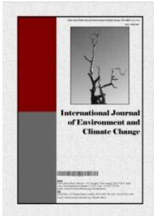

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Alternative Uses, in and off-Field Managements to Reduce Adverse Impact of Crop Residue Burning on Environment: A Review

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ABSTRACT

Residues of various crops are considered nuisance but they can be helpful in increasing organic matter in soil and better cycling of nutrients in soil if managed properly. Better management and utilization of crop residues (CR) is necessary for better productivity and quality of crops. Sowing into loose residues is the major issue in adapting the drill sowing method. Apart from the higher quantity of rice (192.82 mt) and wheat residue (120.70 mt), the residue of sorghum, maize, barley,

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chickpea, groundnut, rapeseed, mustard, sugarcane trash, potato, soybean, sunflower and some other minor cereals also contribute substantially towards total amount of about 462.93 million tonnes in India in 1997-98. Three quarters of the total residue is produced by rice, wheat and oil seed crops with remaining quarter coming from sugarcane and sorghum. Crop residue is important component of low external input for sustainable agriculture without sacrificing productivity. The crop residues left behind is considered as burden forcing farmers to burn them as cheap and easiest method with mistaken belief that it enhances the soil fertility and helps in controlling weeds, insects and pests. Different studies revealed that burning of residues causes air pollution and nutrient loss in soil. Improvements in soil properties and the sustainability in crop productivity could be achieved if CR are proper managed. Long-term field studies at sites carefully selected with variations in temperature, moisture, soil mineralogy and management of agricultural residues representing various cropping systems across regions should be identified and sustained. The possible benefits of crop residues for the improvement of degrading soil fertility would be completely understood only then. Owing to the competing requirements for such biomass for feed, fuel or building material, smallholder farmers typically find it difficult to maintain a soil cover for crop residue or a cover crop.

Keywords: Crop residue burning; incorporation; retention; soil properties; crop productivity.

1. INTRODUCTION

In South Asia (India, Pakistan, Nepal, Bangladesh, and Bhutan), rice-wheat (RW) crop systems cover an area of 13 Mha [1,2]. In India, RW systems produce about 20% of total cereal production and 40% of wheat. Most of the rice produced in Pakistan is grown in RW systems, and RW systems are used to grow the majority of wheat in Bangladesh and Nepal. More than 85% of the RW system in South Asia is located in the Indo-Gangetic Plains (IGP). India's IGP occupies approximately 20% of the total geographical area (329 Mha) and approximately 27% of India's net cultivated area, generating about 50% of the country's total food consumption [3]. Continuous rotational cultivation of rice and wheat, intensive tillage for both crops, removal of CR and high use of water and chemicals, has resulted in many adverse effects on productivity and the external environment. The CR comprises the plant materials that are left after the harvesting and threshing of crops. These residues were formally considered to be waste but with growing awareness and successive researches, it is being realized that CR are not waste but an important natural resource. Surplus wastes on farm could be converted into useful material through recycling of CR. These products can help in nutrient replenishment, improvement in soil fertility and ecological balance for better crop production. Wheat straw is used by many farmers as animal feed but rice straw is still a major issue as it is considered as poor feed for animals due to its excessive silica content [2,4]. Combine harvester leaves behind a swath of loose paddy residue, which interfere with drill sowing of wheat. To overcome this challenge farmers resort to burning of CR, which not only lead to loss of huge biomass but also causes environmental pollution (Fig.1).

Fig. 1. A view of in-situ burning of crop residue

In-situ burning of paddy straw is a common management practice in north India though in rest parts of the country rice straw is used for compost making, and several other purposes [5,6,7]. Air pollution is one of the major problems caused by residue burning. The expected values of CH_4, CO, N_2O, and NOx emissions from paddy and wheat straw burning in India in the year 2000 were 110, 2306, 2, and 84 Gg, respectively [8,9,10].

Each ton of paddy straw contains high amount of nutrients i.e., P_2O_5, N, K_2O, S are 2.3, 5.5, 25 and 1.2 kg respectively and 50-70% of micro-nutrients absorbed by rice are in straw and 400 kg of carbon [11]. Other than nutrients loss, various soil properties like pH, soil temperature, soil moisture, levels of soil organic matter and available phosphorus in soil are also significantly altered by residue burning in field. Farmers' burn rice straw as a quick and cheap way to clear their fields for sowing of wheat. The consequence of burning is the loss of 90% of N, 60% of S, 20-25% of P and K in the straw, and all organic matter (all C) [12] A negative K balance results from the removal of all the straw from the field [13], as 80-85% of the K absorbed by the rice and wheat crops remains in the straw. Approximately 16 Mt of Punjab rice stubble is estimated to be burned every year within a span of only a few weeks [14]. The resulting air pollution has significant adverse effects on both human and animal health [14].

The present review article focuses on the major issues related to crop residue burning, as well as different management approaches, alternative uses, and mechanization solutions for preventing CR burning.

