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Burning issues of paddy residue management in north-west states of India

Shiv Kumar Lohan[a], H.S. Jat[b,*], Arvind Kumar Yadav[c], H.S. Sidhu[d], M.L. Jat[b], Madhu Choudhary[c], Jyotsna Kiran Peter[e], P.C. Sharma[c]

[a] Department of Farm Machinery & Power Engineering, Punjab Agricultural University, Ludhiana 141004, India
[b] International Maize and Wheat Improvement Centre (CIMMYT), NASC Complex, New Delhi 110012, India
[c] ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal 132001, India
[d] Borlaug Institute for South Asia (BISA), Ludhiana 141004, India
[e] SamHigginbottom University of Agriculture Technology and Sciences (SHIATS), Allahabad 211007, India

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ABSTRACT

Disposal of paddy residue has turn out to be a huge problem in north-west Indian states, resulting farmers prefer to burn the residues in-situ. Paddy residue management is of utmost important as it contains plant nutrients and improves the soil-plant-atmospheric continuum. Burning biomass not only pollutes environment and results in loss of appreciable amount of plant essential nutrients. The objectives of the review paper is to access the amount of residue generation, its utilization in-situ and ex-situ, emphasize harmful effects of residue burning on human health, soil health and environment of north-west states of India specially in Punjab and Haryana. This paper also discusses the possible strategies, financial and socio-economic evaluation of the paddy residue management technologies and accentuates the assessment of range of potential policy instruments which would offer avenues for sustainable agriculture and environment. Timely availability of conservation agriculture (CA) machinery is of utmost significance to manage the paddy residues in-situ. Collection and transportation of voluminous mass of paddy residue is cumbersome, therefore, ex-situ residue management is still not an economically viable option. The agricultural waste opens vivid options for its versatile usage and is possible if residue is collected and managed properly. It is a prerequisite for surplus residues to be used for CA. There is an urge to create awareness among farming communities to incline them to understand importance of crop residues in CA for sustainability and resilience of Indian agriculture.

1. Introduction

The remains of the field crops after harvest is of enormous use which is a natural resource that add to soil structure and fertility. Their deployment may differ among various countries. Few opt to use crop residues as an option to feed animals, nutritional added value compost, and mushroom cultivation and even they are burnt in fields, whereas there is relevant possibility of spawning bio-energy for rural supply and development [1–3]. China [4], Indonesia [5], Nepal [6], Thailand [7], Malaysia [8], Japan [9], Nigeria and Philippines [10,11], utilizes crop residues as source of energy, whereas Philippines [10,11], Israel, China [4,12] uses it for composting while Lebanon, Pakistan [13,14], Syria [15], Iraq, Israel, Tanzania, China [12,16] and African countries involve these to offer it feed for animals [1,11,17]. Open residue burning is a common practice in Asia [18] and in other countries as well i.e. China [12,17,19], USA, Philippines [10,11], Thailand [10], Indonesia [5], Taiwan [10], Pakistan [13,14], Nepal [6] and India [6,20,21].

India is an annual gross crop residue producer of 371 million tons (mt), of which wheat and paddy residues constitutes 27–36% and 51–57% respectively [2,6]. The bio-energy potential annually generated from various residual agricultural mass is estimated to be 4.15 EJ, equivalent to 17% of India's aggregated consumption of principal energy [22–24]. Uttar Pradesh (53–60 mt) is a leading state of India for residue generation followed by Punjab (44–51 mt), Maharashtra (46–56 mt) and West Bengal [22]. Cereal crops (paddy, wheat, maize, millets) contributes 70% residue of which paddy crop is the contributor of 34% [25–28], however, results from the characterization analysis had revealed 84% of crop residues burning is from paddy-wheat system

* Corresponding author.
Email addresses: shivkumarlohan@rediffmail.com (S.K. Lohan); H.Jat@cgiar.org (H.S. Jat); yadav.arvind580@gmail.com (A.K. Yadav); H.Sidhu@cgiar.org (H.S. Sidhu); M.Jat@cgiar.org (M.L. Jat); madhucssri@gmail.com (M. Choudhary); jyots.kp@gmail.com (J.K. Peter); pcsharma@cssri.ernet.in (P.C. Sharma)

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(RWS) while remaining 16% is from other types of crop rotations [17,29]. The extreme amount of residue from wheat, barley and pearl-millet is used as animal fodder, whereas stubbles of cotton and red gram are used as firewood fuel at household. Mustard husks are chiefly engaged to the fuel for brick kilns [30,31]. Paddy residues, which are the most generous agricultural biomass from the paddy cultivation, have a crucial part to act on [17,32]. The paddy crop residue is burnt in-situ (Fig. 1), which is a common management practice in north-west (NW) India viz. Punjab, Haryana as well as Uttar Pradesh. Whereas, in rest of the country viz. Gujarat, Maharashtra, Tamil Nadu, Bihar, Assam, West Bengal and Jammu & Kashmir uses it as cattle feed, thatching for houses in rural areas, fuel for domestic cooking and industry, mulching material, compost making, power generation, biofuels, and in boilers for parboiling paddy [8,18,29,33,34]. With a global outlook of practicing agricultural residue burning in NW India, it is a contributor of 20% organic carbon (OC) and elemental carbon (EC)towards the overall budget of emission from agricultural waste burning. It was estimated that OC, EC and SPAHs from crop residue burning releases 505,968 Gg y^{-1}, 5992 Ggy^{-1} and 182,932 Mgy^{-1}, respectively. In India, in the year 2000, the predicted values of CH_4, CO, N_2O, and NO_x emissions from paddy and wheat straw burning are 110, 2306, 2 and 84 Gg respectively [2,21].

