rice straw as a feedstock for the manufacture of bioethanol (30-42% cellulose content) and bio-oil through quick pyrolysis.

**Biomass Pellets and Briquettes:** Low density straw is compressed into dense, energy-rich cylinders (6-25 mm diameter) that can be used as fuel. The Commission for Air Quality Management (CAQM) has ordered the use of biomass pellets in brick kilns and instructed coal-based thermal power plants within 300 kilometers of Delhi to co-fire them with coal at a 5-10% replacement. This creates a large scale policy backed demand for straw that can directly reduce burning.

## CONCLUSION:

Crop residue is not waste, it is an essential agronomic and energy resource whose improper handling has serious negative effects on the environment, human health and the economy. India's yearly loss of 141 million tonnes of CO<sub>2</sub>-equivalent released due to residue burning alongwith the degradation of soil organic matter and local air quality issues is a problem that may be solved using sustainable alternatives.

*In-situ* technology, especially Happy Seeder, Super SMS and Pusa Decomposer can eliminate burning, improve soil health, reduce GHG emissions by 38-50% and increase crop yields. Biochar, biogas and biomass pellets are examples of *ex-situ* processes that contribute to India's energy security, generate income for farmers and give additional climate benefits. It is both technically and financially viable to turn agricultural residue from a disposal issue into a key component of a circular bioeconomy.

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