2. CROP RESIDUE IN INDIA

In north-western India, only around 15% can potentially be used for these purposes and the rest must be managed with in-situ (on site) management technologies.The quantity of CR generated in an area is dependent on two main factors depend crop yield and crop type. It should be noted that CR comprises not only the aboveground portion that is not harvested, but also the above ground part. Root systems are residues of crops that are continuously introduced into the soil. Different types of crop produce different residue amounts and sizes at different depths. It is estimated that an annual gross quantity of 686 mt CR is available in India out of the 39 CR produced by 26 crops [15]. Cereals (rice, wheat, maize, pearl millet, barley, small millets and sorghum) contribute the largest amount of 368 mt (54%) of the total residues produced in India, followed by sugarcane at 111 mt (16%). With regard to the individual crop level, rice contributes the largest amount of 154 mt gross residues, followed by wheat (131 mt). Residues produced by fibre crops accounts for 20% of total CR generated in the country. Among the fibre crops, cotton generates 74% of total fibre CR. Oil seed residues were burnt in Rajasthan and Gujarat while burning of fibre crop residue was dominant in Gujarat (28.6 Mt). The total amount of residue generated is the gross residue potential, while the residue left after any competing usage is considered the surplus residue potential (such as cattle feed, animal bedding, heating and cooking fuel and organic fertilizer). In view of the surplus portions of residues available from the selected crops, the annual national potential is approximately 230 mt $year^{-1}$, i.e., the surplus is available for 34% of the gross residue produced in India. In North West India, farmers have deemed about 23 mt of rice residues produced in rice-based cropping systems to be a nuisance, which is disposed of by burning in fields [16]. Approximately 25 percent (1.5 -2.0 t ha^{-1}, a total of approximately 16 mt) of wheat residues left is in the field (after their forage collection is done), which ultimately get burned by farmers without any convincing justification (s). 80 percent of rice straw is burning on fields in Punjab, Haryana, and Himachal Pradesh (Gupta et al. 2003). The quantity of CR produced can be calculated as the product of residue to crop ratio, dry matter to crop biomass ratio and total crop production. The residue to grain ratio varied from 1.5 to 1.7 for cereal crops, 2.15 to 3.0 for fibre crops, 2.0 to 3.0 for oilseed crops and 0.4 for sugarcane. Total amount of crop residue generated by nine major crops namely cereals, oilseeds, fibres and sugarcane were 620.4 Mt. In India the production of cereal crop residues (Table 1) was highest in Uttar Pradesh (72 Mt) followed by Punjab (45.6 Mt) and West Bengal (37.3 Mt). Uttar Pradesh also generates maximum sugarcane residue (44.2 Mt) whereas Gujarat (28.6 Mt) is dominant in production of fibre crop residue followed by West Bengal (24.4 Mt) and Maharashtra (19.5 Mt). In case of oilseed crop residue production in Rajasthan and Gujarat is about 9.26 and 5.1 Mt residues respectively.

Table 1. 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 and 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

Data source: Jain et al. [17]

3. ADVERSE EFFECTS OF BURNING CROP RESIDUES

India alone accounts for 18% of Asia's total biomass burned per year [18]. Crop residue burning is extremely harmful to the environment. Crop residue burning is largely responsible for the release of toxic greenhouse gases (GHGs). Global warming is intensified by these gases. Crop residue burning emits particulate matter (PM) and smog, posing health hazards, reducing biodiversity, and declining soil health [19]. Crop residue burning causes the loss of organic carbon, nitrogen, and other nutrients by releasing contaminants such as CO2, CO, NH3, NOX, SOX, non-methane hydrocarbon (NMHC), volatile organic compounds (VOCs), semi volatile organic compounds (SVOCs), and particulate matter (PM) [20,21]. In the year 2008-09, Jain et al. [17] reported that in-situ burning of 98.4 Mt of crop residues resulted in significant amounts of CO (8.57 Mt), CO_2 (141.15 Mt), SO_X (0.037 Mt), NOx (0.23 Mt), NH_3 (0.12 Mt), NMVOC (1.46 Mt), NMHC (0.65 Mt), and PM (1.21 Mt) being released (Table 2). Carbon dioxide emissions were responsible for 91.6 percent of all emissions. Among the crops, burning of rice straw contributed the highest i.e. 40% of total emission followed by wheat and sugarcane at 22 and 20% respectively. The greatest emissions were generated from Uttar Pradesh and Punjab i.e. 23 and 22%, respectively. Burning of crop residues was identified as a major health hazard as it causes major atmospheric pollution problems, high nutritional loss and soil health deterioration. The quantity of PM, CO, CO_2, SO_2 and ash released from each ton of paddy straw burnt is 3, 60, 1460, 2 and 199 kg respectively [17]. According to Hayashi et al. [9], rice and wheat straw burning emit 0.11, 2.306, 0.002 and 0.084 Mt of CO, CO2, N2O, and NOx, respectively. Therefore, the release of these gases degrades air quality, adversely affecting human health, causing eye and skin diseases, whereas very small particles also cause chronic heart and lung diseases.

Crop burning contributes greatly to climate change by increasing PM levels in the atmosphere. In Delhi, PM emissions from crop residue burning are 17 times higher than emissions from all other sources combined [22]. $PM_{2.5}$ and PM_{10} are divided into two categories based on their size (aerodynamic diameter) and chemical composition. PM2.5, or fine particulate matter, has an aerodynamic diameter less than 2.5 m, while PM10, or coarse particulate matter, has an aerodynamic diameter greater than 10 m. Lighter particulate matter has the potential to stay trapped in the air for longer [6,17], and the impact of these lighter PM is exacerbated by weather conditions. Since these particles are small in weight, they remain in the air and create smog. The WHO standard for permissible levels of PM2.5 in the air is 10g m-3, while the permissible level for $PM_{2.5}$ in India is 40g m^{-3}, according to the National Ambient Air Quality Standard. Paddy residue burning alone produces 60 to 390 mg m^{-3} of $PM_{2.5}$ per year in Punjab's Patiala district [19]. These particles are swept away by the wind due to their light weight. Smoke from crop residue burning in Punjab and Haryana blows through northern India and Pakistan during October. The smoke blends with rain, dust, and industrial waste as the weather cools in November, creating a dense haze. Wind typically assists in the dispersal of air pollution, and its absence worsens the problem for many days [23]. During October-November, residue burning causes traumatic road accidents due to poor visibility in NW India and various health issues [16]. The estimated emissions from open-field combustion of crop residue (rice and wheat straw), assuming that 25% of the usable residue is burned in the field, were 110 Gg CH_4, 2306 Gg CO, 2.3 Gg N_2O and 84 Gg NO_x in India in 2000 [8]. A study conducted in Punjab by the National Remote Sensing Agency reported that the combustion of wheat CR contributed approximately 113 Gg (Giga gram = 10 billion gram) of CO, 8.6 Gg of NO_2, 1.33 Gg of CH_4, 13 Gg of PM_{10} and 12 Gg of $PM_{2.5}$ during May of 2005 and the combustion of rice straw/stubble in the October of the same year contributed an estimated 261 Gg of CO, 19.8 Gg of NO_2, 3 Gg of CH_4, 30 Gg of PM_{10} and 28.3 Gg of $PM_{2.5}$ during October 2005 [24].

