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New Delhi

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Contents

1. Introduction

Growing food consumption in developing countries has resulted in a massive increase in global food production. Rice-wheat (RW) cropping systems cover 13 million hectares in South Asia (India, Pakistan, Nepal, Bangladesh, and Bhutan). Rice-wheat cropping systems account for roughly 20% of total cereal production and 40% of wheat production in India. The Indo-Gangetic Plains (IGPs) are home to more than 85 percent of South Asia's RW system. India's IGPs cover around 20% of the country's overall geographical area (329 Mha) and about 27% of the country's net cultivated land, producing about 50% of the country's total food consumption.

Continuous rice and rotational wheat agriculture, intensive tillage for both crops, Crop Residue (CR) removal, and use of excessive water and chemical has created environment and ecological imbalance. The CR consists of plant materials left behind after harvesting and threshing crops. These residues were once thought to be waste, but with increased knowledge and further investigation, it is becoming clear that they are not waste but rather an essential natural resource. CR recycling could be used to transform surplus farm waste into usable material. These items can aid in nutrient replenishment, soil fertility enhancement, and ecological balance, all of which are beneficial to crop output. Many farmers utilize wheat straw as animal feed, but rice straw is still a problem because its high silica concentration makes it poor and animal population in rural area is also decreasing. The combine harvester leaves a swath of loose paddy residue, interfering with wheat drill seeding. To meet this difficulty, farmers turn to CR burning, which wastes a lot of biomass and pollutes the environment. On the other hand, National agencies are constantly developing regulations and options for managing these wastes, including their conversion to reusable resources.

India creates an average of 500 million tonnes (Mt) of crop residue per year, according to the Indian Ministry of New and Renewable Energy (MNRE). According to the same research, the bulk of crop residue is used for feed, fuel, and other home and industrial reasons. However, there is still a 140 million tonne surplus, of which 92 million tonnes is burned each year. Table 1 compares the amount of agricultural waste produced in Mt/year by some Asian nations. It's also worth noting that the amount of agricultural waste burned in India is substantially more significant in volume than the total amount of agricultural waste produced in other nations in the region.

Table 1. Agricultural waste generation in India compared to other select nations in the same region.

Country	Agricultural Waste Generated (million tons/year)
India	500
Bangladesh	72
Indonesia	55
Myanmar	19

Paddy straw in-situ burning is a widespread management method in north India, whereas rice straw is used for composting and other purposes in the remainder of the country. One of the most severe consequences of residue burning is air pollution. In India in 2000, CH_4, CO, N_2O, and NO_x emissions from paddy and wheat straw burning were 110, 2306, 2, and 84 Gg, respectively.

P_2O_5, N, K_2O, and S are 2.3, 5.5, 25, and 1.2 kg per tonne of paddy straw, respectively, and straw includes 50-70 percent of micronutrients absorbed by rice, as well as 400 kg of carbon. In addition to nutrient loss, residue burning in the field alters many soil parameters such as pH, soil temperature, soil moisture, amounts of soil organic matter, and accessible phosphorus. Farmers burn rice straw as a quick and inexpensive technique to clear their fields for wheat planting. Burning causes the loss of 90 percent of N, 60 percent of S, 20-25 percent of P and K, and all organic matter (all C) in the straw. Removing all the straw from the field results in a negative K balance, as 80-85 percent of the K absorbed by the rice and wheat crops remains in the straw. Every year, in Punjab, approximately 16 Mt of rice stubble is projected to be burned in a matter of weeks. The ensuing air pollution has serious health consequences for both humans and animals.

India, in particular, is the world's second-largest producer of rice and wheat, these two crops that produce a lot of waste. Agricultural waste can be beneficially used in a variety of agro-based applications as well as other industrial operations. The cost of collecting, processing, and transportation, on the other hand, can be significantly higher than the revenue generated by the waste's beneficial use. Crop residues are a significant part of agricultural waste that can actually be used for the benefit of society due to their organic makeup. Large amounts of crop residue combined with unsustainable management practices have significant adverse environmental consequences that extend well beyond India.

Here we will discuss the key difficulties with crop residue burning and various management strategies, alternate applications, and mechanized options for reducing CR burning.

2. Crop Residue: composition and decomposing mechanisms

Table 2 summarises the general categories of crop residues produced by the major cereal crops and sugarcane. Crop residues, notably field leftovers, are a natural resource that has traditionally contributed to soil stability and fertility by ploughing directly into the soil or composting. Irrigation efficiency and erosion control can both be supported by good field residue management. On the other hand, traditional sustainable approaches have been hampered by crop production's large-scale and rapid pace. Burning leftover crop residue is prevalent in many developing countries, particularly Asia. While burning has environmental consequences, ploughing millions of hectares of farm residue into the ground in a short period necessitates significant and costly technical support.

Table 2. Crop residues produced by major crops.

Source	Composition
Rice	Husk, bran
Wheat	Bran, straw
Maize	Stover, husk, skins
Millet	Stover
Sugarcane	Sugarcane tops, bagasse, molasses

Lignocellulosic biomass refers to the non-food components of plants, such as stalks, straw, and husks. Cellulose, hemicellulose, and lignin make up the majority of plant biomass, with smaller amounts of pectin, protein extractives, sugars, nitrogenous material, chlorophyll, and inorganic waste. Unlike cellulose and hemicellulose, lignin offers structural stability and is nearly impervious to water. Lignin resists fermentation because it is chemically and biologically resistant. Lignocellulosic biomass is increasingly recognized as a valuable commodity due to its widespread availability as a raw material for the manufacturing of biofuels The world's major crops, such as maize, wheat, rice, and sugarcane account for most lignocellulosic biomass.

Several countries use crop leftovers created by agricultural activities in various ways. Depending on the eventual use, they are used in processed or unprocessed form. Its use as animal feed, composting, bio-energy production, and deployment in other extended agricultural activities such as mushroom cultivation are all possibilities. Crop leftovers are used to generate bioenergy and compost in several countries, including China, Indonesia, Nepal, Thailand, Malaysia, Japan, Nigeria, and the Philippines.

Several researchers have focused on pre-treatment approaches for lignocellulosic biomass for biofuel conversion. The lignin layer is usually pre-treated or acted upon by lignin-degrading microorganisms to break down the lignin layer and degrade cellulose and hemicellulose matter to the corresponding monomers and sugars for effective biomass to fuel conversion as a result of these approaches, the surface area, porosity, and crystallinity of cellulose and hemicellulose and the degree of polymerization increase. Mechanical, chemical, physicochemical, and biological pre-treatments are all possibilities.

Using microorganisms to control agricultural waste could also be an effective solution for soil cleansing and pollution reduction. Microbial populations reduce the biomass's complex compounds into simpler ones that can be reused or recycled through natural processes. Microbial decomposition strategies minimise soil toxicity, enhance plant growth by providing growth-promoting compounds and provide plant nutrients by sequestering minerals from the soil. Depending on the bacteria, fungi, or algae involved in the degradation, the procedures can be aerobic or anaerobic. Thus, anaerobic and aerobic processes and associated techniques such as composting, vermicomposting, biogas production, bio-methanation, and bio pile farming could be used to bioremediate agricultural waste successfully.

Anaerobic digesters can convert biomass into biogas, a renewable energy source comprising about 50% methane and a solid residue that can be used as a nutrient-rich fertilizer. Anaerobic digestion is a viable valorisation technology because it can convert practically any kind of biomass into highly energy biogas, including various types of organic waste, slurry, and manure. Because agricultural by-products contain a high percentage of biodegradable components, it is a practical and environmentally friendly approach and a viable choice for recycling them. Anaerobic digestion is a microbial conversion process in an aqueous environment and can be done without prior pre-treatment. Distinct groups of symbiotic microorganisms carry out individual processes of degradation and conversion. For methane fermentation, it uses a regulated substrate and methanogenic microorganisms. In anaerobic digestion, which takes three phases, the hydrolytic bacteria degrade polymeric organic materials into monomers (sugars, amino acids) in the first step. The monomer is then degraded to fatty acids (acetate, formate) in the second stage, and the acids are then converted to carbon dioxide and methane by acetotrophs, methylotrophs, and hydrogenotrophs bacteria in the third stage.

