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Rice Residue Burning: It's issues & Sustainable Management in India: A Review

Dr. Prachi Shukla[1], Akanksha Singh[2], Dr. Suman Prasad Maurya[3], Sarita Srivastav[1]
[1]Assistant Professor, Department Human Development & Family Studies, College of Community Science
[2]Subject Matter Specialis, Krishi Vigyan Kendra Kotwa Azamgarh-I,
E-mail: singhakku3216@gmail.com
[3]Retired Professor, Acharya Narendra Dev University of Agriculture &Technology Kumarganj, Ayodhya

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ABSTRACT

Among different crops, cereals generate maximum residues (352 Mt), followed by fibres (66 Mt), oilseeds (29 Mt), pulses (13 Mt) and sugarcane (12 Mt). Cereal crops (rice, wheat, maize, millets) contribute 70%, while rice crop alone contributes 34% to the crop residues. Rice is grown in more than 100 countries around the world with about 40 countries rice produced more 10-20 lakhs tones of rice and the total rice production in world for year 2022 was 776,461,457 metric tonnes, Rice production also produces the challenges of the management of its residues that is in the form of paddy straw, roots, un-grained paddy and the paddy husk. According to Food and Agriculture Organization Corporate Statistics database, India in 2022 was the highest producing paddy rice followed by china [18]. India, therefore, faces the challenge of management of its rice residues. Rice residue burning is a great concern for environment, animal and human health. The burning of rice crop residue causes atmospheric pollution by emitting trace gases which forms 'Black Cloud' adversely affects human health as well as environment. The air pollutants are also a hazard to people's health particularly to those within local proximity to paddy areas. The literatures and studies reveal losses in mineral and biomass. Nutrient concentration in residue depends on the soil condition, crop management, variety and season. The paper highlights the reasons for burning rice crop residue especially with respect to India and the measures taken to manage them. This paper has been expanded to include an analysis of contemporary government interventions, socio-economic dimensions, and future-oriented strategies for rice residue management in India. By integrating technological advancements, policy frameworks, and farmer-centric practices, this review seeks to present a holistic understanding of sustainable residue management.

Introduction

The Indian agriculture sector has been growing at an average annual growth rate of 4.6 per cent during the last six years. It grew by 3.0 per cent in 2021-22 compared to 3.3 per cent in 2020- 21 [1]. According to a press release, in recent years, India has also rapidly emerged as the net exporter of agricultural products. The Economic Survey 2023 revealed that in 2022-23, India's agricultural exports reached a record high of $52.50 billion. This was a 20% increase from 2020-21, when exports were $41.3 billion. In 2020-21, exports of agriculture and allied products from India grew by 18 per cent over the previous year [2]. The interventions of the Government have been in line with the recommendations of the Committee on Doubling Farmers' Income, which had identified improvement in crop and livestock productivity, diversification towards higher value crops, better resource efficiency [3]. As per Second Advance Estimates for 2022-23, Total Foodgrain production in the country is estimated at record 3235.54 lakh tonnes which is higher by 79.38 LMT as compared to previous year 2021-22.Total production of Rice during 2022-23 is estimated at (record) 1308.37 lakh tonnes. It is higher by 13.65 lakh tonnes as compared to previous year [4]. As a result, food grains will continue to be the primary pillar of food security, and rice, wheat, and pulses will continue to be staple foods for the vast majority of the rural population. West Bengal is the top rice producing state in the country, accounting for around 13-15% of total rice output, with Uttar Pradesh (13.75 million tonnes) and Punjab (12 million tonnes) dealing for second and third place, respectively. Other important rice producing states in India are Tamil Nadu, Andhra Pradesh, Bihar, Chhattisgarh, Odisha, Assam, and Kerala [5, 6].

Rice (Oryza sativa L.) is the primary staple food for more than half of the world's population. It is believed that rice is the first cultivated crop in the world. 90-95% of the total rice produced in the world is in Asia [7,8]. Rice, wheat, and maize are the world's three leading food crops and together constitute 51% of total calories consumed [9]. Rice is one of the most widely consumed grains in the world. China ranks first and India ranks second in rice consumption worldwide [10].