The heat produced by the burning of residues increases the soil temperature, causing bacterial and fungal populations to dwindle. At 10 mm depth, residue burning raises subsoil temperatures to nearly 33.8–42.2°C [8]. Frequent burning decreases the soil's nitrogen and carbon potential, as well as destroying beneficial microflora and fauna, and eliminating a significant portion of the organic matter. The carbon-nitrogen balance of the soil is totally lost when crops are burned [25,26]. According to NPMCR [27], one ton of straw burns for 5.5 kg of nitrogen, 2.3 kg of phosphorus, 25 kg of potassium, and 1.2 kg of sulphur. Crop residues contain roughly 80% nitrogen (N), 25% phosphorus (P), 50% sulphur (S), and 20% potassium on average, regardless of the crop of origin (K). As a result, if crop residue is left in the soil, it may enrich it with the minerals mentioned above.

4. CROP RESIDUE MANAGEMENT

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

4.1 Management of Paddy / Wheat Residues

Rice straw, unlike wheat residue, cannot be used as fodder in the field. Farmers cannot leave the residue on the field because it takes too long to decay and can also spread crop diseases during the paddy season before. Early wheat cultivation has also been known to have issues with seed residue mulching. This happens largely because the combine harvester does not uniformly disperse the straw across the field. The straw management system, which is now needed on harvesters, is said to make mulching more viable, but it has not been widely adopted by farmers due to the additional costs of fuel and other expenses. It is possible to sow wheat in the midst of the stubble with a machine called a Happy Seeder, but it has not been widely adopted due to technical problems in operations, machine unavailability, and price-related issues.

Table 2. State wise emissions of air pollutants from crop residue burning for the year 2008-09

States	CO_2	CO	NO_x	SO_x	NMVOC	NMHC	NH_3	HCN	PAH	TPM	$PM_{2.5}$	BC
						Gg / yr						
Andhra Pradesh	8009.96	486.41	13.22	2.11	83.01	37.01	6.87	0.79	0.13	68.73	20.62	3.65
Arunachal Pradesh	80.78	4.91	0.13	0.02	0.84	0.37	0.07	0.01	0.00	0.69	0.21	0.04
Assam	1460.41	88.69	2.41	0.39	15.13	6.75	1.25	0.14	0.02	12.53	3.76	0.67
Bihar	5077.03	308.31	8.38	1.34	52.61	23.46	4.36	0.50	0.08	43.57	13.07	2.31
Chhattisgarh	1110.69	67.45	1.83	0.29	11.51	5.13	0.95	0.11	0.02	9.53	2.86	0.51
Goa	39.19	2.38	0.06	0.01	0.41	0.18	0.03	0.00	0.00	0.34	0.10	0.02
Gujarat	6835.92	415.12	11.28	1.80	70.84	31.59	5.87	0.68	0.11	58.66	17.60	3.11
Haryana	13907.71	844.56	22.95	3.67	144.13	64.26	11.93	1.38	0.23	119.34	35.80	6.33
Himachal Pradesh	635.45	38.59	1.05	0.17	6.59	2.94	0.55	0.06	0.01	5.45	1.64	0.29
Jammu and Kashmir	1403.12	85.21	2.32	0.37	14.54	6.48	1.20	0.14	0.02	12.04	3.61	0.64
Jharkhand	1939.61	117.78	3.20	0.51	20.10	8.96	1.66	0.19	0.03	16.64	4.99	0.88
Karnataka	8987.46	545.77	14.83	2.37	93.14	41.53	7.71	0.89	0.15	77.12	23.14	4.09
Kerala	184.66	11.21	0.30	0.05	1.91	0.85	0.16	0.02	0.00	1.58	0.48	0.08
Madhya Pradesh	3032.18	184.13	5.00	0.80	31.42	14.01	2.60	0.30	0.05	26.02	7.81	1.38
Maharashtra	10335.70	627.65	17.06	2.73	107.11	47.76	8.87	1.02	0.17	88.69	26.61	4.71
Manipur	109.00	6.62	0.18	0.03	1.13	0.50	0.09	0.01	0.00	0.94	0.28	0.05
Meghalaya	76.61	4.65	0.13	0.02	0.79	0.35	0.07	0.01	0.00	0.66	0.20	0.03
Mizoram	15.56	0.95	0.03	0.00	0.16	0.07	0.01	0.00	0.00	0.13	0.04	0.01
Nagaland	141.23	8.58	0.23	0.04	1.46	0.65	0.12	0.01	0.00	1.21	0.36	0.06
Orissa	1984.66	120.52	3.28	0.52	20.57	9.17	1.70	0.20	0.03	17.03	5.11	0.90
Punjab	32299.31	1961.41	53.30	8.53	334.72	149.24	27.72	3.20	0.53	277.16	83.15	14.71
Rajasthan	4202.19	255.18	6.93	1.11	43.55	19.42	3.61	0.42	0.07	36.06	10.82	1.91
Sikkim	18.95	1.15	0.03	0.01	0.20	0.09	0.02	0.00	0.00	0.16	0.05	0.01
Tamil Nadu	5099.67	309.68	8.42	1.35	52.85	23.56	4.38	0.50	0.08	43.76	13.13	2.32
Tripura	173.76	10.55	0.29	0.05	1.80	0.80	0.15	0.02	0.00	1.49	0.45	0.08
Uttar Pradesh	33701.42	2046.55	55.61	8.90	349.25	155.72	28.92	3.34	0.56	289.19	86.76	15.35
Uttarakhand	1146.20	69.60	1.89	0.30	11.88	5.30	0.98	0.11	0.02	9.84	2.95	0.52
West Bengal	8219.03	499.11	13.56	2.17	85.17	37.98	7.05	0.81	0.14	70.53	21.16	3.74
Andaman and Nicobar Islands	5.66	0.34	0.01	0.00	0.06	0.03	0.00	0.00	0.00	0.05	0.01	0.00