Government initiatives in the past were mostly focused on using crop residue as a source of energy, both as biogas and supplement for thermal power plants. Anaerobic biodegradation of municipal solid waste and agricultural waste produces biogas with a 40–70% methane content, which usually supplements natural gas quality with a 70–99% methane concentration. It can also be utilized as a transportation fuel or injected into the natural gas system. As per a study, Rice straw biomass with roughly 50% methane content has a biogas production capacity of 0.550 to 0.620 m^3/kg. For dry organic mass fed to the digester, the methane production potential of wheat straw ranges from 0.145 m^3/kg to 0.390 m^3/kg. The methane generation capability of rice straw ranges from 0.241 m^3/kg to 0.367 m^3/kg.

3. Practices in India

India is a farming country with a variety of farming practices that are based on agro-climatic zones. Vast farming practices include rice and wheat cropping patterns in Haryana, Punjab, Rajasthan, Uttar Pradesh, Bihar & Madhya Pradesh. After the harvesting season, these areas are also known for burning straw and stubble. Even though the government began to ban the practice in the 1990s, farmers in Punjab and Haryana, in particular, burn an estimated 35 million tonnes of crop residue from their paddy fields each year in late September and October. This strategy is a low-cost way to get rid of straw while shortening the period between harvesting and growing the second (winter) crop.

The burning of crop residue results in the loss of nutrients and resources. Flaming stubbles cause soil nutrient loss of organic carbon (3850 million kg), nitrogen (59 million kg), phosphorus (20 million kg), and potassium (34 million kg), as well as large volumes of various air pollutants such as CO_X, CH_4, NO_X, SO_X, and particulate matters (PM_{10} and $PM_{2.5}$), in addition to deteriorating ambient air quality. Although the Indian government has taken a few attempts to outlaw the practice in recent years, burning straw and stubble is still a common disposal method in India. The National Green Tribunal (NGT), based in India's capital, has banned the burning of straw and stubble in the four states that border New Delhi

(Haryana, Rajasthan, Punjab, and Uttar Pradesh), which contribute significantly to air pollution during the early winter. Instead of burning straw and stubbles, the government encourages farmers to use them for alternative activities such as mulching or in situ integration. This agricultural waste can be utilized for animal food, electricity generating, mushroom cultivation, and paper.

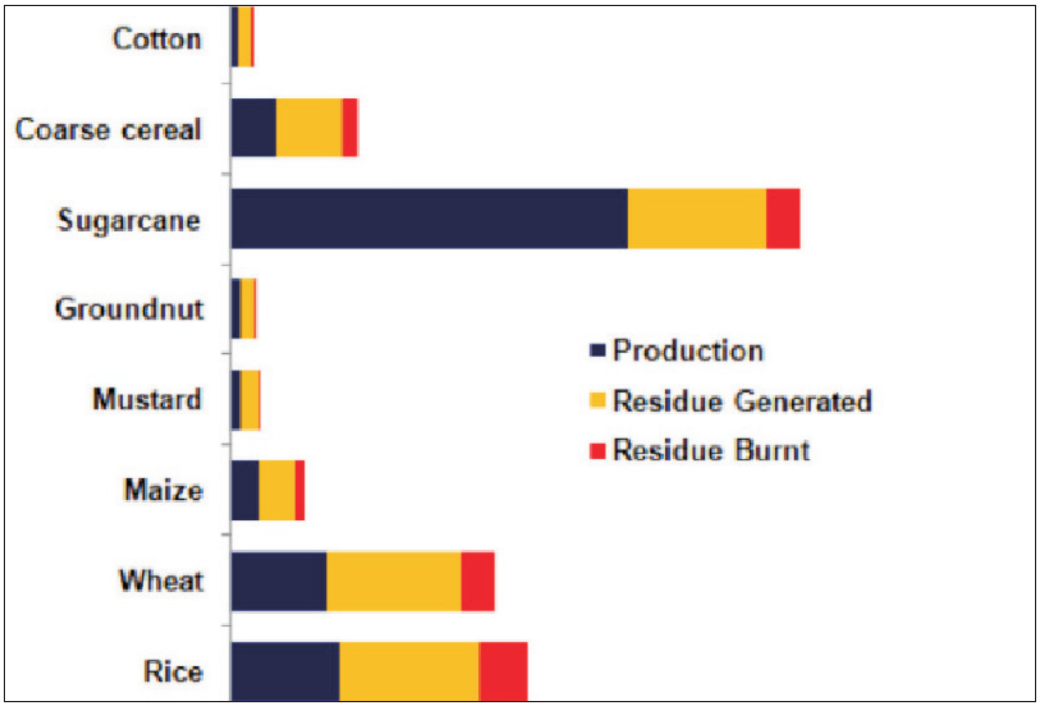

Fig.1. Crop-wise distributions of crop production, residue generated, and residue burnt in India for 2018.

Field view of straw burning

Crop stubble burning is responsible for one-quarter of the air pollution that practically blankets the whole capital city every winter. The Delhi pollution index increased to 12 times the maximum limit for safe air in November 2018. In the morning, the air quality in Delhi was deemed "unhealthy" by the US embassy in New Delhi, as it was more than three times the allowable threshold. The federal government has come under fire after United Airlines, based in the United States, cancelled flights to New Delhi owing to pollution. Apart from the stubble burning, the entire country celebrates Diwali with fireworks, contributing to significant air pollution, particularly in New Delhi. In early 2019, the Supreme Court of India issued a ruling regulating the emission of gases from many sources, including agricultural stubble and rubbish combustion and emissions from motor vehicles. However, the majority of farmers in North India and the rest of the country are not fully aware of long term effect of paddy stubble burning and as dangers of air pollution to human life and the environment. As a result, farmers unintentionally utilize fire on agricultural waste, as they are the first to be affected by smoke inhalers. Farmers in North India, particularly in Punjab and Haryana, are helpless since they have no other realistic option for clearing their crops except to burn them. Everything that poses such serious harm to human health is wrong and need to be addressed in positive perspective. A centralized, designated, and accountable authority should be established to formulate a comprehensive strategy to carry out for sustainable solution for this problem with precise, time-limited goals to implement the prohibition on the combustion of agricultural wastes.

4. An account of crop residue in India

Crop yield and crop type are the two key elements influencing the amount of CR produced in a given region. It should be remembered that CR includes the unharvested aboveground portion and the underground section. Root systems are agricultural remnants placed into the soil regularly. Different varieties of crops yield different amounts and sizes of residue. Cereals (rice, wheat, maize, pearl millet, barley, minor millets, and sorghum) account for the majority of India's leftovers, accounting for 368 mt (54%), followed by sugarcane (111 mt) (16 per cent). When it comes to individual crops, rice generates the most gross residues (154 mt), followed by wheat (131 mt). Fiber crop residues account for 20% of the total CR generated in the country. Cotton accounts for 74% of total fiber CR among fiber crops. The gross residue potential is the overall amount of residue generated, whereas the surplus residue potential (such as cow feed, animal bedding, heating and cooking fuel, and organic fertiliser) is the residue left after any competing uses. Based on the surplus sections of residues available from the selected crops, the yearly national potential is around 230 mt year^{-1}, i.e., the surplus is available for 34% of the gross residue generated in India. In North West India roughly 23 mt of rice residues are produced and burned in fields. After forage harvest, around 25% (1.5-2.0 t ha^{-1}, a total of approximately 16 mt) of wheat residues remain in the field, which farmers then burn without any good rationale(s). In Punjab, Haryana, and Himachal Pradesh, 80 percent of rice straw is burned on fields. The product of residue to crop ratio, dry matter to crop biomass ratio, and total crop production can be used to calculate the amount of CR produced. Cereal crops had a residue to grain ratio of 1.5 to 1.7, fiber crops 2.15 to 3.0, oilseed crops 2.0 to 3.0, while sugarcane had a residue to grain ratio of 0.4. Nine primary crops created a total of 620.4 Mt of crop residue was created during 2018 by nine primary crops, including cereals, oilseeds, fibers, and sugarcane. In India, Uttar Pradesh (72 Mt) produced the most cereal crop residues (Table 3), followed by

Punjab (45.6 Mt) and West Bengal (39.6 Mt) (37.3 Mt). Uttar Pradesh also produces the most sugarcane residue (44.2 Mt), while Gujarat produces the most fiber crop residue (28.6 Mt), followed by West Bengal (24.4 Mt) and Maharashtra (24.4 Mt) (19.5 Mt). The production of oilseed crop residues in Rajasthan and Gujarat is approximately 9.26 and 5.1 million tons.