When cereal crops are harvested, it is estimated that half of the process ends with agricultural waste or crop residue as straw. It is a non-edible product, often left in the field after harvesting. Out of various crops grown, rice, wheat and sugarcane are prone to crop residue burning. These crops are preferred by farmers since they provide higher economic return, as compared to other crops. Harvesting of various crops generates large volume of residues both on and off farm. Ministry of New and Renewable Energy estimated that about 500 Mt of crop residues are generated annually. The generation of crop residues is highest in Uttar Pradesh (60 Mt), followed by Punjab (51 Mt) and Maharashtra (46 Mt). Among different crops, cereals generate maximum residues (352 Mt), followed by fibres (66 Mt), oilseeds (29 Mt), pulses (13 Mt) and sugarcane (12 Mt). Cereal crops (rice, wheat, maize, millets) contribute 70%, while rice crop alone contributes 34% to the crop residues. Sugarcane residues consisting of top and leaves generate 12 Mt, i.e., 2% of the crop residues in India. Crop residues are primarily used as bedding material for animals, livestock feed, soil mulching, bio-gas generation, bio-manure/compost, thatching for rural homes, mushroom cultivation, biomass energy production, fuel for domestic and industrial use, etc. However, a large portion of crop residue is burnt 'on-farm' primarily to clean the field for sowing the next crop. The problem of 'on-farm' burning of crop residues is intensifying in recent years due to shortage of human labour, high cost of removing the crop residue from the field and mechanized harvesting of crops. As per available estimates, burning of crop residues is predominant in four states, namely, Haryana, Punjab, Uttar Pradesh & West Bengal [18]. Traditionally, paddy straw was seen as a versatile by-product of rice cultivation because it was used in many ways including fodder for livestock and as a bedding material. However, the increase in productivity and area under cultivation of rice has led to a huge production of rice straw. Moreover, mechanization decreased the animal dependency and hence the feed requirement. So, the most effective way of disposing of the residue is seen as burning of biomass in the paddy field. It is important to mention that open field burning is a widely practiced method all over the world; although its intensity varies [12] (Gadde et al., 2009).

1.Major Reasons for Burning of Crop Residues at the Farmer's Field

Literature reviewed bring forth that the major reasons for burning of crop residue at farmer's field were as follows:

- Sowing window
- Scarcity of labour for manual harvesting.
- Use of combine harvester with the growth of farm mechanization.
- Timeliness in operation and clearing of field:
- Control of weeds/pests and short-term availability of nutrients.

1.1 Sowing window – the duration between harvesting of crop of one season and sowing time of crop of other is very short for preparing the field. So, often farmers find it quicker to get rid of the crop residue by burning them on their fields and use the duration for sowing of the next crop. Main cause of paddy residue burning is very narrow window of time (20-30 days) available between the harvesting of rice and sowing of wheat. The need to prepare fields for the wheat crop results in hasty burning of rice residue (Ahmed, Ahmad and Ahmad, 2015).

1.2 Scarcity of labour for manual harvesting – availability of labour is limited for harvesting manually which is also time taking. During the harvesting of paddy crop with combine harvester, about 80% of the residues are left in the field as loose straw or in other words, we can say that it leaves 6-10 cm of paddy stalk on the field and the removal of the paddy stalk that remains in the field is a labour intensive process. Several important reasons like short time span for sowing wheat, limited farm mechanization, scarce manpower and poor acceptability of paddy straw as fodder are the root causes behind this residue burning (Dutta et al., 2022).

1.3 Cost involved in harvesting and preparing field - The practice of removal of rice residue (Full Removal) involves the collection, making of bundles, loading, transporting, unloading and stacking of rice straw. All these operations involve labor. To obtain the cost involved in fully removal of residue from rice fields without burning them, was quite high than fully burning the straw on the fields itself. The estimated the total labor time spent on all these operations per acre and multiplied it by the prevailing wage rate for unskilled labor in the area in order to obtain the labor cost [25]. The rise in labour cost and the subsequent costly availability of mechanical implements lead to about 85-90% of paddy straw burnt in-situ in the field [26].

1.4 Use of combines with growth of farm mechanization – Dixit et al. (2022) noted that almost complete rice area harvesting is performed with combine harvester which leave huge chunk of loose straw. Rice residues are often burned because managing of huge amount of straw in short window period is difficult task. Moreover, the loose straw hinders tillage and seeding operations for the following crop [26]. Thus, use of machines for harvesting is good option but the crop residue as paddy straw and stubbles have to be manually removed especially in case of small and marginal farmers, therefore, the burning is economically and time saving. Also the combines are usually used on large farm holding. These farms produce more rice residue and need appropriate management.