States	CO_2	CO	NO_x	SO_x	NMVOC	NMHC	NH_3	HCN	PAH	TPM	$PM_{2.5}$	BC
	Gg / yr											
Dadra and Nagar Haveli	6.81	0.41	0.01	0.00	0.07	0.03	0.01	0.00	0.00	0.06	0.02	0.00
Delhi	25.40	1.54	0.04	0.01	0.26	0.12	0.02	0.00	0.00	0.22	0.07	0.01
Daman and Diu	1.61	0.10	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.01	0.00	0.00
Pondicherry	30.07	1.83	0.05	0.01	0.31	0.14	0.03	0.00	0.00	0.26	0.08	0.01

Data source: Jain et al. [17]

Fig. 2. A view of super straw management system attached behind the combine harvester and direct drilling of wheat seed by happy seeder [19]

Paddy residue can also be used for biomass to energy, mushroom production, cardboard/paper production, and other off-farm applications. However, current technological barriers, supply chain gaps, and a lack of markets have prevented paddy residue from gaining economic value to the point that farmers are inspired to invest time and money in residue collection, and other stakeholders (including entrepreneurs) are encouraged to invest in these options. The amounts of paddy residue that these alternatives can currently use are a fraction of what is actually produced. Paddy residue has a high bulk density and moisture content, which necessitates adequate storage facilities.

Mechanization of crop residue management though most of these practices prevent soil damage that releases carbon and water into the atmosphere; promote soil and water conservation; and increase productivity. Mechanical harvesting has become widespread. As noted earlier, mechanization can displace or substitute for workers in cases of labour shortages. The most contentious form of mechanization is typically the adoption of harvest technologies for rice, wheat and sugarcane because of the large amount of agricultural labour involved.

4.2 In-Field Managements

4.2.1 In-situ management

Lignin, cellulose, hemicellulose, micro- and macro-nutrients are major constituents of CR. Degradation of CR varies depending on their lignin, polyphenol and cellulose content and their crop-dependent C/N ratio, but also on the conditions of the atmosphere and soil (texture, humidity) [28]. When cereal residues with a high C/N ratio (60:1 to 100:1) are introduced into the soil, they slowly decompose, resulting in soil N being immobilized. In zero tillage (ZT) systems, this can be beneficial, providing mulch that protects the soil from erosion and evaporation, but it also ensures that the next crop has less nutrients available. If N is mineralized or immobilized affects the C/N ratio of the organic matter being decomposed by soil microorganisms. If the residue's C/N ratio is > 20:1, net immobilisation will occur. Insufficient N in the substrate allows the species to draw on the mineral N in the soil, resulting in N being immobilised. However, as the decomposition continues due to decreasing C (respiration as CO_2) and increasing N (N immobilised from soil solution), the residue C/N ratio will decrease and a new equilibrium will be reached, followed by mineralization of N [29].

Farmers are increasingly using in-situ application of crop residues because it is a natural process. To avoid N deficiency due to N immobilization, rice straw can be handled in-situ by allowing 10-20 days between its incorporation and the sowing of the wheat crop [30]. The net supply of N from crop residue to successive crop depends upon decomposition period prior to planting of next crop, residue quality and soil environmental conditions. Crops planted immediately after the incorporation of cereal residue into such soils can become N-deficient and require adequate external application of N to meet the needs of micro-organisms and crops. Dordas [31] indicated that in the initial years of zero tillage (ZT) adoption, the net immobilisation process is transitory, and the immobilisation of N under conservation agriculture (CA) systems decreases the risk of leaching and denitrification losses of soil mineral N in the long run. Tyler and Thomas [32] reported that 15-25% extra usable moisture also favours N system losses by leaching and denitrification during the growing season in ZT compared to CT. The stubble is left standing in ZT systems, creating large residues which are not in contact with the soil. As determined by the residue retention/incorporation process, the degree of contact between crop residues and the soil matrix affects decomposition dynamics and nutrient release. However, the practice of in-situ rice straw incorporation as an alternative to burning has been adopted by only a few farmers because of high incorporating costs and energy; as well as time intensive. In addition, it requires high-capacity mould board plough to incorporate residue into the soil, Nonetheless, it has no ill-effects on the next wheat crop yield [5]. Gupta et al., [33] stated that the effect on wheat yield appears only after fourth year of continuous incorporation of straw. This approach also gives certain advantages to the soil. Field applications can be achieved in two ways, but both include collecting crop residue and leaving it on the farmland. They just vary in terms of what happens with tillage the following season. In the first process, the following season's planting is done without tillage or with minimal tillage, while in the second method, crop residue is mechanically introduced into the soil during tillage [34]. Although in-situ crop residue management can save money in the long run on equipment and labor, both methods require specialized (new) equipment, such as machinery for incorporating crop residues into soils or no-till seeding equipment.

