NEW ERA AGRICULTURE MAGAZINE

Smoke to Sustainability: Innovation in Crop Residue Management in India

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Abstract: -

Agricultural intensification in India has brought remarkable gains in food production; yet, it has also led to significant environmental challenges, among which crop residue management has emerged as a critical concern. Annually, the country generates approximately 686 million tonnes (MT) of agricultural residues, with rice and wheat alone accounting for over 198 MT about 105.24 MT and 93.51 MT, respectively. Mechanized harvesting, especially through combine harvesters, has amplified the volume of residual biomass left on fields, creating logistical challenges for timely land preparation between cropping seasons. Faced with a narrow turnaround window of just 15 to 20 days between *Kharif* harvesting and *Rabi* sowing, farmers, particularly in Punjab, Haryana and western Uttar Pradesh, frequently resort to open-field burning as a rapid and cost-effective solution. However, the environmental and socioeconomic consequences of residue burning are profound. It is estimated that between 90 and 140 MT of crop residues are burned in India each year, releasing large quantities of fine particulate matter (PM2.5), carbon monoxide, methane, volatile organic compounds and greenhouse gases such as CO_2, CH_4 and N_2O.

Introduction:

Recent reports indicate that CO_2 equivalent emissions from stubble burning increased from 19340 Gg/year in 2011 to 33,834 Gg/year in 2020. Such emissions not only contribute to regional haze episodes but also exacerbate India's air pollution crisis, with air quality indices in Delhi frequently exceeding hazardous levels (AQI >400) during peak burning periods. Beyond atmospheric impacts, residue burning undermines soil health. The combustion of one tonne of rice straw results in the loss of approximately 5.5 kg of nitrogen, 2.3 kg of phosphorus, 25 kg of potassium and 1.2 kg of sulphur, depleting soils of essential nutrients. Moreover, repeated burning alters soil physical and chemical properties, disrupts microbial communities and

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reduces long-term productivity, ultimately threatening the sustainability of agroecosystems. Public health outcomes are equally concerning, as exposure to smoke has been linked to increased respiratory and cardiovascular morbidity, eye and skin irritation and higher accident risks due to reduced visibility.

In light of these interconnected challenges, the development of sustainable crop residue management (CRM) strategies has become a national priority. Innovations such as in-situ management technologies (e.g., Happy Seeder), the use of crop residues for bioenergy production, composting and their industrial valorization offer promising pathways for transforming what was once considered waste into valuable resources. Furthermore, policy interventions under frameworks like the National Policy for Management of Crop Residue (NPMCR), along with targeted financial and technical support, are playing a pivotal role in encouraging adoption at scale. This article delves into the scale and complexity of India's crop residue problem, unpacks the environmental and socio-economic impacts of residue burning and explores promising innovations and policy measures. By reimagining crop residues not as a waste burden but as a resource with multifaceted value, India has the potential to transition from a system clouded by seasonal smoke to one powered by sustainability, resilience and prosperity.

Types of crop residues

Crop residues can be classified into two main types: field residues and process residues, each offering distinct management opportunities and potential uses.

Field residues, such as stalks, stubble, leaves and husks left after harvest, can be managed in various ways, including in-situ incorporation into the soil, surface retention, or removal for alternative uses like composting and bioenergy production. When left in the field, these residues help reduce soil erosion, conserve moisture and enhance soil fertility.

Process residues, such as rice husk, sugarcane bagasse and molasses, are byproducts of crop processing. These residues find application in industries for energy generation, composting and the production of biodegradable products, thus offering economic value and contributing to waste reduction.

The nutrient content of these crop residues further highlights their agronomic significance. For example, rice residues contain 0.61% nitrogen, 0.18% phosphorus (P_2O_5) and 1.38% potassium (K_2O), while wheat residues provide 0.48% nitrogen, 0.16% phosphorus and 1.18% potassium. Maize residues offer 0.52% nitrogen, 0.18%

phosphorus and 1.35% potassium and sugarcane residues have slightly lower nitrogen content (0.40%) but similar levels of phosphorus (0.18%) and potassium (1.28%). Pulses stand out with their higher nitrogen content (1.60%) along with 0.51% phosphorus and 1.75% potassium. By incorporating these residues back into the soil, farmers can promote nutrient cycling, enriching the soil with essential nutrients like nitrogen, phosphorus and potassium. This practice not only reduces the need for synthetic fertilizers but also enhances soil health over time, offering both environmental and economic advantages. Therefore, crop residues, whether field or process residues, play a critical role in enhancing agricultural sustainability, improving soil fertility and reducing dependence on external inputs, ultimately contributing to a more resilient and sustainable farming system.