1.5 Timeliness in operation and clearing field – the rice field need to be cleared timely for preparation of land for next operations. Burning out residue is easy and quicker disposal of the residue.

1.6 Control of weeds/pest and short-term availability of nutrients – Rice residues are also burnt to destroy weeds and pest that might infest the successive crop. The destroying of weeds through burning is basically done to ensure the availability of nutrients of the soil to the next crop to be sown in the field. It is also opined that the ashes of the paddy straw and stubbles provide a good source of potassium in the field.

2.Adverse Effects of Rice Residue Burning on Humans and Environment :

The burning of rice crop residue causes atmospheric pollution by emitting trace gases which forms ‘Black Cloud’ adversely affects human health as well as environment. The air pollutants are also a hazard to people’s health particularly to those within local proximity to paddy areas.

2.1 Loss of Nutrient concentration in residue: Generally crop residues of different crops contain 80% of Nitrogen (N), 25% of Phosphorus (P), 50% of Sulphur (S) and 20% of Potassium (K). If the crop residue is incorporated or retained in the soil itself, it gets enriched, particularly with organic C and N. Paddy is a water-intensive crop and there is high usage of water in its cultivation. Paddy cultivation can legally begin only around mid-June when the monsoons typically arrive in North India. Crop residue is a good source of nutrients and important component for the stability of agricultural ecosystems. About 40% of the N, 30-35% of the P, 80-85% of the K and 40-50% of the S absorbed by rice remain in the vegetative parts at maturity. Therefore, one ton of rice straw contains 5-8 Kg N, 0.7-1.2Kg P, 12-17 kg K, 0.5-1kg S, 3-4 K Ca, 1-3Kg Mg and 40-70Kg Si (Dobermann and Witt, 2000). Nutrient concentration in residue depends on the soil condition, crop management, variety and season. It is estimated that burning of one tonne of rice straw accounts for loss of 5.5 kg Nitrogen, 2.3 kg phosphorus, 25 kg potassium and 1.2 kg sulphur besides, organic carbon.

2.2 Impact on soil properties: Heat from burning residues elevates soil temperature causing death of beneficial soil organisms. Frequent residue burning leads to complete loss of microbial population and reduces level of N and C in the top 0-15 cm soil profile, which is important for crop root development.

2.3 Emission of greenhouse and other gases: Crop residues burning is a potential source of Green House Gases (GHGs) and other chemically and radiative important trace gases and aerosols such as CH4, CO, N2O, NOX and other hydrocarbons. It is estimated that upon burning, Carbon (C) present in rice straw is emitted as CO2(70% of Carbon present), CO (7%) and CH4(0.66%) while 2.09% of Nitrogen (N) in straw is emitted as N2O. Besides, burning of crop residue also emits large amount of particulates that are composed of wide variety of organic and inorganic species. Many of the pollutants found in large quantities in biomass smoke are known or suspected carcinogens and could lead to various air borne/lung disease.

Why Rice residue burning has negative consequences?

Rice straw burning in the field has an adverse effect on soil and environment (Table 1).

Table 1: Emissions from open burning of rice residue in India.

S.N.	Name of Gases/Pollutants	Rice straw	
		EF (g/kg dm)	India (Gg)
1	CO_2	1,515	127,260
2	CH_4	2.70	227
3	N_2O	0.07	5.88
4	CO	92	7.728
5	NO_X	3.38	588
6	SO_2	0.40	34
7	Total particulate matters	13.00	1,092

8	**Fine particulate matters (PM 2.5)**	3.90	328

Source: Chaudhary et al., 2016.

The practice of burning the residues causes large losses up to 80% N, 25% P and 21% K and 4–60% of S. It also kills soil borne deleterious pests and pathogens. One of the advantages of burning is that it clears the land quickly of residues before the next crop is established, thus, facilitating seed germination and establishment (Sidhu and Beri, 2008). The stubble burning leads to wastage of valuable resources which could be used as a source of carbon, bio-active compounds, feed and energy for rural households and small industries. It further acts as a significant source of the particles of aerosol such as (PM10) and (PM2.5), thereby, affecting the quality of the air locally and radiation budget (Chang and Engling, 2013). Heat generated from the burning of crop residues elevates soil temperature and consequently active beneficial microbial population with their diversity is reduced significantly, impacting adversely on the nutrient transformation in the soil. As a result, the succeeding crops suffer from nutrient deficiencies. Although the effect is temporary and the microbial population is recovered within a certain period, but repeated burnings may exhibit permanent effect on the population of soil microorganisms making the soil unfertile due to reduction in organic matter content accompanied with significant reduction in nutrient mineralization in the soil.