5. SURFACE RETENTION AND MULCHING

The benefits of retention of crop remains on soil surface includes i) lesser weed growth, ii) saves weedicide cost, iii) improves physical, chemical and biological attributes of soils, iv) recycling of plant nutrients, v) lowering fertilizer use in the successive crops [14].

Direct drilling in surface mulched residues is a technique in which straw residues from a previous crop are left on the soil surface without being incorporated. The earlier ZT seed drills sowing in rice residues involved the removal of the loose straw after mixed harvesting, with partial or complete burning of the residues removed [35,36]. The recent 'Happy Seeder' production [37,38] now provides the Indo-gangetic plains (IGP's) RW farmers with the opportunity to directly drill wheat into complete rice residue. The accumulation of residues on the surface aids in the protection of the fertile surface soil from wind and water erosion. The large amount of residues left on the surface often causes machinery failures, delaying the sowing of seeds for the next harvest. Where no-tillage or conservation tillage practices are common, farmers typically use this process. In certain cases, surface preservation of any or all of the residues might be the best choice. Residues slowly decompose on the surface, growing organic carbon and total nitrogen in the top 5-15 cm of soil thus preventing erosion [39]. When compared to burning, leaving residues on the surface increased soil NO_3^- concentration by 46 percent, N uptake by 29 percent, and yield by 37 percent [40,41]. Retention, on the other hand, provides shelter for both harmful and beneficial species, as well as C substrate for heterotrophic N_2-fixation, increased microbial activity, soil C and N, and reduced rice fertilizer N requirements. If N is treated with urea and applied during field preparation, it will decompose and release N to the soil more quickly. Residues slowly decompose on the surface, growing organic carbon and total nitrogen in the top 5-15 cm of soil thus preventing erosion [39]. When compared to burning, leaving residues on the surface increased soil NO_3^- concentration by 46 percent, N uptake by 29 percent, and yield by 37 percent [40,41]. Retention, on the other hand, provides shelter for both harmful and beneficial species, as well as C substrate for heterotrophic N_2-fixation, increased microbial activity, soil C and N, and reduced rice fertilizer N requirements. If N is treated with urea and applied during field preparation, it will decompose and release N to the soil more quickly. Residues slowly decompose on the surface, growing organic carbon and total nitrogen in the top 5-15 cm of soil thus preventing erosion [39]. When compared to burning, leaving residues on the surface increased soil NO_3^- concentration by 46 percent, N uptake by 29 percent, and yield by 37 percent [40,41]. Retention, on the other hand, provides shelter for both harmful and beneficial species, as well as C substrate for heterotrophic N_2-fixation, increased microbial activity, soil C and N, and reduced rice fertilizer N requirements. If N is treated with urea and applied during field preparation, it will decompose and release N to the soil more quickly. Residues slowly decompose on the surface, growing organic carbon and total nitrogen in the top 5-15 cm of soil thus preventing erosion [39]. When compared to burning, leaving residues on the surface increased soil NO_3- concentration by 46 percent, N uptake by 29 percent, and yield by 37 percent [40,41]. Retention, on the other hand, provides shelter for both harmful and beneficial species, as well as C substrate for heterotrophic N2-fixation, increased microbial activity, soil C and N, and reduced rice fertilizer N requirements. If N is treated with urea and applied during field preparation, it will decompose and release N to the soil more quickly [42].

Incorporation of crop residue requires much time for field preparation, the quick and easy option is to collect the residue and use it as mulch in succeeding crop. A lot of machinery is available for this purpose. A no-tillage drill has positive impacts on wheat yield, profitability and resource use efficiency [43]. Only when no-till is practiced consistently and the soil surface is saturated with at least 30% of previous crop residue will the full benefits of no-till be completely realized. Due to direct drilling in standing as well as loose residues, the use of new-generation planters like Happy Seeder and spatial drill will contribute to wider adoption [37]. Chakraborty et al [44] reported that rice straw mulch increased wheat grain yield, reduced crop water use by 3-11% and improved water use efficiency by 25% compared with no mulch. Mulch produced 40% higher root length densities compared to no mulch due to retention of soil moisture in deeper layers [45]. Rice residue management in no-till systems has a number of advantages, including soil moisture conservation, weed suppression, and improved soil quality [46], as well as a reduction in greenhouse gas emissions of nearly 13 t ha^{-1} [47], and regulates canopy temperature at the grain-filling stage to mitigate the terminal heat effects in wheat [33,48]. The suppression of weeds with straw mulch might help to reduce herbicide requirements.

6. FARM MECHANIZATION AND CROP RESIDUE MANAGEMENT

Although farmers are aware of the adverse effects of crop burning, they rely on it due to the lack of economically viable and acceptable machinery and alternatives to dispose of residue. However, deploying advanced technology, including the concurrent use of straw management systems, fitted combine harvesters and happy seeders for direct drilling is a viable solution to eliminate burning. In recent years, manufacturers have enhanced their crop residue-management systems to provide finer chopping, wider and more even spreading, and better seed-soil contact for better crop emergence and yield [49].

Resource conservation technologies (RCTs) based farm machinery provides a better promise in managing paddy residues for improving soil health, productivity, reducing pollution and achieving sustainable agriculture [50,51,52]. For direct seeding of successive crop in loose and anchored straw load up to 10 t ha^{-1}, advance technology of zero-till seed-cum-fertilizer drill/seed planters, (happy seeder, spatial zero seed cum fertilizer drill) were available in the country [10,53,54]. These technologies are incredibly valuable for managing crop residues for controlling of weeds, conserving soil moisture content and nutrients. The happy seeder technology represented a burst through for paddy–wheat crop rotation in NW India.