Table 3. Crop-wise residue generated in various states of India.

States	**Crop residue generated (Mt yr^{-1})**			
	Cereal crops	**Fiber crops**	**Oilseed crops**	**Sugarcane**
Andhra Pradesh	33.07	16.07	2.50	5.80
Arunachala Pradesh	0.56	0.00	0.06	0.01
Assam	8.15	2.01	0.29	0.41
Bihar	19.87	3.27	0.20	1.87
Chhattisgarh	8.87	0.01	0.11	0.01
Goa	0.24	0.00	0.01	0.02
Gujarat	8.18	28.62	5.06	5.85
Haryana	24.73	7.58	2.15	1.93
Himachal Pradesh	1.95	0.00	0.01	0.02
Jammu & Kashmir	2.76	0.00	0.11	0.00
Jharkhand	7.34	0.00	0.09	0.13
Karnataka	11.73	3.55	0.81	8.80
Kerala	1.14	0.01	0.00	0.10
Madhya Pradesh	16.05	3.51	2.13	1.12
Maharashtra	8.75	19.51	0.57	22.87
Manipur	0.78	0.00	0.00	0.01
Meghalaya	0.44	0.13	0.01	0.00
Mizoram	0.10	0.00	0.00	0.01
Nagaland	0.89	0.01	0.06	0.07
Orissa	13.38	0.56	0.16	0.24
Punjab	45.58	9.32	0.08	1.76
Rajasthan	22.19	2.96	9.26	0.15
Sikkim	0.14	0.00	0.01	0.00
Tamil Nadu	11.69	0.78	1.56	12.37
Tripura	1.22	0.02	0.00	0.02
Uttar Pradesh	72.02	0.04	2.49	41.13
Uttarakhand	2.40	0.00	0.03	2.11
West Bengal	37.26	24.43	0.95	0.62
Andaman & Nicobar Islands	0.04	0.00	0.00	0.00
Dadra and Nagar Haveli	0.05	0.00	0.00	0.00
Delhi	0.17	0.00	0.00	0.00
Daman & Diu	0.01	0.00	0.00	0.00
Pondicherry	0.10	0.00	0.00	0.06

Table 4. Gross and surplus crop residues biomass potential in India.

Crops	Gross potential (million tonnes)	Surplus potential for bioenergy (million tonnes)	Surplus for bioenergy generation (%)
Cereals (rice, wheat, barley, jowar, ragi, & small millets)	367.7	90.1	29
Oilseeds (Rapeseed-mustard, sesame, linseed, niger, safflower, soybean, groundnut, sunflower)	48.8	13.7	30
Pulses (pigeonpea, guar, chickpea, lentil)	17.9	5.1	38
Sugarcane	110.6	55.7	39
Horticultural crops (banana, coconut, arecanut)	61.4	22.5	42
Others (cotton, jute)	79.8	47.3	38
Total	**686**	**234.5**	**34**

Table 5. Estimated area under Rice, residue produced & burnt in Punjab, Haryana & Western Uttar Pradesh (2018).

State	Area under rice (mha)	Area under RWCS (mha)	Rice residue production (mt)	Rice residue burnt (mt)
Punjab	2.9	2.6	22.0	18.7
Haryana	1.3	1.0	7.5	3.0
Western Uttar Pradesh	1.3	0.7	4.4	1.3
Total	**5.5**	**4.3**	**33.9**	**23**

Fig.2. Yearly changes in rice straw generation (million tonnes) in India.

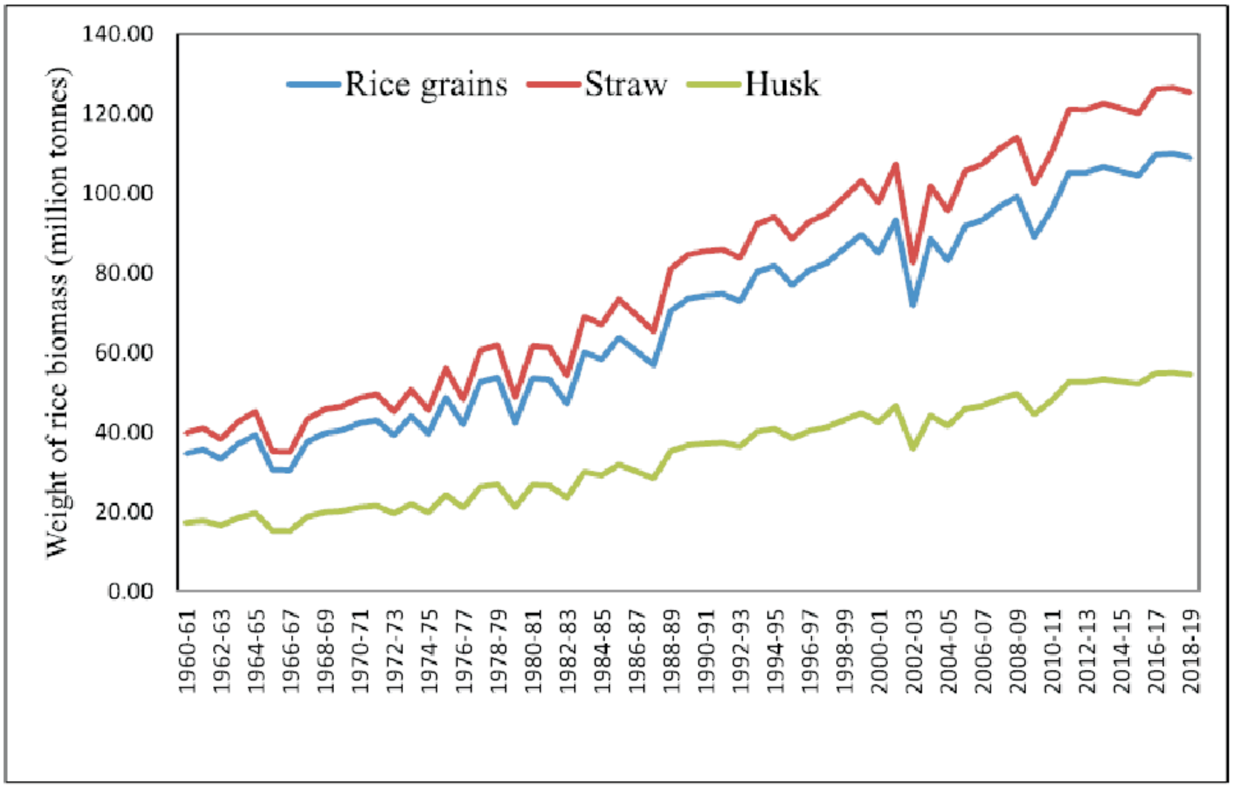

Fig.3. Annual production of rice biomass in India.

5. Effects of stubble burning

5.1. Environmental effects

Burning crop residues causes plenty of environmental problems. Crop residue burning has the most harmful effects because it emits greenhouse gases (GHGs), contributing to global climate change. It leads to increased levels of Particulate Matter (PM) and other air pollutants, which cause health problems, loss of agricultural land diversity, and deterioration of soil fertility. Burning crop stubble in an open field impacts on soil fertility, degrading the total nutrients present in the soil.

5.2. Air pollution

GHG emissions, CO, NH_3, NO_X, SO_X, non-methane organic compounds (NMHCs), volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and PM all are produced by crop residue burning, resulting in the loss of organic carbon, nitrogen, and additional nutrients that would otherwise be preserved in soil. Every year, roughly 22 Mt of CO_2, 0.92 Mt of CO, and 0.03 Mt of SO_2 are produced in Punjab from around 15 Mt of rice residues. According to a study, GHG emissions account for 91.6 percent of total air emissions caused by the burning of 98.4 Mt of agricultural residue, with CO, NO, NMHCs, and SVOCs accounting for the remaining 8.4 percent. Aerosols are also released when stubs are burned; the open burning of rice straw in India, Thailand and the Philippines results in severe air emissions of SO_2, NO_x, CO_2, CO, and CH_4.