Crop Residue management

Crop residues, often considered waste, can be a valuable resource for agricultural sustainability, environmental health and rural livelihoods. Several sustainable crop residue management (CRM) strategies offer both environmental and economic benefits:

- **In-situ Incorporation**: Using tools like rotavators and mulchers, crop residues are integrated into the soil, boosting organic carbon, microbial biomass and nutrient cycling. This approach can increase soil organic matter by 10–15% over 3–5 years, improving soil structure and resilience.
- **Mulching and Conservation Agriculture**: Leaving residues on the soil surface conserves moisture, prevents erosion and improves soil fertility. Machines like the Happy Seeder allow direct sowing into paddy residues, reducing the need for burning and increasing wheat yields by 5–7% compared to conventional tillage.
- **Composting and Vermicomposting**: These processes decompose residues into nutrient-rich organic matter, reducing reliance on chemical fertilizers and enhancing soil fertility by improving nutrient bioavailability and microbial diversity.
- **Bioenergy Generation**: Crop residues can produce biogas, bioethanol and biomass-based electricity. India has the potential to generate approximately 16,700 MT of bioenergy annually, reducing fossil fuel dependence and contributing to renewable energy goals.
- **Industrial Applications**: Crop residues are used in industries like paper manufacturing, biodegradable product production and particle board manufacturing, creating income

streams for farmers and promoting circular bioeconomy models.

- **Biochar Production**: Pyrolysis of crop residues creates biochar, which improves soil properties, enhances nutrient use efficiency and serves as a method for carbon sequestration.
- **Mushroom Cultivation**: Crop residues like paddy and wheat straw are used as substrates for growing high-value mushrooms, providing farmers with a profitable, low-input venture.
- **Animal Bedding and Feed**: Crop residues, though low in digestibility, can be enhanced through treatments like urea-ammoniation or molasses enrichment. This makes them suitable for livestock feed and bedding material, offering additional income opportunities for farmers.

Government initiatives and policy support

The Government of India has implemented several initiatives to address the environmental, health and economic challenges posed by crop residue burning. Key programs include:

- **Sub-Mission on Agricultural Mechanization (SMAM)**: Provides financial assistance for the purchase of CRM equipment like Happy Seeders, Straw Reapers and Zero till Drills.
- **Rashtriya Krishi Vikas Yojana (RKVY)**: Supports state governments in conducting CRM demonstrations and capacity-building programs.
- **Agro Machinery Service Centres (AMSCs)**: Enable farmers to access costly CRM machinery at affordable rates.
- **State-Level Demonstrations**: Raise awareness and confidence through on-field demonstrations of CRM technologies.

Despite these efforts, adoption remains uneven, with barriers such as pest concerns, operational difficulties and labour shortages preventing full uptake. A 2024 Council on Energy, Environment and Water (CEEW) report found that nearly 50% of farmers in Punjab continue burning residues, even with access to CRM machinery. Overcoming these barriers will require integrated efforts, including technology dissemination, behavioural change and institutional support.

Future thrust

A comprehensive strategy for effective crop residue management (CRM) should involve several key approaches. Public-Private Partnerships (PPPs) can play a vital role by fostering collaboration between government, industry and farmers to develop residue-based value chains, such as bioenergy and bioplastics. Extension and awareness campaigns are crucial, with Krishi Vigyan Kendras (KVKs), NGOs and digital platforms strengthening efforts to educate farmers on the benefits of CRM and share success stories. Additionally, offering financial incentives for sustainable practices while imposing penalties for residue burning will help ensure that alternatives are both accessible and viable. Research and development (R&D) investments are needed to develop cost-effective, context-specific CRM technologies tailored to different agro-ecological conditions. Finally, an integrated policy framework that aligns the efforts of agriculture, energy, environment and health ministries is essential for a coordinated and effective approach.

Conclusion

Despite India's progress in promoting sustainable crop residue management, several challenges remain. A holistic strategy that integrates government initiatives, private sector participation, extension services and targeted incentives is crucial to effectively transform crop residues from a burden into a valuable resource. Such an approach will not only enhance environmental sustainability but also boost agricultural productivity and foster rural economic growth.