3.Sustainable Ways Towards Rice Residue Management :

Rice residues are presently managed through different applications in various areas of life namely construction, mechanical removal from fields, agriculture applications,

3.1. Construction application: Crop residues are processed for use in construction applications. For example, rice husk is used as a cement mix. Banana peels and sugarcane wastes are utilized in the paper industry. These alternative measures have been suggested by scientists and agriculturists over the past decade as an alternative to crop residue burning, but due to lack of awareness and social consciousness among the farmers, these measures have not been fully implemented.

3.2. Baling and removing the straw: Removing the crop residues from the field is an alternative for management that would reduce burning of residues and utilize them for other purposes. Under baling/collection, baler is used to make compact bales of paddy stubble. Two machines are required to enable this- raker for heaping straw into rows and baler for compacting the straw into bales. Raker makes single linear heaps of straw and baler compacts it into rectangular or cylindrical bales depending of type of baler used. Once straw is baled at the field, custom built trolleys are used for transporting these bales directly to end users or conversion plants for further processing rice straw into useful products or fuels (ex-situ management). This practice is also producing lesser quantity of residue during harvesting.

3.3. Agricultural applications: Removal/bailing practice for paddy straw is utilizing in These include mushroom cultivation, composting, biochar, and in-situ management through mechanical intensication. Each is discussed below:

Mushroom Cultivation: Straw of rice and wheat is an excellent substrate for mushroom cultivation. Generally, edible mushrooms are used not only for their nutritional value but are now also in demand for their medicinal properties and therapeutic attributes (Chang, 1996; Ribeiro and Salvadori, 2003; Borchers et al., 2004). Among various mushrooms, Agaricus bisporus (button mushroom), Calocybe indica (milky mushroom), Pleurotus ostreatus (oyster mushroom), Volvariella spp. (paddy straw mushroom), Lentinula edodes (Shiitake mushroom) and Auricularia polytricha (Jew's ear mushroom) are commonly available edible species in India. Button mushroom is grown on composted substrates and a variety of substrates have been used in composting world over. These composted substrates show huge variation in the yield of button mushroom, indicating thereby the role of various physicochemical factors and the compositional changes in the substrate (Sharma, 1991) as these are important factors contributing to the composting process and hence to yields. Consequently, the growing of mushrooms on paddy straw is one such avocation, which if put into practice, cannot only lead in the improvement of dietary and economic standards of the masses but also in combating environmental pollution due to burning of this precious agro-waste. Moreover, paddy straw is cheaper. Therefore, it can be profitably utilized for the mushroom production to combat the day after day increasing cost of mushroom production. Although paddy straw does not provide good physical structure to compost, yet it gives good results when mixed with wheat straw in different ratios (Rana, 1998). Therefore, the growth of mushrooms fully depends upon the compost for their nutrition. Efficiency of the mushrooms to utilize various constituents of compost depends upon the substrate used in composting which further depends on many physiochemical factors responsible during the composting process and mushroom growth. Mushroom cultivation of Mushroom variety such as Dingri mushroom is cultivated on soaked and treated rice straw in proliferated polythene bags with mushroom spawn and feeding media.

Livestock feed: Rice straw, a byproduct of rice cultivation, presents a potential feed source for livestock, particularly ruminants. In areas facing feed scarcity, it offers a readily available and cost-effective option.