For uniform spreading of paddy straw after harvesting of paddy by combine harvester, a Straw Management System (SMS) in which straw spreader is attached to the rear side of combine harvester just beneath the straw walkers and behind the chaffer sieves. The loose residues falling from the harvester straw walker is spread behind the harvester by the spinning discs. The straw from the combine harvester's straw walkers is fed into the machine from one side and discharged through the housing's outlet. The chopped material is blown off tangentially and deflected using a deflector for uniformly spreading the residues in the entire width of combine harvester.

Fig. 3. A view of combine harvester and fine chopping of residue

Fig. 4. A view of sowing of wheat seed by happy seeder in paddy residue retention

Happy Seeder-based systems emerge as the most profitable and scalable residue management practice as they are, on average, 10–20% more profitable than burning [37]. This option also has the largest potential to reduce the environmental footprint of on-farm activities, as it would eliminate air pollution and would reduce greenhouse gas emissions per hectare by more than 78%, relative to all burning options. Happy Seeder is a cost-effective solution that could be embraced by the 2.5 million farmers in northwest India who've been active in the rice-wheat cropping cycle, obviating the need to burn. It can also lower agriculture's contribution to India's greenhouse gas emissions. Better practices can help farmers adapt to warmer winters and extreme, erratic weather events such as droughts and floods, which are having a terrible impact on agriculture and livelihoods. In addition, India's efforts to transition to more sustainable, less polluting farming practices can provide lessons for other countries facing similar risks and challenges.

7. OFF-FIELD MANAGEMENTS

7.1 Baling and Removing the Straw

Surplus straw from agriculture may be used for a number of useful purposes such as livestock feed, fuel, building materials, livestock bedding, composting for mushroom cultivation, bedding for vegetables such as cucumber, melons etc. and mulching for orchards and other crops. The organic-C status of the soils was significantly increased when crop residues were incorporated. Similar was the trend in the available and total forms of NPK in soil. The increase in nutrient status of soil may be ascribed to the average addition of 6 t ha^{-1} yr^{-1} of wheat straw and 12 t ha^{-1} of rice straw for seven years. The addition of crop residues N and P were converted to unavailable forms through immobilization and adsorption, respectively. The residue generated from the paddy-wheat cropping system can be have too many uses but this is possible if the residue is carried out off the field. In some parts of NW India straw reapers are in practice to collect the straw from the field and it is gaining popularity in wheat straw collection instead of rice because of its economical use for feeding animals. For removal and collection of straw after combine harvesting and using the residues for off farm works; straw baler machines is very promising technology and commercially available. These balers, however, recover only 25–30% of potential straw yield after combining, depending upon height of plant cut by combines. Baler makes rectangular or round bales by collecting the loose straw from the ground. Machine can recover about 200–250 bales weighing between 15 and 30 kg (depending upon moisture and field condition) with a size of 460×360 mm bale from combines harvested field. The speed of operation can be varied between 2–3 km h^{-1} in combine harvested fields depending upon the field conditions. The fuel consumption varied between 8.5–11.01 ha^{-1} [55]. The energy requirements vary widely from 0.6 to 1 kW h ton^{-1} and cost of operation is Rs. 6170 per hectare. It can also be used for paper and bioethanol processing, mushroom cultivation, bioconversion, and engineering applications after baling crop residues [2,56]. In the case of fodder, residues tend not to be exported entirely because cropland is fertilized with manure from cattle fed with crop residues in mixed agriculture. It is not technically feasible and also not an economical choice for farmers to gather and store this enormous amount of residue for off-farm use [56].

7.2 Machines and Equipments for In-Situ Crop Residue Management

In conjunction with recent state regulations outlawing the use of fire to destroy field crop waste in northwest India, some farmers are benefitting from technological innovations that can help prevent damaging smog levels in the capital Delhi and other areas. Currently, the majority of farmers in northwest India burn leftover vegetation residue to prepare fields for planting in rice-wheat crop rotations, leading to undesirable consequences for soil quality, the environment, animal and human health. Rice-wheat crop rotations make up 84 per cent of burned crops, a key source of atmospheric pollution.

As per the view of users the machine (combine harvester) finishes the task of reaping, threshing and winnowing in a few hours and is also economical. However, the machine appears to be the key reason behind the problem because it only reaps the grains, leaving stalks or stubble of around 40 cm. Those who want fodder have to get the stubble removed manually or use specialised machines to do the job. But that is costly. For every 0.4 ha of wheat crop, the cost of renting a combine harvester is just Rs. 800. Once the machine has harvested, the cost of getting the stubbles removed is Rs 3,500 ha^{-1}. So the value of fodder is discounted because it is more economical for the farmers to just burn and clear the fields. It is also suggested that a mechanism be set to provide free equipment to farmers having two acres or less land (one acre equals 0.4 hectare) to help them reuse the stubble.

In-situ incorporation enhanced decomposition of combine harvested residues to advance nutrients in the soil can be useful. Residue incorporation in the soil has several positive impacts on soil health attributes such as pH, organic carbon, infiltration rate and water holding capacity [8,10]. It enhances hydraulic conductivity, cation exchange capacity (CEC) and decreases soil bulk density by altering soil structure and aggregate stability, producing surface crust, evaporating water from the top few inches of soil and preventing nutrient leaching. It also increases the microbial biomass and enhances activities of enzymes such as dehydrogenase and alkaline phosphatase [57]. Previous studies had revealed the effect of straw and N application unaided or in blend leads to increased biomass carbon, phosphates and respiratory activities of the soil [58].