Keeping in view the above facts, the present article focuses assessment and management related to paddy remains, their generation, utilization and approximation of energy generation from paddy residue in NW states of India. This paper showcases the practice of paddy residue burning along with the magnitude of pollution caused and its impact on soil health, human health and environment. Moreover, the site specific relevant technologies developed for residue management, energy requirement during residue management practices and alternative use of paddy residue as cited in various literatures is also discussed. We hypothesized that management and utilization of crop residues in a sustainable and eco-friendly manner would definitely help in policy formulation by State Governments of NW India. The concept of residue management as per socio-economic and bio-physical conditions helped various stakeholders such as agricultural scientists, engineers, farmers, agro industry owners, farm machinery manufacturers, custom hiring service centers, NGOs, policy formulators and decision makers to keep clean and safe environment while sustaining farmer's income and soil health.

2. Methodology

2.1. Area, production and productivity of paddy-wheat crop in NW India

The area, production and productivity of paddy crop of NW states of India (Punjab and Haryana) is sourced from the Agricultural statistics at a glance [35], Statistical Abstract of Punjab [36], Haryana [37] and India [38]. Since the problem of paddy residue burnt is in combine harvested area under paddy-wheat crop rotation, therefore, area that fall for burning of paddy residue was calculated by subtracting the area under basmati variety of paddy, and area of zero/ happy seeder technology under combine harvested paddy crop. The residue of basmati/scented variety is not burnt in in-situ field and is extensively in use as animal fodder. Basmati is a famous variety of paddy crop raises a superior price; therefore, manual harvesting is the suited practice to minimize grain loss while it may has elevated loss when associated with combined harvesting [6]. About 90% of paddy area in Punjab and 75% in Haryana is harvested by combine harvester and this practice is increasing in different regions of the country where the paddy-wheat system is practiced [39–44].

2.2. Determination of amount of paddy residue available in the region

Paddy crop residue includes leaves, straw and husks that are left behind after the crop has been harvested. The quantity of paddy crop residues generated in NW states of India was estimated by crop-to-residue ratio (CRR) method. The CRR values were determined by an earlier study conducted [45,46] and used to find out the total crop residue production and its surplus value in the state in 2014–15. Total crop residue generated was predicted as:

$$\begin{aligned} &\textit{Total crop residue generated } (CRR) \\ &= \textit{Area covered by the crop } (Ai) \textit{ x yield of the crop } (Yi) \textit{ x cro} \\ &\quad - \textit{to} - \textit{residue ratio of the crop } (CRRi). \end{aligned}$$

2.3. Estimation of power generation potential

The estimation of power generation assumes that the total biomass residue is restricted for electrical output in its end use [21,22,45]. Po-

Fig. 1. *In-situ* burning of paddy crop residue.

tential for power generation from biomass is calculated as follows:

$$\textit{Power generation potential } (MWe) = \textit{Total available biomass } (kilo-tons\ yr^{-1})\ x\ \textit{Energy content of biomass } (MJ\ kg^{-1})\ x\ \textit{Net p}$$

The energy content of biomass (on a dry, ash-free basis) is similar for all plant species, laying in the range 17–21 MJ kg^{-1}. For calculation work, lower range values had been taken with an assumption of taking minimum possible power generation potential on yearly.

2.4. Energy requirement for various residue management practices

The energy expenditure in the residue management and crop establishment for the two practices was estimated by calculating the expanse of energy sources (human labour, machines, fuel, electricity, water) involved in the production process per hectare and then multiplied by their corresponding energy equivalent. The values of energy equivalents from various sources used in the study were; 1.96 MJ $h^{-1}$for humans, 11.93 kW h for electricity, 0.63 MJ l^{-1} for water, 56.31 MJ l^{-1} for diesel, 62.7 MJ l^{-1} for farm machinery and 64.8 MJ kg^{-1} for tractor as provided by Singh and Mittal [47].

The human energy consumption (MJ ha^{-1}) per operation i.e. spreading residues, tillage, sowing and irrigation was determined by the number of human labour used, capacity of one human labour to do the operation and the energy equivalents. Fuel consumption for tractor-powered farm operations was from the actual fuel consumed (l h^{-1}) and EFC (ha h^{-1}) of the machine. Net fuel energy consumption was determined by multiplying the fuel energy equivalent (MJ l^{-1}), consumption (l ha^{-1}) and effective field capacity (ha h^{-1}). To calculate the electric energy required to pump water was deducted on the basis of amount of electricity consumed (kW h) and rate of area covered for irrigation (ha h^{-1}) and the energy equivalents of electricity. The energy contribution of machinery per field operation was determined through values of weight of each machine/implement, its estimated life, effective field capacity of machine and the energy equivalents of farm machine.

3. Results and discussion

3.1. Area and production of paddy-wheat crop at NW states of India

This section describes the scenario of paddy crop production, in the NW states of India, which will help to better understand the utilization pattern, key issues of burning paddy residues in-situ, harmful effects of residue burning on human health, soil health and environment. Despite semi-arid climatic conditions, a significant increase in area and production of paddy-wheat crop took place after 1960 in NW states of India, especially in Haryana and Punjab. These states represent a extremely productive paddy-wheat region in the Indo-Gangetic plain of India and thus called “food bowl of India” (Fig. 2). In the last four decades, these states has contributed 40% wheat and 30% rice to the central stock in India thereby, played a significant role in maintaining food security [44,48–50]. The total food grain production amplified in figures of 3.16–37.46 mt and 2.68–16.75 mt along with the productivity from 657 to 4143 kg ha^{-1} and 719–3772 kg ha^{-1} in Punjab and Haryana state, respectively from the year 1965-66 to 2014-15. As presented in Table 1, paddy production increased from 0.34 to 11.10 mt in Punjab and 0.23–4.13 mt in Haryana from 1965 to 66–2014–15, Whereas, wheat production increased from 2.45 to 15.78 mt in Punjab and 1.06–11.06 mt in Haryana during the same period [36,38,47,51–53]. Various practices for management of paddy residue after harvesting and technology for wheat sowing in paddy-wheat rotation are presented in Fig. 3.