Feeding only rice straw does not provide enough nutrients to the ruminants to maintain high production levels due to the low nutritive value of this highly lignified material. The high level of lignification and silicification, the slow and limited ruminal degradation of the carbohydrates and the low content of nitrogen are the main deficiencies of rice straw, affecting its value as feed for ruminants [23] (Sarnklong, Cone, Pellikaan and Hendriks, 2010). FAO reported that rice straws are a poor livestock feed, and rice straw is no exception. It contains about 80 percent of substances which are potentially digestible and are therefore sources of energy, but actual digestibility by ruminants is only 45 to 50 percent. Furthermore, the amount an animal can eat is limited to less than 2 percent of body weight because of the slow rate at which it is fermented in the rumen. The net result is an energy intake which provides little or no surplus energy for growth, work or production. The most important consideration in obtaining more animal products from straw in the Asian setting is to improve digestibility and intake so that more energy is available for productive purposes. Protein supplements increase intake, while the alkali treatment of straws increases digestibility and usually voluntary intake as well. The chemistry of straw and its digestion and the chemical changes caused by alkali treatment are receiving increasing attention from animal nutritionists. Straws contain only 3 to 5 percent crude protein. Animals on an unsupplemented straw diet will usually not gain any weight and very often will actually lose weight. To obtain any production the straw must be supplemented, preferably with both nitrogen/ protein and energy. For good growth on straw diets, a level of 8 to 10 percent protein is needed for young stock; this also improves consumption and thus increases energy intake. The level of phosphorus in rice straw (0.02 to 0.16 percent) is less than the level of about 0.3 percent that animals need for growth and normal fertility. A level of about 0.4 percent of calcium in the diet is usually considered adequate for livestock, and many samples of rice straw have this amount, the range being from 0.25 to 0.55 percent. Nevertheless, many balance experiments with cattle fed rice straw have shown negative balances of calcium even when the calcium content of the straw was apparently adequate (Nath et al., 1969). While the significance of these negative calcium balances has been questioned (Negi, 1971), the fact remains that in the same experiment higher positive calcium balances have been observed on wheat straw and sorghum stover diets than on rice straw diets, even though the calcium intake on the rice straw diets was higher[24]. It would therefore seem prudent to feed a calcium supplement with rice straw diets. and areas of copper deficiency are widespread in India and occur in a number of rice-growing areas. Thus the routine provision of supplements containing at least these two trace minerals would seem to be warranted [24]. Rice straw differs from other straws in having a higher content of silica (12–16 vs. 3–5 percent) and a lower content of lignin (6–7 vs. 10–12 percent). Whereas in all other straws lignin is the chief cause of low digestibility, in rice straw it is silica. Rice straw stems are more digestible than leaves because their silica content is lower; therefore the paddy crop should be cut as close to the ground as possible if the straw is to be fed to livestock. Thirty percent of rice straw silica is dissolved in the digestive tract, absorbed as silicic acid and excreted in the urine. The concentration of silicic acid in urine far exceeds its solubility limit, and thus it polymerizes into large insoluble molecular aggregates. With some species of grass containing 4–5 percent silica, silicious Urinary calculi are commonly formed in sheep and cattle. Though rice straw contains nearly three times more silica than any of these grasses, urinary calculi are not, in general, a serious problem. When they occur in stock fed rice straw they are probably made up of carbonates and bicarbonates [24]. (2025)

Surface retention and mulching: Mulching is a conservational and climate smart agricultural practice where crop residues are retained onto the surface as a cover/mulch by chopping/shredding it to smaller pieces and spreading it evenly on the ground. Surface retention of residue in soil can be managed by the technology of happy seeder and zero tillage. It was also observed that with the practice of surface retention of residues enhances the soil NO3 by 46%, N uptake by 29%, and yield by 37% than burning. The soil physical properties viz. soil moisture, temperature; aggregate formations are also affected by residue management practices. Surface retention is also act as mulch and mulching play important role in suppression of weeds. There are numerous benefits of rice crop residue retention as mulch in cropland. On-site residue retention improves soil physical, e g., structure, infiltration rate, plant available water capacity, chemical, e.g., nutrient cycling, cation exchange capacity, soil reaction and biological, e.g., SOC sequestration, microbial biomass C and species diversity of soil biota.

Residue incorporation: Crop residue incorporation involves mixing or blending crop residue with 0-15cm top soil layer. Soil incorporation or mixing is similar to mulching as far as the first stage is concerned which is chopping/cutting the rice straw and evenly spreading it in the field. The key line of differentiation here is that straw is not retained as the top layer. In-situ incorporation of residue increases the soil nutrient as N, P, K and SOM.

Composting: Composting is not a new concept to India. While small scale backyard composting and making compost from organic material in management of solid wastes (MSW) is common. However, there is no information in the literature to prove that it is also the case for the agriculture industry in India. In a publication, Hettiarachchi et al. (2018) discussed the common challenges faced in organic waste composting. This is one of the challenges but the agricultural community does not have to worry about if they make compost on-site out of their crop residue as it can be easily fed back to the same agricultural lands. Higher organic carbon content in crop residue makes it an ideal raw material for compost similar to animal manure and food waste. Composting is the natural process of rotting or decomposition of organic matter by microorganisms under controlled conditions (Misra et al.,2003). As a rich source of organic matter, compost plays an important role in sustaining soil fertility and ultimately achieving sustainable agricultural productivity.