On a long-term basis increase is witnessed in the availability of iron, copper, zinc and manganese content in the soil and it also prevents the leaching of nitrates. An increase in organic carbon increases bacteria and fungi in the soil. Researchers found that soil treated with crop residues contained 5–10 times more aerobic bacteria and 1.5–11 times more fungi than soil from which residues were either burned or removed [59,60]. Due to increase in microbial population, the activity of soil enzymes responsible for conversion of unavailable to available form of nutrients also increases. It is reported that an addition 36 kg per hectare of nitrogen and 4.8 kg per hectare of phosphorus (6 g of N and 0.8 g of P per kg of paddy straw) leads to save 15–20% of total fertilizer's use. Field incineration of crop residues disturbs C and N dynamics in agro-ecosystems and atmospheric greenhouse gas concentrations during combustion besides subsequent incorporation of the burned crop residues in soil [61]. One of the studies revealed a 10 years of continuous residue addition with no-till results in 25% higher SOC compared to conventional tillage (CT) [62]. In that same time frame, the SOC content was 17% greater with minimum tillage than CT.

7.3 Crop Residues as Livestock Feed

Traditionally, the CR in India are utilized as animal feed such as or by supplementing with some additives. However, crop residues, being unpalatable and low in digestibility, cannot form a sole ration for livestock. Rice residues are considered bad feed for livestock, with a high silica content (4-7 percent) [12]. It differs from other straws in having a higher content of silica (12-16 vs. 3-5%) and a lower content of lignin (6-7 vs. 10-12%). Various approaches may be used to increase the nutritional value of rice straw.

Fig. 5. A view of straw bailer for bailing of paddy / wheat straw in combine harvested field

Crop residues have been subjected to physical, chemical, and biological treatments in order to weaken and break down lingo-celluloses bonds, increasing their nutritional value [63]. About 75% of wheat straw is utilized as fodder for animals, chopped in small pieces with the help of special cutting machine though this requires additional operation and investment. Although rice straw stems have a lower silica content than leaves, they are more digestible; thus, if the straw is to be fed to livestock, the rice crop should be cut as close to the ground as possible. To complete the nutritional requirements of animals, the residues need processing and enriching with urea and molasses, and supplementing with green fodders.

7.4 Crop Residues as Compost / Mechanized Composting

For preparing compost, crop residues are used as animal bedding and then heaped in dung pits. In the animal shed each kilogram of straw absorbs about 2-3 kg of urine, which enriches it with N. The residues of rice crop from one hectare land, on composting give about 3 tons of manure as rich in nutrients as farmyard manure (FYM). The crop straw compost can be fortified with P using indigenous source of low-grade rock phosphate to make it value added compost with 1.5% N, 2.3% P_2O_5 and 2.5% K_2O [64]. However, mechanized composting can significantly improve the bio-physical processes of composting. The compost product can be used as medium for growing vegetables and other crops or spread on the rice field as soil amendment. It enhances nutrient (i.e., nitrogen and carbon contents) and organic matter content of the soil.

8. PRODUCTION OF MUSHROOM CROP

Mushroom cultivation is a lucrative agri-business enterprise that produces food from rice and wheat straw while also promoting the environmentally safe disposal of this by-product. Because of its short 14-day incubation period, the paddy straw mushroom, *Volvariella volvacea,* is considered one of the easiest mushrooms to cultivate [65].

Paddy straw is key ingredient to be utilized as a raw matter for mushroom culture in Punjab [66] although generally farmers use wheat straw as raw material. A recent research conducted on paddy straw management [7] revealed the estimated cost for these operations as Rs. 510 per quintal in the case of paddy straw (raw material) as compared to Rs. 810 per quintal with wheat straw use. Therefore, use of paddy straw for mushroom production results in a net saving of Rs 275 quintal per heactare as compared to wheat straw. Paddy straw may also be used to make paper, pulp board, cushioning for packaged goods [67], and floor tiles [68]. Rice straw can produce 5–10% mushroom products (50–100 kg mushroom per 1 ton dried straw) [69]. The oyster mushroom Pleurotus spp., on the other hand, is cultivated. Provides on-farm technology for bioconversion of low-quality straw into nutrient-dense foods.

9. BIOCHAR PRODUCTION AND UTILIZATION

Biochar, a carbon-rich commodity, is used as a soil amendment to boost soil fertility, carbon conservation, and water filtration [70]. It is created by the thermal decomposition of organic materials or biomass at temperatures ranging from 500 to 700°C with a small supply of oxygen. Hydrothermal carbonization (HTC) is a new advanced carbonization technology that has recently been introduced. HTC of lignocellulosic biomass is a process that breaks down the plant cell wall entirely, allowing for the rapid conversion of biomass into a carbon-rich, lignin-like commodity (hydrochar). The heating value of hydrochar is substantially higher than that of the raw material [71]. Rice straw can be used to make biochar, which has a lot of promise. In addition, carbon sequestration by biochar application reduces the danger of climate change caused by GHG pollution in the atmosphere. The carbon footprint of using biochar as a soil modification is lower than the carbon footprint of using it as a fuel [72]. However, despite its enormous potential, the production of biochar necessitates the use of energy for carbonization and transportation of rice straw and biochar items. Studies demonstrating the feasibility of biochar production from rice straw in terms of energy balance and economic benefits are still required.

10. USE OF RICE STRAW FOR BIOGAS PRODUCTION

The biomass of paddy residues is efficient source of energy generated through anaerobic digestion, gasification and pyrolysis technologies which offers an instant result for the decline of

CO_2 concentration in the environment [73,74]. Using anaerobic digestion of one tonne of paddy residue, 300 m^3 of biogas can be obtained [75]. The process generates suitable quality of gas consisting 55–60% methane and the spent slurry can be used as manure [76]. One tonne of paddy biomass can generate 300 kW h of electrical energy through gasification. It assures a way to consume crop residues in non-destructive way to pull-out high-quality fuel gas and harvest manure to be recycled in soil [77].