3.2. Residue produced from various crops

Overall residue generation in Punjab and Haryana state from all crops was 40.14 and 24.70 mt respectively [25,27,28,46,54]. Straw and husk of wheat and paddy alone contributed more than 86% in Punjab and 80% in Haryana, and rest contribution was from cotton, mustard and sugarcane crops (Fig. 4). The Punjab state produces 55.39 mt crop residues, among which, 22.32 mt (40.17%) of the total residues have been found surplus with an average density of 4430 kg ha^{-1} [22,27,45]. Wheat, paddy, barley and maize are the major additional biomass contributor of 74.76% while cotton contributes 25.01% and least is by sugarcane i.e 0.2%.

3.3. Utilization (ex-situ) of paddy residues

Paddy residues consists of straw and husk, which have numerous supreme uses and have great economic values such as animal feed, fodder, roof thatching, packaging, composting, fuel for household industries (combustion with coal, wood, *etc*) [30]. Additionally paddy residue plays an imperative role in moderation of soil temperature, moisture and controls the *Phalaris minor* (a problematic weed) while its retention on soil surface. The competitive uses for paddy residues are different in diverse provinces depending on their availability and requirements.

3.3.1. Domestic/industrial fuel

The rural population of Himachal Pradesh, Uttarakhand, Jammu & Kashmir, depends primarily on fuel-wood for fulfilling domestic needs/ industrial fuel for cooking (combustion with dung cake/ wood/ coal) [27,30].

3.3.2. Cattle feed

The NW states of India, does not practice feeding cattle with paddy straw because of its low feed value because the nutrients present in rice straw are not readily digestible to the livestock because of high silica and ligno-cellulosic content along with very low protein 2–7%). However, the residue of basmati variety of paddy is frequently consumed as animal fodder [30,55] because of its high palatability. The basmati paddy straw is fed to animals mixed with green fodder only in dire scarcity of fodder availability [56]. Wheat straw is valuable and is intensively collected, subsequently stored and used round the year as feed with the sale of surpluses. Buffalo are stall-fed throughout the year on a basal diet consisting primarily of hewed wheat straw ‘*bhusa*’. The basal diet, particularly of lactating animals, is supplemented with green fodder and other crop byproducts.

3.3.3. Use of straw for cattle's bed

The paddy wastes are used as bed material for cattles during winters is been a regular practice in few regions of India. The bed material of paddy helps improving milking capacity in terms of quality and quantity contributing to comfortable sleep of cattle warmth, udder health and leg health. Moreover, the straw material leads to a hygienic, relaxed, greasy surrounding and it even prevents the chances of injury and lameness [30]. The paddy straw used for bedding could be subsequently routine for composting. Each kg of straw absorbs about 2–3 kg of urine from the animal shed. Moreover, It can be composted by alternative methods on the farm itself. The residues of rice from one hectare gives nearly 3.2 t of manure as it possess plentiful of nutrients as farmyard manure [25].