Table 6 shows the principal polluting gases, PM, aerosol, and trace gases emissions resulting from agricultural residue burning. PM emissions from crop residue burning are 17 times higher than emissions from other sources such as motor vehicles, waste incineration, and industrial waste. Regarding the national emissions budget, crop residue burning in the country's northwest region generates a significant amount of roughly 200 organic carbon compounds. It is estimated that 730 Mt of biomass is burned annually in Asian countries, with India ranking 18th. Burning crop residue raises PM levels in the atmosphere and contributes significantly to temperature change. Fine black and brown carbon particles (primary and secondary) alter solar light absorption and hence contribute to global climate change.

Table 6. Release of major pollutants into atmosphere during crop residue burning.

Category	**Pollutant**	**Source**
Particulate matters	$PM_{2.5}$ and PM_{10}	Condensation after combustion of gases and incomplete combustion of organic matters
	PM_{100}	Incomplete combustion of in-organic materials, particles on burnt soil
Gases	CO	Incomplete combustion of organic matters
	CH_4	Incomplete combustion of organic matters
	O_3	A secondary pollutant formed due to the the reaction of nitrogen oxide and hydrocarbon
	NO, NO_2 N_2O	Oxidation of Fuel-N or N_2 in the air at high temperatures
	Polycyclic aromatic hydrocarbons (PAHs)	Incomplete combustion of organic matters

Usually, PM within the air is classified as $PM_{2.5}$ and PM_{10} in terms of its particle size ($PM_{2.5}$ is fine particles with a diameter <2.5 µm and PM_{10} is coarser, with a diameter <10 µm). PM pollution worsens under some climatic conditions when the lightweight particles stay in the air for an extended time causing severe air pollution. Light weight PM materials will remain suspended within the air for an extended time and might travel a prolonged distance with the wind. With the onset of cooler weather in November, the smoke mixed with fog, dust, and industrial pollution, forms a thick haze. If there is a lack of wind in the season, the thick haze will continue for many days, as was the case throughout November 2017. Many major cities, including New Delhi, Lucknow, and Kanpur, faced elevated pollution levels.

According to the United Nations, the allowable Limit of $PM_{2.5}$ in the air is 10 µg/m^3, but India's National Air Quality Standard allows for a reasonable level of $PM_{2.5}$ of around 40 µg/m^3. The capital territory of the metropolitan center, on the other hand, recorded a mean of 97 µg/m^3, which is double that of any other Indian location and ten times that of the UN criteria.

Table 7. Emission levels of air pollutants during harvesting season in Haryana and Punjab

[Source: Delhi Pollution Control Committee (DPCC), 2016]

Pollutants	Area in Delhi	Current Level (µg/m^3)	Permissible Limit (µg/m^3)
$PM_{2.5}$	Punjabi Bagh	650	60-80
PM_{10}	Punjabi Bagh	1000	60-80
CO	IGI Airport	6.3	2-4
SO_2	IGI Airport	29.8	60-80
NO_X	Anand Vihar	167	60-80

Increasing people's sickness-prevention costs and more importantly, their operating capacity. As this is widely known that the release of harmful gases from agricultural residue burning can cause coughing, asthma, emphysema, bronchitis, eye irritation, corneal opacity, and skin problems, inhaling PM can aggravate existing cardiac and pulmonary conditions and has been linked to premature death of persons who already have these conditions. Approximately half of the world's population currently lives in cities plagued by severe air pollution, which harms human health via the cardiovascular and respiratory systems. Air pollution causes eye irritation, bronchitis, asthma, and many others. Around the world, 3.3 million people die prematurely each year due to air pollution. This number will quadruple by 2050 if air pollutants continue to climb. According to the Organization for Economic Cooperation and Development (OECD), air pollution causes roughly 20,000 premature deaths in Delhi NCR alone, with this number estimated to rise to 30,000 by 2025 and 50,000 by 2050. (OECD, 2016). Table 7 demonstrates that current pollution emission levels in most parts of Delhi are well over the allowable limits.

Burning crop wastes also put the life of milk-producing animals in danger. Animals can die due to air pollution because high CO_2 and CO levels in the blood affect normal haemoglobin, causing mortality. More than 60,000 individuals living in rice-growing areas are at risk of air pollution due to rice stubble burning.

According to house surveys, paddy husk burning generates many other issues, including increased health costs in polluted areas. The longevity of animals, birds, and insects is also affected by open burning in the field. Burning occasionally also reduces visibility and increases the severity of traffic accidents. The answer to whether or not households aware of the adverse impacts of rubbish burning is 'yes' in roughly 90% of cases; however, almost no household would take precautionary action to tackle pollution-related diseases.

5.3. Effects on soil fertility

According to the Punjab Government's Department of Agriculture, Punjab soils typically have low nitrogen, low to medium phosphorus, and moderate to high potassium. Furthermore, soil organic carbon levels have plummeted to dangerously low, and organic manure and crop debris have not been applied appropriately. More than 300 kilograms of nitrogen, 30 kg of phosphorus, and 300 kg of potassium are extracted from the soil per hectare when 7 t/ha rice and 4 t/ha wheat are grown. According to the Punjab Agricultural University's Department of Soil Sciences, burning crop leftovers adds to the loss of soil organic carbon. Furthermore, the CO_2 and soil nitrogen balances fluctuate rapidly, converting nitrogen to nitrate. It may lead to the depletion of 0.824 million tons of nitrogen-phosphorus-potassium (NPK) from the soil annually.

The burning of agriculture residues raises the soil temperature and causes depletion of the microorganism and flora population. In addition, repeated burns can diminish by more than 50% of the bacterial population. Long-term burning also reduces the amount of 0-15 cm soil loss and loss of total nitrogen, biomass, and potentially mineralized nitrogen and organics. The residue burning will increase the dirt temperatures to about 35.8-42.2 °C at 10 mm depth, and semi-permanent effects will reach up to 15 cm of the highest soil. Furthermore, frequent burning reduces the nitrogen and carbon content in the soil, kills the microflora and fauna, which are helpful to the soil, and removes a significant portion of organic matter. With crop residue burning, the carbon-nitrogen equilibrium of the soil can be lost. According to the National Policy for Management of Crop Residues (NPMCR), open incineration of 1 tonne of stubble would result in the loss of all organic carbon, 5.5 kg of nitrogen (N), 2.3 kg of phosphorous (P), 25 kg of potassium (K) and 1.2 kg of sulphur (S) in the soil. If the crop residue incorporates into the soil itself, it will also enrich it with C, N, P and K.

The burning of rice and wheat residues contributes to a loss of about 80% of nitrogen, 25% of phosphorus, 21% of potassium and 4-60% of soil sulphur, although it does destroy unwanted bugs and diseases borne by the soil. Crop residue burning also contributes to a depletion of the essential crop nutrients. Around 25% of nitrogen and phosphorus are kept in crop residues, making 50% of sulphur and 75% of cereals potassium intake viable nutrient sources. As shown in Table 8, burning rice residue resulted in almost complete loss of carbon, nitrogen, and approximately 20–60% of P, K, and S.

Table 8. Nutrient losses as a result of the burning of rice residue in Punjab.

Nutrient	Concentration in Straw (g/kg)	Percentage Lost in Burning	Loss (kg/ha)
C	400	100	2400
N	6.5	90	35
P	2.1	25	3.2
K	17.5	20	21
S	0.75	60	2.7

6. Reasons behind stubble burning by farmers

Farmers of north India burn around 50% of paddy straw in their fields. One of the most important reasons is that the farmers want to save labour costs and save their time for the further sowing of the wheat crop because there is very less time gap between the harvesting of paddy crop and wheat sowing. If the farmers naturally wait for the decomposing of stubble in soil, it will take more time, so they prefer burning. Because of its high silica content, rice straw is considered useless as fodder for non-basmati rice. Farmers think that burning will kill all the harmful insects and weeds, so insecticide will also reduce their expenses on the crop. Some farmers also realized that stubble burning in a field reduced the fuel cost of tractors. The ash made from stubble burning acts as a source of potassium and it can also reduce the acidity of the soil. Another reason behind this stubble burning is the lower-income farmers, so they cannot buy the costly implements like Rotavator, Happy seeder and Super seeder, etc., which help to manage stubbles in-situ. These tools also require tractors of more than HP for their working. Earlier, massive labour in Punjab and Haryana helped farmers in harvesting manually, and no stubble was left over the field. However, to save time, farmers are now using combine harvesters, which results in stubble being left on the ground, and due to a labour shortage, burning is preferred as a quick solution.