11. OTHER METHODS

11.1 Crop Residues as Surface Mulch in Other Crops

The rice straw can be used as mulch for other crops. The beneficial effects of this practice is to improve crop yields at comparable irrigation regimes and saving of irrigation water and fertilizer nitrogen at comparable yields have been reported in several crops e.g. in forage maize, sugarcane, sunflower, soybean, potato and chillies by reducing the evaporation (E) component of the ET and acting as barrier to vapour flow, and moderating soil temperature [78]. The response is more under high temperature, low rainfall year and on coarse texture soils. Higher soil water in the profile, especially the root zone, in the mulched plots caused better stand establishment, and early seedling vigour. Straw mulching economized fertilizer N for comparable crop yields amounting to 25 kg N ha^{-1} in Japanese mint, 50 kg in forage maize, and 30 kg N ha^{-1} in Chilli. More favourable soil temperature and higher water content under mulched than un-mulched soil increases mineralization of soil N. Due to the scarcity of labour and high cost involved in collection and applying straw mulch, this technology has not become popular with the farmers.

11.2 Diversification of Crops

State and federal governments in the Green Revolution belt have begun to move away from paddy cultivation in order to address groundwater shortages and stagnant yields. In selected districts, a centrally funded scheme launched in 2013-14 aimed to diversify at least 5% of paddy land to more locally suited crops (e.g. maize, millets, and oilseeds). However, despite the scheme's numerous provisions (cluster demonstrations, knowledge trainings, farm machinery subsidies, and so on), most farmers have not found it profitable to diversify from paddy cultivation to other Kharif crops. The widespread market support and yield advantages paddy enjoys over other choices for Kharif cultivation have hampered the effective translation of policy objectives of crop diversification to field results.

11.3 Improved Short-Term Paddy Varieties

To reduce water consumption in paddy cultivation in the Western Indo-Gangetic Plains, research organizations have produced short-duration paddy varieties. While traditional varieties (those that mature in 160 days) are still grown for their higher yields, varieties that mature in 135-145 days are becoming more common. Some speculate that the adoption of such varieties could extend the period between paddy harvest and wheat sowing, allowing farmers to clear fields and minimize residue burning. However, more research and policy focus would be needed to determine its efficacy.

11.4 Technological Interventions and Best Practices Possible to Deal with the Issue of Stubble Burning

Both in situ and ex situ agricultural management practices can be adopted to manage crop residue. Ex situ practices involve taking the residue away from the field and converting it to compost or baling rice residue for power plants [19]. However, there are trade-offs for ex-situ management of crop residues, and they are not always economically viable or sustainable. Labour availability and costs are a problem, and therefore composting is not an economically viable option for the farmer. Baling is also not a viable option as the baler costs more than 10 lakhs, and the operational window to use it is 10-15 days. For the rest of the year it lies unused, and even the depreciation costs cannot be recovered. Moreover, taking out residues from the field and not recycling them back are counterproductive for soil health.

The in-situ practices involve managing the residue at the site of production. There are technologies like Rotavator, and mulcher but they are not entirely suitable and could lead to higher production costs and delayed planting of wheat crop. The concurrent use of super straw management system (SMS) and Turbo Happy

Seeder efficiently takes care of the residue and also brings down the operational cost of preparing the field for the next crop. It performs three operations in one go hence, increasing time efficiency: shredding the harvested crop, spreading the stubble across the swath and simultaneously sowing the wheat seeds [38]. Scientific studies have shown that it saves approximately 10 lakh litres of water on day one of seeding crop, increases profit amounting to Rs 20,000 - 25,000 per hectare per year for a farmer. Gradually, it also leads to a reduction in the use of nitrogen fertilizers by the farmers. It eventually results in reduction in emissions of greenhouse gases from the agricultural fields. In situ crop residue management with technology not only provides many advantages to the farmer, but it is also a viable option to avoid residue burning.

12. CONCLUSION

Crop residues (CR) are of great economic value being used as livestock feed, fuel and industrial raw material. However, management challenges of the CR are varied across the region and its socio-economic needs. The estimated amount incorporated with standard uncertainties provides a complete view about the amount of crop residue generation every year. Crop residue management is also critical, as machines are increasingly being used to harvest crops, leaving large quantities of residue in the field. There are several options for management of CR such as: burning, incorporation and surface retention. Every management option has its advantages as well as disadvantages. Therefore, it is the location, soil and situation, which will govern the practice to be selected. Of course, intensive research is required to solve this problem of managing CR. Sometimes surface retention may be the best option in many situations. For sowing/ planting of subsequent crops having CR, both stubbles and loose straw in the field needs to be managed, for that intensive investigation in different crop growing areas is required. Ex situ alternatives for crop residue incineration alike assortment, gasification as a fuel for the boilers, transforming converting into briquettes and planning suitable harvester should be promoted.

In situ alternatives like managing crop residue by happy seeder, zero-till machine, double disc coulters, straw choppers are required for practicing and adoption of conservation agriculture (CA) in the region, which will reduce the residue burning in rice-wheat rotation. Promotion of organic recycling practices and incentives to farmers will ensure sojourn prevalent practices leading to pollution and wastage of potential resources. The first constraint to handling crop residues in-situ is the lack of RCT machinery; other constraints include the lack of residue-based power plants and biochar units for ex-situ residue management. Government should promote and provide need based support alternative options to stop residue burning. The other important point for successful CA adoption is the need to provide farmers with credit to purchase equipment, machinery, and inputs at fair interest rates through banks and credit agencies. There is also a need to think about the issues facing the implementation of these CA technologies at the level of farmers. Under such circumstances, in the initial years followed by large-scale demonstrations in subsequent years, farmers need participatory on-farm research to evaluate/refine the technology.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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