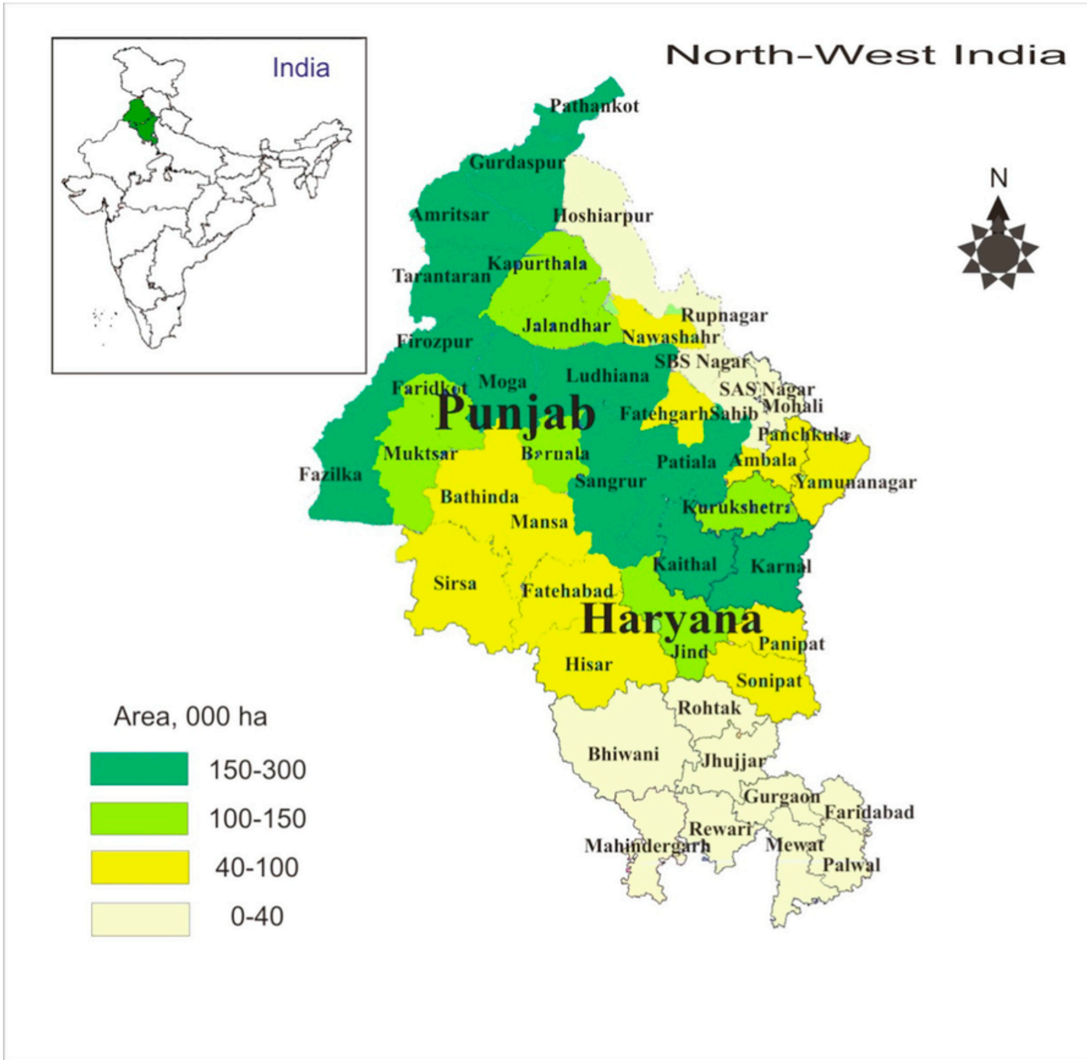

Fig. 2. Paddy-wheat area (000 ha) of north-west India.

3.3.4. *Source of energy*

The biomass of paddy residues are 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 [53,57,58]. Using anaerobic digestion of one tonne of paddy residue, 300 m^3 of biogas can be obtained [8]. The process generates suitable quality of gas consisting 55–60% methane and the spent slurry can be used as manure [25,59,60]. 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 [67].

3.3.5. *Production of mushroom crop*

Paddy straw is key ingredient to be utilized as a raw matter for mushroom culture in Punjab [61] but in general farmers are in use of wheat straw as raw material. For production of button mushroom, some operations like washing of straw and draining of excess water, cutting of straw, and preparation of bundles are necessary. A recent research conducted on paddy straw management [34] revealed the estimated cost for these operations of 7$ per quintal in the case of using paddy straw as a raw material rather it was 11$ per quintal when wheat straw is used as a base material. Therefore, use of paddy straw for mushroom production provide great help to the mushroom growers of an amount of 3.75$ per quintal as net saving. Paddy straw can also be used in the fabrication of paper, pulp board, cushioning material in the packaging of manufactured goods [31] and floor tiles [55].

3.4. *Area under paddy residue burning*

The burning of residue after harvest has a strong regional and crop specific variation with considerable spatial and temporal heterogeneity [27]. According to estimates from various researchers, farmers burn 30–90% of paddy residue in Punjab albeit with a strong regional variation (Table 2). Incineration of paddy residues leaves behind the burnt ashes and blackening of the soil and can be easily monitored through remote sensing. GIS has been a strong tool in various studies to estimate the potential of crop residues for energy generation. Globally, various reports revealed the utilization of GIS for estimating the theoretical amount of agricultural residues and their energy potential [29,44,62–65]. These studies have approached to estimate the theoretical volume of crop residues [66]. The tool is important as it facilitates exploration of spatial data and can be used successfully to create numerous levels of information.

Table 1
Time series area, production and productivity of paddy-wheat crops in north-west states of India.

Year	Punjab						Haryana					
	Area, 000 ha		Production, mt		Productivity, t/ha		Area, 000 ha		Production, mt		Productivity, t/ha	
	Paddy	Wheat	Paddy	Wheat	Paddy	Wheat	Paddy	Wheat	Paddy	Wheat	Paddy	Wheat
1965–66	285	1608	0.34	2.45	1.19	1.52	192	743	0.22	1.06	1.16	1.43
1970–71	476	2404	0.96	5.36	2.01	2.23	269	1129	0.46	2.34	1.71	2.07
1975–76	858	2617	2.49	6.64	2.91	2.54	303	1226	0.63	2.43	2.06	1.98
1980–81	1322	3052	4.15	9.18	3.14	3.01	484	1479	1.26	3.49	2.60	2.36
1985–86	1778	3158	5.43	11.87	3.05	3.76	584	1700	1.63	5.26	2.80	3.09
1990–91	2179	3335	7.00	12.37	3.21	3.71	661	1850	1.83	6.44	2.77	3.48
1995–96	2519	3337	7.90	12.72	3.14	3.81	830	1972	1.85	7.29	2.23	3.70
2000–01	2646	3481	9.66	14.49	3.65	4.16	1054	2355	2.70	9.67	2.56	4.11
2005–06	2802	3522	10.48	15.72	3.74	4.46	1047	2303	3.19	8.85	3.05	3.84
2010–11	2818	3510	10.54	16.47	3.74	4.69	1243	2504	3.47	11.58	2.79	4.62
2014–15	2894	3514	11.10	15.78	3.84	4.49	1350	2510	4.13	11.06	3.06	4.41

[Ref. 35–38].