Production of Biochar: As a measure for controlling GHG emissions, agricultural research community has been constantly looking for ways to effectively enhance natural rates of carbon sequestration in the soil. This has increasingly interested the scientists in applying charcoal, black carbon and biochar as a soil amendment to stabilize the SOC content. These techniques are viewed as a viable option to mitigate GHG emissions while considerably reducing the volume of agricultural waste. The process of carbon sequestration essentially requires increased residence time and resistance to chemical oxidation of biomass to CO2 or reduction to CH4, which leads to a reduction of CO2 or CH4 release to the atmosphere (Srinivasarao et al., 2013). The partially burnt products are pyrogenic carbon/carbon black and become a long term carbon sink with a very slow chemical transformation, ideal for soil amendment (Izaurralde et al., 2001; McHenry, 2009). Biochar is a fine-grained carbon-rich porous product obtained from the thermo-chemical conversion called the pyrolysis at low temperatures in an oxygen-free environment (Amonette and Joseph, 2009). It is a mix of C, H, N, O, S and ash in different proportions (Masek, 2009). When added to the soil, the highly porous nature of the biochar helps in improved water retention and increased soil surface area. It mainly interacts with the soil matrix, soil microbes, and plant roots (Lehmann and Joseph, 2009), helps in nutrient retention, and sets off a wide range of biogeochemical processes. Many researchers have reported an increase in pH with its usage (Tryon,1948; Gaunt and Cowie, 2009). Specially, biochar is used in various applications such as the water treatment, construction industry, food industry, cosmetic industry, metallurgy, treatment of wastewater and many other chemical applications. In India, currently use of biochar application is limited and mainly seen in villages and small towns. Based on its wide applicability, promotion of biochar production and usage seems to be a better proposition in India In-situ Management with Mechanical Intensification.

Bio-oil production. : Kumar, Jain and Kumar (2025) explored a novel process to utilize rice straw by converting it into bio-oil through direct thermal liquefaction of rice straw using three different solvents: ethanol, guaiacol, and their mixtures, at temperatures ranging from 220 °C to 320 °C, with a fixed residence time of 20 min in an autoclave reactor. The highest bio-oil yield was achieved at 280 °C, with guaiacol producing the highest yield of 83 wt%, followed by the ethanol + guaiacol mixture and ethanol solvent yielding 75 wt% and 63 wt% of bio-oil, respectively. The study also explored a two-stage liquefaction process that involved an initial liquefaction at 220 °C using ethanol, followed by a second liquefaction of the resulting solid residues at 240–280 °C with guaiacol. This process achieved a maximum bio-oil yield of 74.7 wt% at 260 °C [30]. Biswas, et al. (2018) also The pyrolysis of rice straw has been carried out using under CO_2 environment at temperatures ranging from 300 to 450 °C to study the effect of CO_2 and temperature. The results showed that both the temperature and reaction atmosphere had an influence on the and nature of the products. The main compounds observed in the bio-oil were , 2-ethyl-Phenol, 2-methyl-Phenol, 2-methoxy-Phenol, 2-Methoxy-4-vinylphenol, 2, 6-dimethoxy-Phenol. Bio-oil produced at 400 °C indicated the higher proton percentage 34.5% in this region (1.5–3.0 ppm), higher than the other conditions. The bio-chars were in nature [31].

Other ways of rice residue management:

Decomposing rice residue in the fields: There are technology of decopmositing rice straw and residue in the field through intervention of incorporating and activating microbial reaction in the residue. Rice residue takes longer time to decompose naturally due to its contents, slow microbial action and temperature of the environment especially in the northern states of India where the temperature is less than 30 degree which restricts the growth of microbes that decompose the residue.

Mechanization improvement: Combines used to harvest rice leave loose straw in the fields that needs management. A crop residue management machine that can chop paddy residues and mix them with the soil of the combined harvested paddy field. For this purpose, two important units are attached to the developed machine: the chopping and incorporation units. The tractor operates this machine as the main source, with a power range of about 55.95 kW [29].