Table 9. Constraints faced by farmers in the management of rice residue in India.

Reported constraints	States of India
Short time between harvest of kharif rice and sowing of rabi crops	Punjab, Haryana, Western Uttar Pradesh
Shortage of labour and high labour-cost	Punjab, Haryana, Western Uttar Pradesh, West Bengal, Tamil Nadu, Andhra Pradesh
Problem of land leveling after residue incorporation in soil	All states
Small land holdings for the adoption of sustainable technologies	West Bengal, Tamil Nadu, Odisha
Relatively costly rice-straw management practices compared to burning	All states
Inadequate timely supply of custom hiring services for straw-management machineries (Happy-Seeder; Rotavator; Baeler; Chopper; Zero-till-Seed Drill etc.)	West Bengal, Tamil Nadu, Andhra Pradesh.
The unwillingness of farmers to put extra effort into composting straw	Punjab, Haryana, Western Uttar Pradesh
Lack of technical knowledge among the farmers about in-situ straw management	All states
In the present scenario, the rice straw has limited economic value to the farmers	All states
Decreasing demand of rice straw for cattle feed	All states
Drastic reduction in demand of rice straw for thatching	All states
Lack of economically viable alternatives for ex-situ straw management	Punjab, Haryana, Western Uttar Pradesh
Lack of logistics and storage for handling the enormous amount of straw in a short time	All states
Rapid enhancement of intensive agriculture and increased mechanization	All states
Limited and unorganized market for rice-straw	All states

7. Crop residue management

Crop residue can be managed in two ways (i) on the field and (ii) off-field management methods.

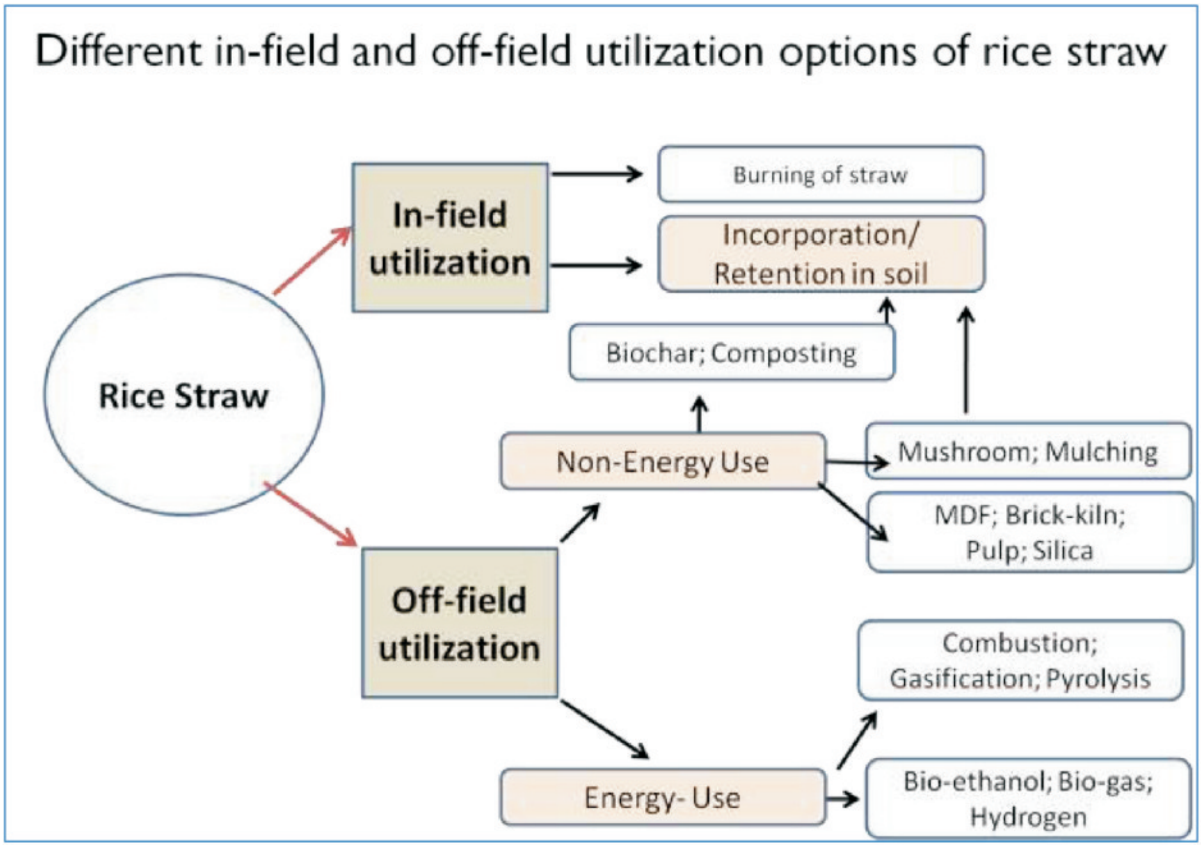

Fig.4. Rice straw management options.

7.1. On-field managements

The key elements of CR are lignin, cellulose, hemicellulose, as well as micro and macronutrients. CR degradation is affected by their lignin, polyphenol, cellulose content, crop-dependent C/N ratio, and atmospheric and soil conditions (texture, humidity). When cereal leftovers with a high C/N ratio (60:1 to 100:1) are placed into the soil, they degrade slowly, immobilizing soil nitrogen. This can be useful in zero tillage (ZT) systems, as it provides mulch that protects the soil from erosion and evaporation, but it also means that the following crop will have fewer nutrients available. The C/N ratio of the organic matter being degraded by soil microorganisms is affected by whether N is mineralized or immobilised. Inadequate N in the substrate permits the species to draw on mineral N in the soil, resulting in N immobilisation. Net immobilisation occurs when the C/N ratio of the residue is more than 20:1. The residue C/N ratio will drop as decomposition progresses due to decreasing C (respiration as CO_2) and increasing N (N immobilised from soil solution), and a new equilibrium will be attained, followed by N mineralization.

Farmers are increasingly employing in-situ crop residue application since it is natural. The net supply of nitrogen from crop residue to subsequent crops is determined by the time it takes to decompose before the next crop is planted, the quality of the residue, and the soil environment. Crops planted soon after grain residue is incorporated into such soils may become N-deficient, necessitating external N delivery to suit the needs of microorganisms and crops. Rice straw can be treated in-situ to minimise N deficit due to N immobilisation by allowing 10- 20 days between its integration and the seeding of the wheat crop. The net immobilisation process is transitory in the early years of zero tillage (ZT) adoption, but N immobilisation in conservation agriculture (CA) systems reduce the risk of leaching and denitrification losses of soil mineral N in the long run.

In comparison to CT, 15-25 percent more useable moisture favours N system losses via leaching and denitrification during the growing season in ZT. In ZT systems, the stubble is left standing, resulting in enormous residues that are not in contact with the soil. The degree of contact between crop residues and the soil matrix, as indicated by the residue retention/incorporation process, impacts breakdown kinetics and nutrient release. However, due to high integrating costs and energy and time commitment, only a few farmers have used in-situ rice straw integration as an alternative to burning. It also necessitates using a large-capacity mould board plough to absorb residue into the soil; yet, it has no negative impact on the subsequent wheat crop output. After the fourth year of continual straw integration, wheat yield is affected. This method also has specific benefits for the soil. Field applications can be made in two ways: collecting crop residue and spreading it across farmland. They only differ in terms of how tillage is handled the following season. The following season's planting is done without tillage or with limited tillage in the first approach, whereas crop residue is mechanically put into the soil during ploughing in a second way. Although in-situ crop residue management saves money on equipment and labour in the long term, both methods necessitate specialised (new) equipment, such as machinery for incorporating crop wastes into soils or no-till planting equipment.