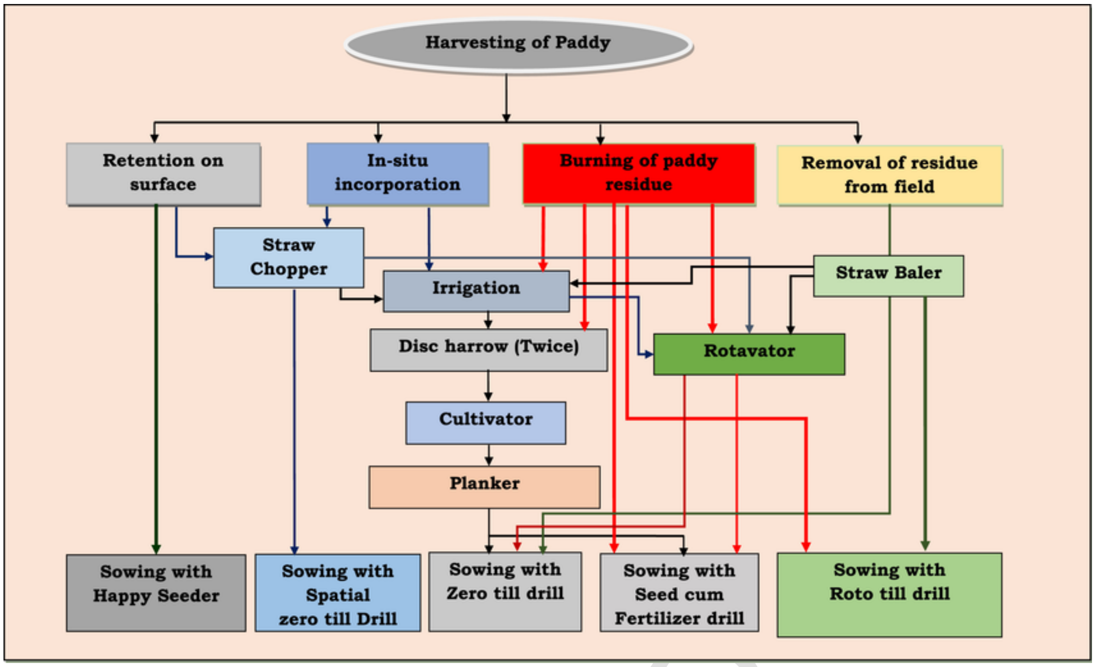

Fig. 3. Various practices for managing paddy residues in paddy-wheat rotation.

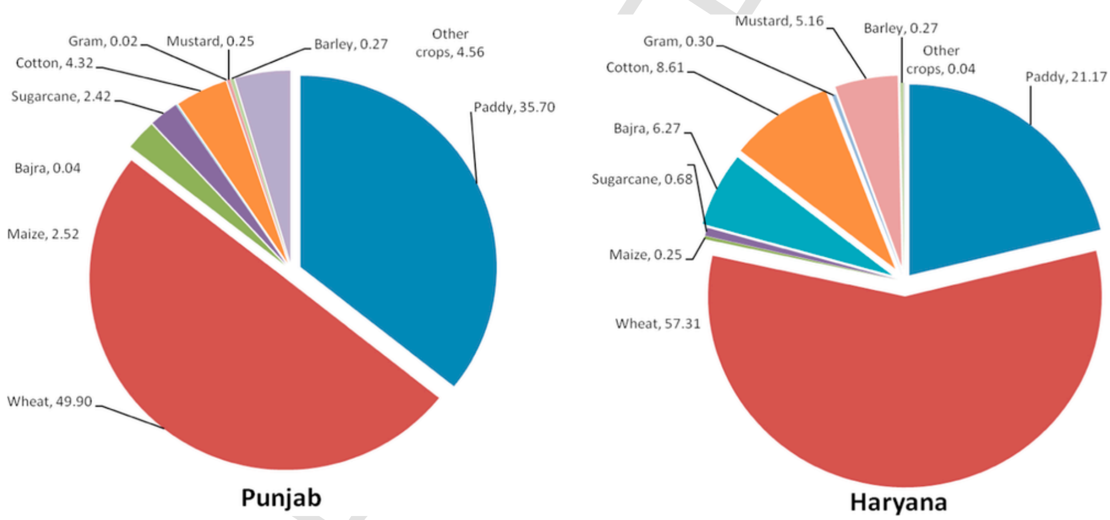

Fig. 4. Crop wise percentage of residue generation in Punjab and Haryana, [22,27,31,45,46].

Table 2
Extent of paddy residues burnt in Punjab state of India.

S. No.	Available paddy residues, mt	Percentage of Paddy Residues burnt, %	References
1.	–	30–40	[141]
2.	12.0	48	[33]
3.	14.0	50	[45,46]
4.	15.0	50	[30,44]
5.	–	74	[78]
6.	18.0–20.0	80	[34,80,106,129]
7.	21.0–23.0	81–82	[31,91,123,142]
8.	17.0	90	[20,54,143]

As residue burning and ploughing the fields are gradual processes, all burning area may not be picked up in the single date imagery. An estimation done using course resolution AWiFS and LISS-III satellite data explored about 12.68 m ha in Punjab state and 2.08 m ha in Haryana state of paddy area burnt every year [68,69]. Active fire data of MODIS and Suomi NPP VIIRS for spatial and temporal features of incinerating residual crops in states of Punjab and Haryana revealed the estimated number of incineration-identified by MODIS are 15,222 and by VIIRS are 15,568 in kharif 2014 [70]. On 5×5 km analysis of total fire recognitions, total fire strength, frequency of incidences of fire during 2004–2014, MODIS active fire proposed that central and southern districts of Punjab are involved in severe burning activities. However, using the same fire datasets to evaluate fire attributes such as frequency of fire, intensity and seasonality of different fires during 2002–2010, [71] found highest number of fire-incidents was observed in 2009 and near about 63,696 incineration incidents happened per year during 2002–2010.

In an another study, the results based on the analysis of incineration incidents noticed by Along-Track Scanning Radiometer(ATSR) sensors from 1998 to 2009 in various parts of India revealed that out of total incineration incidents identified, 25–45% were from Maharashtra and Madhya Pradesh [72]. Images published by NASA in 2015, showcased large-scale smoke evolving from the fields of Punjab due to straw incineration that alarmed environmentalists with the National Green Tribunal issuing legal notice to the state government [7,23,73,103]. A regularly monitored stubble burning area using satellite images could help controlling serious environmental problems.