4. Government Initiatives and Policy Frameworks in India

The Government of India has recognized crop residue burning as a serious environmental and agricultural challenge. Several programs and policy initiatives have been launched in recent years to address this issue. The **National Policy for Management of Crop Residue (NPMCR)**(2014) emphasizes in-situ residue management, promotion of machinery like Happy Seeders and Rotavators, and awareness campaigns through KVKs (Krishi Vigyan Kendras). Under the Sub-Mission on Agricultural Mechanization (SMAM), subsidies up to 80% are provided to individual farmers and custom hiring centers for purchasing residue management equipment. Additionally, the Crop Residue Management (CRM) Scheme introduced in 2018 specifically targets Punjab, Haryana, Uttar Pradesh, and NCT Delhi to curb stubble burning through mechanization and training. The National Clean Air Programme (NCAP) and the Commission for Air Quality Management (CAQM) in NCR region have also enforced legal frameworks and incentive-based interventions. Further, states like Punjab and Haryana have adopted reward-based monitoring systems, offering financial incentives to panchayats that achieve zero-burning status.

5. Technological Innovations in Residue Management

Technological advancements have been pivotal in reducing the practice of open-field residue burning. Machines such as the Happy Seeder, Super SMS, Rotavator, Straw Baler, and Reaper Binder enable direct sowing and straw management. The PUSA Decomposer, developed by the Indian Agricultural Research Institute (IARI), contains ligninolytic fungal strains that accelerate the decomposition of paddy straw within 25 days, turning it into organic manure. Emerging technologies like bioenergy conversion systems, biogas plants, and bioethanol production units utilize rice straw as feedstock, offering dual benefits of waste reduction and energy generation. Artificial intelligence (AI) and remote sensing tools are also increasingly being used to monitor burning activities and assess air quality impacts.

6. Socio-Economic Impacts of Rice Residue Management

Residue management practices directly affect rural livelihoods, labour dynamics, and farm economics. The cost of mechanization and labour shortages have historically driven farmers toward burning. However, adoption of sustainable alternatives like composting, mushroom cultivation, and biochar production can enhance farm incomes. According to the Indian Council of Agricultural Research (ICAR, 2023), farmers adopting in-situ management technologies have reported a 15–20% reduction in fertilizer costs and 10–12%

yield increase in subsequent wheat crops. Women farmers and rural youth, through SHGs and agri-startups, are also playing an increasing role in straw-based enterprises, such as packaging, handicrafts, and bioenergy ventures, contributing to rural entrepreneurship and job creation.

7. Future Prospects and Policy Recommendations

To ensure the long-term sustainability of rice residue management, the following strategies are recommended:

1. Integrated Residue Management Models combining bioenergy, composting, and livestock feed utilization.
2. Enhanced financial incentives for farmers adopting in-situ methods and penalties for repeated burning.
3. Stronger research–extension linkages, enabling KVKs and universities to demonstrate low-cost technologies.
4. Public–Private Partnerships (PPP) to establish straw-based biomass power plants.
5. Awareness and education campaigns at grassroots levels, focusing on the environmental and health consequences of burning.
6. Promotion of circular economy approaches, transforming paddy straw into valuable inputs for energy, construction, and agriculture.

Conclusion

Crop residues are not the agricultural waste but it is most valuable for the managing system as well as for human welfare. As crop residues have multiple functions in the soil, affecting directly and indirectly diverse ecosystem services, investments in research to better understand the impact associated with residue management are essential to define strategies for the industrial use of this raw material. The main advantage of Crop Residue Management includes fuel and labour savings as well as long-term benefits to soil structure and fertility. Control of burning of crop residue to prevent environmental degradation and loss of soil nutrients and minerals by promotion of in-situ management (incorporation in soil, mulching, baling/binding for use as domestic/industrial fuel, fodder) of crop residue; Diversified use of crop residue for various purposes like charcoal gasification, power generation, as industrial raw material for production of bio-ethanol, packing material, paper/board/panel industry, composting and mushroom cultivation etc. It is assumed that India will become the most populous country by 2050 in the world. It will be a major challenge to ensure food security for all as well as to keep the environment safe and pollution-free. This expanded review underscores that rice residue is not agricultural waste but a potential resource. The integration of policy interventions, technological innovations, and community participation forms the cornerstone of sustainable management. As India advances toward carbon neutrality and food security, crop residue management will remain a crucial determinant of agricultural resilience and environmental sustainability.

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