7.1.1. Surface retention and mulching

The advantages of keeping crop residue on the soil surface include: i) reduced weed emergence, ii) cheaper weedicide costs, iii) improved physical, chemical, and biological properties of soils, iv) plant nutrient recycling, and v) reduced fertilizer use in subsequent crops. A practice where straw remnants from a previous crop are left on the soil surface without integration is known as direct drilling in surface mulched residues. Previously, seeding rice residues with ZT seed drills is required the removal of loose straw following mixed harvesting and partial or complete burning of the residues removed. With the recent ' Happy Seeder ' system, RW farmers in the Indo-Gangetic plains (IGP) can now drill wheat directly into the rice residue. The collection of leftovers on the surface helps protect the rich surface soil from wind and water erosion. Surface preservation of any or all residues may be the best option in some instances. Residues break down slowly on the surface, accumulating organic carbon and total nitrogen in the top 5-15 cm of the soil, delaying erosion and leaving leftovers on the surface improved soil NO_3^- content by 46 percent, N absorption by 29 percent, and yield by 37 percent when compared to burning. On the other hand, retention provides a safe habitat for both dangerous and beneficial species and a carbon source for heterotrophic N_2-fixation, enhanced microbial activity, soil C and N, and lower rice N fertilizer requirements.

Because incorporating crop leftover into the soil takes a long time due to field preparation, it is faster and easier to collect the residue and utilize it as mulch in the following crop. There is a lot of equipment available for this. Wheat production, profitability, and resource efficiency all benefit from a no-tillage drill. The full benefits of no-till will only be achieved when no-till is implemented consistently and the soil surface is saturated with at least 30% of previous crop residue. New-generation planters like Happy Seeder and spatial drill will contribute to greater adoption due to direct drilling in standing and loose residues.

In comparison to no mulch, rice straw mulch enhanced wheat grain output, reduced crop water usage by 3-11 percent, and improved water use efficiency by 25%. Mulch retained soil moisture in deeper levels, resulting in 40 percent larger root length densities than no mulch. Rice residue management in no-till systems has several benefits, including soil moisture conservation, weed suppression, improved soil quality, and a reduction of nearly 13 t ha^{-1} in greenhouse gas emissions, and regulates canopy temperature at the grain-filling stage to mitigate terminal heat effects in wheat. Herbicide requirements may be reduced if weeds are suppressed by straw mulch.

In-situ straw mulching in wheat

7.1.2. Farm mechanization and crop residue management

Despite being aware of the negative consequences of crop burning, farmers continue to use it due to a lack of economically viable and suitable machinery and options for disposing of leftovers. However, a possible option is using sophisticated technology to avoid burning, such as straw management systems, fitted combine harvesters, and happy seeders for direct drilling. Manufacturers have improved crop residue management technologies in recent years to enable finer chopping, wider and more equal spreading, and greater seed soil contact for improved crop emergence and yield. Farm machinery based on resource conservation technologies (RCTs) holds more promise for managing paddy leftovers to improve soil health, productivity, reduce pollution, and achieve sustainable agriculture. Advance technologies of zero-till seed-cum-fertilizer drill/seed planters (happy seeder, spatial zero seed cum fertilizer drill) are available in the country for direct sowing of the consecutive crop in loose and anchored straw load up to 10 t ha^{-1}. These technologies are beneficial for managing agricultural leftovers, weed management, and soil moisture and nutrient conservation. In NW India, the happy seeder method represents a breakthrough in paddy-wheat crop rotation.

Rice stubble in the field after combine harvesting

SMS mounted combine harvesting

Straw chopping cum mulching

Straw reaper

A Straw Management System (SMS) is mounted to the back side of the combine harvester just beneath the straw walkers and below the chaffer sieves for uniform distribution of paddy straw after paddy harvesting by a combine harvester. The straw from the straw walkers on the combine harvester is fed into the machine from one side and expelled through the housing's exit. The spinning discs disseminate the loose residues dropping from the harvester straw walker behind the harvester. The chopped material is blown off in a tangential direction and redirected by a deflector to evenly distribute the residues across the breadth of the combine harvester.

Because Happy Seeder-based systems are 10–20 percent more profitable than burning and this mechanization approach emerges as the most profitable and scalable residue management approach. In comparison to all other burning choices, this option has the greatest potential to reduce the

Super seeder

Straw chopping and mulching

environmental footprint of on-farm activities since it would eliminate air pollution and reduce greenhouse gas emissions per acre by more than 78 percent. It's a low-cost approach that might be adopted by the 2.5 million farmers in northwest India involved in the rice-wheat cropping cycle, eliminating the need to burn. It can also help India reduce its greenhouse gas emissions from agriculture. Droughts and floods are wreaking havoc on agriculture and lives, and better techniques can help farmers adjust to warmer winters and extreme, irregular weather events like droughts and floods. Furthermore, India's efforts to transition to more sustainable, less polluting agricultural techniques can serve as a model for other countries facing comparable dangers and concerns.

Happy seeder

7.2. Off-field managements

7.2.1. Baling and removing the straw

Straw from agriculture can be used for various reasons, including livestock feed, fuel, construction materials, livestock bedding, mushroom composting, bedding for cucumber, melons, and other vegetables, and mulching for cucumber, melons, and other vegetable orchards and other crops. The residue generated by the paddy-wheat cropping system can be put to various applications, but only if it is transported off the field. Straw reapers are used in some parts of North-Western India to harvest straw from the field, and wheat straw collection is gaining popularity as a substitute for rice because of its cost-effectiveness for animal feed. Straw baler machines are a promising technology commercially available for removing and collecting straw after combine harvesting and utilising the wastes for off-farm operations. However, depending on the height of the plant chopped by combines, these balers only recover 25–30% of possible straw yield after combining. Balers collect loose straw from the ground to construct rectangular or round bales. The machine can recover roughly 200–250 bales weighing between 15 and 30 kg (depending on moisture and field condition) with a 460–360 mm bale size from a combined harvested field. Depending on the field conditions, the pace of operation in combine harvested fields can range from 2-3 km/h. The energy requirements range from 0.6 to 1 kW h ton^{-1}, with an operating cost of Rs. 6170 per acre. After baling crop leftovers, it can also be utilised for paper and bioethanol processing, mushroom culture, bioconversion, and engineering uses.

Straw baler

Long-term increases in the availability of iron, copper, zinc, and manganese in the soil are observed and the prevention of nitrate leaching. Bacteria and fungus in the soil increase as organic carbon levels rise. Soil treated with agricultural leftovers has 5–10 times more aerobic bacteria and 1.5–11 times more fungus than soil that had been burned or removed. The activity of soil enzymes responsible for converting unavailable to available forms of nutrients increases as the microbial population grows. It has been observed that adding 36 kg of nitrogen and 4.8 kg of phosphorus per hectare (6 g of N and 0.8 g of P per kilogram of rice straw) saves 15–20 percent of total fertilizer use. In addition to the subsequent absorption of the burned crop remains in the soil, field burning of crop residues disrupts C and N dynamics in agro-ecosystems and atmospheric greenhouse gas concentrations during combustion. One study found that 10 years of continuous residue addition with no-till results in a 25% greater Soil Organic Carbon(SOC) than conventional tillage (CT). SOC content was 17 percent higher with little tillage than CT throughout the same period.

7.2.2. Crop residues as livestock feed

In India, the CR has traditionally been used as animal feed (or supplemented with chemicals). On the other hand, Crop leftovers are unappealing and have a low digestibility; thus, they cannot be used as a sole feed for cattle. Rice residues are considered poor cattle feed due to their high silica concentration (4-7 percent). It varies from other straws because it contains more silica (12-16 percent vs. 3-5 percent in other crop straws) and less lignin (6.7 vs. 10-12 percent in others). Rice straw's nutritional value can be increased through a variety of methods. Physical, chemical, and biological treatments have been used on crop residues to weaken and break down lingo-cellulose connections, enhancing their nutritional value. Around 75% of wheat straw is used as animal fodder, chopped into small bits using a special cutting machine, although it takes more work and cost. Rice straw stems contain less silica than leaves but are more digestible; therefore, if the straw is to be fed to livestock, the rice crop should be cut as close to the ground as practicable. The wastes must be processed and enriched with urea and molasses and supplemented with green fodders to meet the nutritional needs of the animals.