Table 2 presents an estimation of the paddy cultivation area which is about 4.05 mha with production of paddy crop and paddy residues as 15.37 mt and 18.45 mt in both the states of NW India. The glitch of agro remains burning after harvesting is more in combined harvested paddy field excluding the residue generated from basmati variety of paddy crop. The residue of basmati variety is not burnt in in-situ field and is widely used as good quality animal fodder. Basmati variety of paddy crop draws an elevated price; therefore, it is harvested manually to elude cost of grains accompanying with combine harvesting [6]. By subtracting the area under basmati variety and zero tillage practices presently, the left over area is determined as 66.8% and 24.3% of the total paddy area in Punjab and Haryana state respectively which is in-situ burnt in field (Table 3). The percentage of paddy residue burning area is less in Haryana state, from the total paddy area. This is because the zone under basmati variety of rice is higher (815 thousand ha) and combine harvested area under paddy crop is less (75%) in Haryana compared to 30,000 ha basmati area and 90% combine harvested area of the Punjab state.

3.5. Reasons for burning of paddy residues in-situ

3.5.1. Scarcity of labour for manual harvesting

There has been a progressive shift from manual and animal power to electrical and mechanical because manual labour and animal power were not sufficient to cope with the work load of intensive agriculture. The contribution of agricultural workers to the total workers has been reduced from 62.67% to 35.96% from 1970 to 71–2012-13 in Punjab state [48]. The mechanization has tremendously increased due to the shortage of labour, increasing wage rates during harvesting season, failing number of livestock [74–77]. In Punjab state, the human power has substantially reduced from 7.5% to 0.69% due to increase in mechanical power from 17% to 76% and electrical power from 1.7 to 23.5 from 1960 to 61–2012-13 [43]. In case of manual harvesting, most of the residue is removed from the fields and utilized as feed for livestock, fuel and thatching [27]. Even today basmati variety of crop is primarily harvested manually for a number of reasons, including reduced grain breakage, being more prone to lodging (reducing the effectiveness of mechanical harvesting) and more limited field size [78].

Table 3
Estimation of paddy residue burnt area in north-west states of India (2014-15).

	Punjab	Haryana	Total
Total Paddy area, 000 ha	2845.0	1206.0	4051.0
Total Wheat area, 000 ha	3512	2499.0	6011.0
Paddy-Wheat rotation area, 000 ha	2680.9	1113.9	3794.8
Area under Basmati rice variety, 000 ha	30.0	815.0	845.0
Paddy area excluding basmati rice variety, mt	2815	391.0	3206.0
Area harvested by combine harvester, 000 ha	2533.5	351.9	2885.4
Area under zero tillage, 000 ha	633.38	0.50	633.8
Paddy residue burning area, 000 ha	1900.13	351.40	2251.5
Production of Paddy, mt	11.10	4.0	15.37
Production of Paddy residue, mt	13.32	4.8	18.45
Amount of paddy residue burnt, mt	8.75	1.29	14.42
Percent burnt area, %	66.79	29.14	55.58

*Authors calculations based on the data available from [35–38].

3.5.2. Use of combine harvester with the growth of farm mechanization

Farm Mechanization has made significant contributions in enhancing agricultural productivity and cropping intensity of the region. The farm power availability has been increased from 0.37 to 5.68 kW ha^{-1} which led to increase in cropping intensity of Punjab state from 112% to 196% and total food grain productivity from 668 to 3638 kg ha^{-1} from 1960 to 61–2012–13 [48]. Mechanical power is the most common source of power and is readily available in the mode of tractors and engines. The reason for popularity of power operated machines is availability of more horse power, higher speed resulting in more field capacity, and timeliness of various farm operations. Timely harvest is of utmost importance, because an delayed harvest of crops proceeds to a substantial shortfall of grains as well as straw leading to over ripeness causing damage and grains by shattering and also hampers the seed bed preparation and sowing operations for the next wheat crop. Traditional method of harvesting paddy requires about 150–200 man-h ha^{-1}. The constraints overcome through the introduction of combine harvesters. It provide solutions for scarcity of labour during peak harvesting season and also assist in achieving target in time, minimizing drudgery, reducing crop losses and improving the quality of paddy. The Combine Harvester is a machine exclusively to harvest and recover grain from standing crop. The combine harvester cuts the crop, feeds the crop to the cylinder, threshes the grain from ear head, separates the grain from straw, cleans the grain and handles the clean grain unit in one operation. The number of combine harvester in the country increased dramatically approximately from 5000 in 1990–91 to 13,800 in 2012–13 [48,79]. On contrary, combine harvester tend to leave a huge mass of residue (up to 9.0 t ha^{-1}) remained in the field after harvest and farmers are not furnished and prepared to manage large mass of residues left in the field [43]. Thus, a farmer thinks of economical and easier to burn the residue in the field to enable early sowing.

3.5.3. Timeliness in operation and clearing of field

The time gap between paddy harvesting and planting of wheat in NW India is 7–10 and 15–20 days in basmati/scented and coarse grain rice, respectively [6]. The combine harvesters cut the paddy crop a certain height above the ground, thereby creating two distinct straw components after harvesting: (i) the standing stubble residues; and (ii) the windrows of loose crop residues, big uneven heaped lines of straw. This heavy straw load of up to 7.5 t ha^{-1} is available in the field. It is particularly the latter that are a nuisance for establishing the subsequent crop and in absence of technologies for paddy residue management; farmers prefer burning the paddy residues in the field [27,29]. Traditionally burning offers a quick approach to empty the field with remaining paddy biomass and facilitates further seed bed preparation for sowing of next successive crop, whereas incorporation or collection is perceived to be too costly [6,11,80].

3.5.4. Control of weeds/pests and short term availability of nutrients

Burning delivers a swift method to control weeds, insects, diseases and pests, both by eliminating them straight away and even modifies their habitat [6,27]. It is also remarked to improve soil productiveness of agricultural land, although incineration actually has a differential influence on soil health. Residual ash left behind burning behaves as a fertilizer and is a predominantly suitable source of potassium. It rises the short-term availability of specific nutrients (e.g. P and K) and lowers soil acidity, but leads to a loss of further nutrients (e.g. N, P and e.g. N, P and S) and organic carbon [81–83]. Burning effectively excludes pathogens on residues, although it has restricted utility for soil disinfection [27,84–87].