7.2.3. Crop residues as compost / mechanized composting

Crop wastes are utilized as animal bedding and then placed in dung pits to make compost. Each kilogram of straw absorbs roughly 2-3 kg of urine in the animal shed, enriching it with nitrogen. When rice crop wastes from a hectare of land are composted, they yield around 3 tonnes of manure as nutrient-dense as farmyard manure (FYM). Crop straw compost can be reinforced with P utilizing a locally available low-grade rock phosphate source, resulting in a value-added compost with 1.5 percent nitrogen, 2.3 percent phosphorus, and 2.5 percent potassium. On the other hand, mechanized composting can significantly improve the bio-physical composting processes. The compost product can be used as a growing medium for vegetables and other crops or applied as a soil amendment on rice fields. It enhances the nutrient (i.e., nitrogen and carbon contents) and organic matter content of the soil.

7.2.4. Production of mushroom crop

Mushroom growing is a profitable agri-business that creates food from rice and wheat straw while also supporting ecologically friendly waste disposal. The paddy straw mushroom, Volvariella volvacea, is regarded as one of the easiest mushrooms to cultivate due to its short 14-day incubation. Paddy straw is a significant element for mushroom growing in Punjab, while most farmers use wheat straw as a raw material. The cost of these processes has been estimated to be Rs. 510 per quintal in the case of paddy straw (raw material) against Rs. 810 per quintal in the case of wheat straw. Rice straw can provide 5-10% mushroom products (50-100 kg mushroom every tonne of dry rice straw).

Mushroom growing using rice stubble

7.2.5. Biochar production and utilization

Biochar is a carbon-rich material used as a soil amendment to improve soil fertility, carbon storage, and water filtration. It is produced by the thermal decomposition of organic materials or biomass at temperatures between 500 and 700°C in a small amount of oxygen. Hydrothermal carbonization (HTC) is a brand-new improved carbonization method. HTC of lignocellulosic biomass is a process that completely breaks down the plant cell wall, allowing for quick conversion of biomass into a carbon-rich, lignin-like product (hydrochar). Hydrochar has a significantly higher heating value than the basic material. Biochar can be made from rice straw, which has much potential.

Biochar production using rice stubble

Utilizing biochar as a soil amendment has a smaller carbon impact than using it as a fuel. Furthermore, carbon sequestration by biochar minimizes the risk of climate change-induced by GHG emissions in the atmosphere. Biochar manufacturing requires energy consumption for carbonization and transportation of rice straw and biochar items despite its vast potential. Additional studies are needed to show that biochar production from rice straw is feasible in terms of energy balance and economic benefits.

7.2.6. Use of rice straw for biogas production

Paddy residue biomass is an efficient source of energy generated by anaerobic digestion, gasification, and pyrolysis processes, providing an immediate reduction in CO_2 levels in the environment. 300 m^3 of biogas may be produced by anaerobic digestion of one tonne of rice residue. The process produces a high-quality gas with a 55–60% methane content, and the leftover slurry can be used as manure. One tonne of paddy biomass may provide 300 kWh of electrical energy through gasification. It ensures a non-destructive approach to extract high-quality fuel gas from agricultural waste and harvest manure to be recycled in soil.

7.3. Industrial uses of rice straw

The vast opportunities lie in rice straw's industrial Use, which is relatively unexplored throughout the world in general and in India in specific. The major industrial use of rice-straw can be listed as,

(i) Bioethanol Production

(ii) Production of rice-straw briquette and pellets

(iii) Paper-pulp/Board/Eco-panel making

(iv) High-value industrial products for commercial Use

7.3.1. Bioethanol production

Biofuels have been studied as a potential replacement for existing fossil fuels for many years. Bioethanol trumps them all when it comes to replacing gasoline. This has made bioethanol (derived primarily from agricultural biomass) a popular biofuel for transportation worldwide, with the dual benefit of lowering the usage of fossil fuels (petroleum oils) and reducing pollution. Rice straw is one of bio-ethanol production's probable sources. It provides a clean energy solution for meeting energy demand on a long-term basis, additional income and the long-term usage of rice straw, which is currently burned and causes significant air pollution.

Rice straw has a high concentration of hexose (C6-compound) and pentose (C5-compound) sugars, making it a potentially useful lingo-cellulosic feedstock for bio-ethanol production. Rice straw is composed of 30–42 percent cellulose, 19–24 percent hemicellulose, 8–17 percent lignin, 6–20 percent ash and silica (silicon dioxide or SiO_2), and 16–19.3% extractives. The process entails the hydrolysis of polysaccharides into simple sugars, followed by fermentation to produce ethanol. Typically, ethanol is produced by fermenting glucose (C6-sugar), chosen as a primary energy source by fermentative microbes. From 2 mol of glucose, roughly 1 mole of ethanol is created.

The three basic processes required for the production of bio-ethanol from rice straw are (i) delignification (pretreatment) to liberate cellulose and hemicelluloses from the straw matrix; (ii) depolymerization of carbohydrate polymers (hydrolysis/saccharification) to produce simple sugars; and (iii) fermentation of mixed pentose and hexose sugars to produce ethanol. From 1 tonne of rice straw, 220 to 300 litres of bioethanol can be generated. However, there are a few issues that obstruct large-scale commercial bio-ethanol production:

i. A major worry is the availability of both timing and quantity of feedstock. Season to season and location to location variations also influence availability of paddy straw. If the seasonal component cannot be eliminated, the site of bio-ethanol plants should be determined based on the ease with which the feedstock can be obtained. There are three types of agricultural raw materials that can be used to make bioethanol: simple sugars, starch, and lignocellulose. As a result, the bioethanol industry's most pressing task is to maximise both the environmentally friendly and economically viable process of production using appropriate feedstock.

ii. Variability in the market price of bioethanol feedstocks impacts production costs. Feedstocks accounted for more than a third of the total production expenses, demonstrating their supremacy in terms of bioethanol yield. Despite its low cost and wide availability, lignocellulosic biomass has yet to be commercialised for bioethanol production on a big scale.

iii. Cost of transportation remained another concern if the bioethanol producing plant is not situated nearby the crop fields.

iv. The expense of establishing a bioethanol plant that uses upgraded and cutting-edge technologies and the operational costs and the need for qualified employees with relevant backgrounds are all critical. If there isn't a barrier or a gap, this technical knowledge is crucial for increasing bio-ethanol production to the maximum degree possible.

v. Standard pretreatment technique is another major technical gap that involves the constant effort of researchers to meet the challenge.

vi. High moisture content, low heating value, high ash content, and poor grindability are the additional bottlenecks in rice straw utilization. Rice straw is also resistant to hydrolysis due to its complex chemical makeup and resistant structure. The cellulose and hemicellulose in rice straw are generally thickly coated by lignin layers. They are protected from enzymatic hydrolysis by the lignin layers. The lignin structure can be broken by several pretreatments, exposing cellulose and hemicellulose to enzymatic action. Pretreatments reduce the crystallinity of cellulose and increase biomass surface area for subsequent enzyme action, in addition to breaking the lignin seal. Pretreatment procedures have traditionally been regarded as the most expensive process for synthesizing ethanol from lignocellulolytic materials.

vii. Other issues with this type of industrial straw include a scarcity of competent indigenous microorganisms that can use both hexose and pentose simultaneously, a relatively high saccharification cost, and silica interference during the delignification and saccharification processes.

7.3.2. Production of rice-straw briquette as fuel in brick kiln and straw pellets for domestic uses

Rice straw has a calorific value of 3400–3600 kcal kg^{-1}. As a result, densification in pellets or briquettes is a viable option for overcoming the waste's bulkiness as an energy source. Pellets or briquettes will have a consistent size, density, and quality, increasing the energy density. Straw densification through pelletizing can increase bulk density from 600 to 800 kg m^{-3}. Rice straw briquettes are made using binders. Rice bran, soybean waste, and sawdust can be used as binders in the piston-mold process to make solid fuel rice straw briquettes. In addition to binders, the size of the feed material, operating parameters (temperature and pressure), and the densification equipments all impact the quality of rice straw briquettes; however, due to high silica content, the rice-straw as it is not preferred, as silica causes clinkerization that might result in choking of furnace bed of grates.