3.5.5. Miscellaneous reasons of residue burning

Some farmers have felt the poor storage facilities for straw and lack of market utilities of residue forces them to burn the stubble in the grounds to get rid of it [74–77]. Few farmers have also realized that the burning in-situ includes reduced tractor fuel cost on left over stubble incorporation by roto-till-drill [88].

3.6. Consequences of crop residue burning

The incineration of crop residue have become an essential source of atmospheric pollution in the NW India during paddy harvesting seasons [33,89–91]. The practice has an adverse impact on health of population and even affects the regional climate and crop output (Fig. 5). Burning of paddy residues leads to the following conditions;

3.6.1. Depletion of air quality owing to aerosols and trace gas emission

Several studies have been conducted to achieve stats behind depletion of air quality due to aerosols and trace gas emissions [92–96]. These gases and aerosols consists of carbonaceous matter which have vital part to play in the global climate change and may lead to a regional increase in the levels of aerosols, acid deposition, increase in tropospheric ozone and depletion of the stratospheric ozone layer. Black carbon emissions are the second largest contributors to current global warming, after carbon dioxide emissions [97,98]. Incinerating fields is a process of uncontrolled combustion through out which carbon dioxide (CO_2), the principal outcome of the combustion, is emitted into the atmosphere along with carbon monoxide (CO), unburnt-carbon (as well as traces of methane i.e. CH_4), nitrogen oxides (NO_x) and comparatively less amount of sulphur dioxide (SO_2). The burning of one tonne of paddy straw liberates 3 kg particulate matter, 60 kg carbon monooxide, 1460 kg carbon dioxide, 199 kg ash and 2 kg of sulphur dioxide. It also emits huge quantity of particulates that are comprised of varied variety of organic and inorganic species. About 70%, 7% and 0.66% of C present in paddy straw is released as CO_2, CO and CH_4, respectively, though 2.09% of N in straw is emitted as N_2O upon incineration [93,99]. The annual contribution of 0.10 Tg of SO_2, 0.96 Tg of NO_x, 379 Tg of CO_2, 23 Tg of CO and 0.68 Tg of CH_4 was estimated from burning of crop residues. The estimated value of PM2.5 mass concentration varies from 60 to 390 mg m^{-3} during paddy residue burning with principal contribution from organic carbon (OC:33%), though contribution from EC centers at 4% in Patiala district of Punjab state [10].

During harvesting, about 50% of OC is obtained from water soluble organic carbon (WSOC) [30,43,100]. A substantial increase in the quantity of PM10 and PM2.5 was observed at Mandi-Govindgarh (an industrial town of Punjab) because of three reasons viz. (i) threshing process leading to entrainment of rice husk particles in air, (ii) the shattering process which leads to entrainment of dry shell of wheat seed and (iii) stubble burning [88]. During post-harvesting season, the values of PM10 and PM2.5 showed a declining trend because of the reduced quantum of stubble burning and dispersion of pollutants. The ratio of the average BC concentration contrasted to the PM2.5 concentrations revealed that BC contains about 11.9% of the fine particulate

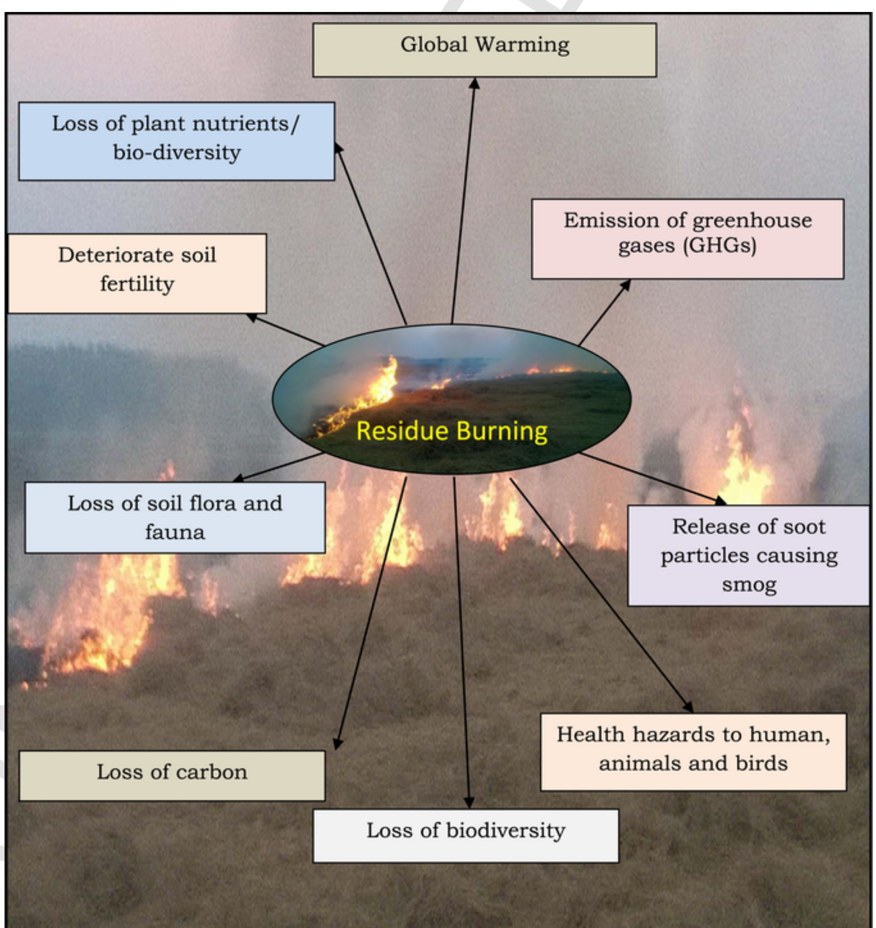

Fig. 5. Consequences of crop residue burning.

matter collected at all sites on field burning experiment and about 14.7% for simulation in the chamber [5].