Rice straw briquette and straw pellet

7.3.3. Paper-pulp/board/eco-panel making

Rice straw is a readily available and suitable substrate for India's paper and board-making industry. Rice straw morphological variances and the fact that wax and silica have a negative impact on particle board qualities are all contributing to straw board production issues. Due to technological and economic considerations, Indian mills employ chlorine as a bleaching chemical without regard for environmental quality. In the future, novel bleaching chemicals such as ozone and H_2O_2 and xylanase enzymes may be utilised. Another cleaner (green) technological solution that might be utilised as panels and dividers instead of ply board is an eco-panel composed of rice straw. However, these established technologies' eco-efficiency (both economic and ecological) must be tested in India. Punjab has previously used more than 0.2 million tonnes of rice straw for ply board and eco-panels.

Rice straw paper board

Rice straw paper pulp

Rice straw paper making

7.3.4. High-value industrial products for commercial Use

This method involves first extracting the high-value components from straw and then using the residual portions to produce biogas. Lignin, silica cellulose, and hemicellulose constitute high-value compounds. Cellulose, which makes up 30–44 percent of rice straw, is generally recovered as a solid, while hemicellulose is mostly isolated as hydrolysates. Selective hydrolysis of cellulose and hemicellulose produces xylo-oligosaccharides (sugar polymers) and ethanol, both of which have great commercial value. Pure lignin (isolated by nano-filtration technology in thermo-chemical pretreatment of a straw) could be used in agricultural chemicals, slow-release fertilizers, dispersants in cement, dust-suppressants for roads, antioxidants, raw material for tyres, carbon-fiber generation, substrates for plastics and polymer foams, grease, cosmetic industries, and other applications.

7.4. Other methods

7.4.1. Crop residues as surface mulch in other crops

Other crops can be benefited from the rice straw mulch. By reducing the evaporation (E) component of the Evapotranspiration and acting as a barrier to vapour flow, and moderating soil temperature, this practice has been shown to improve crop yields at comparable irrigation regimes and save irrigation water and fertilizer nitrogen at comparable yields in several crops, including forage maize, sugarcane, sunflower, soybean, chickpea, potato, and chillies. The response is stronger in high-temperature, low-rainfall years, especially coarse-textured soils. In the mulched plots, more soil water in the profile, notably in the root zone, resulted in better stand establishment and early seedling vigour. Straw mulching reduced fertiliser N use for comparable crop yields of 25 kg N ha^{-1} in Japanese mint, 50 kg in fodder maize, and 30 kg N ha^{-1} in Chilli. The mineralization of soil N is increased when the soil temperature is warmer and the water content is higher in mulched soil than in unmulched soil. This approach has not gained traction among farmers due to a lack of labour and the expensive cost of collecting and applying straw mulch.

Rice straw mulching in vegetable crops

7.4.2. Diversification of crops

To address groundwater problems and sluggish yields, state and federal governments in the Green Revolution area have begun to move away from paddy agriculture. A centrally supported scheme initiated in 2013-14 in a few areas aims to diversify at least 5% of paddy acreage to more locally suitable crops (e.g. maize, millets, and oilseeds). Despite the scheme's many provisions (cluster demonstrations, knowledge training, farm machinery subsidies, and so on), most farmers have not found it profitable to switch from paddy to other Kharif crops. The strong market support for paddy and the yield advantages over alternative crop options for Kharif cultivation have inhibited the efficient translation of policy goals for crop diversification to field results.

7.4.3. Improved short-term paddy varieties

Research groups have developed short-duration paddy cultivars in the Western Indo-Gangetic Plains to reduce water usage in paddy agriculture. Traditional varieties (those that mature in 160 days) are still grown higher larger yields, although 135-145 day varieties are becoming more popular. Some believe adopting such types may lengthen rice harvest and wheat sowing, allowing far mers to clear fields and reduce residue burning.

8. Technological interventions and best practices possible to deal with the issue of stubble burning

Crop residue can be managed using both in situ and ex situ agricultural management techniques. Taking the waste out of the field and converting it to compost or baling rice residue for power plants are examples of ex-situ techniques. However, there are trade-offs to ex-situ crop residue management, and they aren't always economically or environmentally viable. Composting is not an economically viable choice for the farmer due to a lack of labour and high labour costs. Baling is also not a viable alternative because the baler costs more than ten lakhs and has a 10 to 15-day working period and same is unused for the rest of the year, and even the depreciation costs aren't recouped. Furthermore, removing residues from the field and not recycling them is detrimental to soil health.

In-situ procedures include dealing with waste at the point of production. There are technologies such as the Rotavator and the Mulcher, but they are inappropriate and could result in greater production costs and delay planting the wheat crop. The employment of a super straw management system (SMS) and a Turbo Happy Seeder at the same time efficiently manage residue and lowers the cost of preparing the field for the next crop. Crop residue management in situ with technology benefits the farmer and is also a realistic solution for avoiding residue burning. It does three things at once, saving time: shredding the harvested crop, spreading the stubble across the swath, and sowing the wheat seeds all at the same time. According to scientific studies, it saves roughly 10 lakh gallons of water on the first day of seeding a crop and enhances profit by Rs 20,000 to 25,000 per hectare each year for a farmer. Farmers gradually reduce their use of nitrogen fertilisers as a result of this. It finally leads to a reduction in greenhouse gas emissions from agricultural lands.

9. Government support and policies

Containment of crop residue burning remains a major challenge before the government. There has been continuous judicial scrutiny of the action taken regarding this by central and state governments. The central and state governments have been designing programmes to promote crop residue management technologies. Some of these schemes/programmes and institutional mechanisms of delivery are briefly enlisted below:

- "Project for promotion of technologies to stop burning of straw" was proposed under "Rashtriya Krishi Vikas Yojana (RKVY)" during the year 2009-10. Under this straw management equipment viz. Rake, Baler, and Happy Seeder provided a 50% subsidy to the farmers.
- The project for the establishment of Agro Machinery Service Centres (AMSC) was started by the Government of Punjab to offset the high cost of machinary and make available the machinery for use on a rent basis. Any individual farmer, cooperative society, and entrepreneur could initially set up the AMSC and subsidy were provided by the government. It was made mandatory for the AMSC to have a Happy Seeder and Laser land leveller.
- Sub-Mission on Agricultural Mechanization (SMAM)- This scheme has been established for promoting and providing financial incentives on the purchase of straw management equipment in the states. In 2016, the "Scheme for promotion of Straw Management Equipment" for Punjab, Haryana and Uttar Pradesh was started under SMAM by the Department of Agriculture, Ministry of Agriculture, Cooperation and Farmer Welfare.
- Promotion of agricultural mechanization for in-situ management of crop residue- A special scheme to support the efforts of the Government of Punjab, Haryana, Uttar Pradesh and NCT of Delhi, to address air pollution and to subsidize machinery required for in-situ management of crop residue, a new Central Sector Scheme (100% Central Share) for the period 2018-19 to 2021-22 proposed in the budget 2018-19 announcement.
- Crop Diversification Programme (CDP), a sub-scheme of Rashtriya Krishi Vikas Yojana (RKVY), is being implemented in the original green revolution states of Punjab, Haryana and Western Uttar Pradesh from 2013-14 to diversify areas from water-guzzling crop like paddy to alternate crops like maize, pulses, oilseeds, cotton, and agroforestry plantation. Under CDP, assistance is provided to the States for conducting cluster demonstrations on alternate crops, promoting water-saving technologies, farm machinery distribution, setting up value addition facilities, awareness through training, etc. The scheme has been continued.
- Incentives for the use of biomass in energy generation- special boilers have been designed for low density and calorific value, high lignin, silica and ash content of paddy straw. The Ministry of New

and Renewable Energy, India, has implemented various programmes to develop and deploy biomass-based power generation. To encourage investment in the sector, fiscal and financial incentives have been provided, including capital/interest subsidy, accelerated depreciation, concessional duties, and relief from taxes, apart from the preferential tariff for grid power being provided in the most potential States.

Along with these schemes, there are many other supports such as incentives to farmers to stop burning and programmes for infrastructural development etc., which are mainly focused on managing crop residue in economically viable & sustainable and ecologically sound ways.

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