3.6.2. Liberation of soot particles and causing smog in the environment

Due to residue burning, generated particulate matter (PM2.5), being extremely light weight, can stay in the air for a long time, causes smog and travel hundreds of miles along with wind [29,55]. All emissions from burning residues are fugitive and smoke outflows through unplanned exit routes in the downwind direction. Particulates in the air are categorized into aerodynamic diameter size and chemical composition. Particulate matter (PM) is mostly quantified in terms of the mass concentration of particles within definite size classes: PM10 or coarse (with an aerodynamic diameter of less than 10 μm) and PM2.5 or fine (with an aerodynamic diameter of $<$ 2.5 μm). PM2.5 has greater stability timing in air when contrasted to PM10 because of the balance between the downward force of gravity and aerodynamic drag force [105].

Smog, the expression is derived from the terminologies smoke and fog [55]. In case of temperature inversion, the pollutants are trapped at ground level, where it causes most harm. Cold air becomes imprisoned beneath the layer of warm air that acts as a lid and the contaminants in the cooler layers cannot be dispersed while the pollutants stay concentrated at ground level. This causes poor visibility and increases traumatic road accidents/ other mishaps [30,55]. At locations of dense smoke, journey takes approximately 20% more time, impacting on time as well as fuel costs [106,107].

3.6.3. Health hazards to human, animal and birds

The incineration of crop residues contributes to emissions of harmful air pollutants, which can cause severe impacts on human health *viz;* aggravated chronic heart diseases and lung ailments, besides causing respiratory problems such as asthma, coughing; particularly affecting children, geriatrics and pregnant women [43,87,91,101,107–109]. Various studies have also ascribed greater threats for leukemia, blood bone marrow disease, vertigo, drowsiness, headache, nausea, aplastic anemia, and pancytopenia and myelodysplastic syndrome cytopenia to benzene exposure [110,111]. Mitigating the paddy residue burning could drop the annual average concentration of benzene and ensure agreement with the National Ambient Air Quality Standards. Calculations of extreme lifetime cancer threat due to benzene amounts to 25 and 10 per million inhabitants for children and adults, correspondingly, beyond the United States Environmental Protection Agency (USEPA) threshold of 1 per million inhabitants [111]. It also reduces the Red Blood Cell (RBC) count in humans and adversely affects the oxygen carrying capacity in the body. A socioeconomic study [30] revealed that the affected members of Punjab State underwent at least half a month from such problems and had to pay Rs. 300–500 per household on medicine as documented in the year 2008-09. In addition, there were few instances where a family member had to be hospitalized for 3–4 days and supplementary compensation was incurred. Total health cost losses was far higher if expenses on averting events, productivity loss due to illness, monetary value of uneasiness and usefulness could be calculated and the economic cost of motor vehicle accidents caused by low visibility and blocking or slowing down traffic especially on countryside roads. Total annual welfare loss in values of health damages due to air pollution triggered by the incineration of paddy residue in Punjab state sums to Rs. 76 millions [30].

Inhaling fine particulate matter (FPM) adversely affected animal health too. It caused corneal irritation and temporary blindness and chronic bronchitis leading to asthma like conditions. Severe exposure led to potential decrease in milk yield, and sometimes death of animal due to conversion of normal Hb to deadly Hb because of high level of CO_2 and CO in the blood [112]. Farmer's friends' pests and micro-organisms like bacteria, earthworm *etc* dies due to fire. Reptiles like snakes, frogs, earthworms, lizards die in the holes. Leaves of trees burn and greenery all around are lost. Nests of birds are also shattered due to this practice. Sparrows, eagles, vultures are becoming extinct; one of the main cause of this is stubble burning [[30,38,88], 113].

3.6.4. Deterioration in soil health and fertility

Heat from burning of residues raises soil temperature leading death of bacterial and fungal populations. However, the death is temporary as the microbes regenerate after a few days. Repeatative burning in the field, however, permanently diminishes the microbial population (mesothermic flora). Burning immediately increases the exchangeable NH_4±N and bicarbonate extractable P content but there is no build up of nutrients in the profile [114,115]. Long-term burning reduces total N and C and potentially mineralized N in the 0–150 mm soil layer. The residue burning kills micro flora and fauna beneficial to soil and removes a large portion of the organic material, thereby depleting the organic matter in the fields [6,14,21,100]. It was estimated that burning of straw raised the soil temperature up to 33.8–42.2 °C at 10 mm depth [21]. About 23–73% of nitrogen is lost and the fungal and bacterial population are decreased immediately up to 25 mm depth of soil. The burning of straw raised the temperature of the soil in the top 75 mm to such a high degree that the carbon-nitrogen equilibrium in soil changes rapidly [30,100].

3.6.5. Loss of plant nutrients/ vegetation

Residue burning affects nutrient budget and resource loss and harm soil properties, thus calling for improvement in harvesting technologies and sustainable management of paddy-wheat system. Carbon, nitrogen and sulphur present in straw are entirely burnt and lost to the atmosphere burning. The retained crop residues enrich the soil, predominantly with organic carbon and nitrogen [104]. These nutrients then have to be replenished through organic or inorganic fertilizers, which come at a cost. In addition to complete amount of C, 80% of N, 25% of P, 50% of S and 20% of K existing in straw is lost due to burning [31,44]. One tonne of paddy residues contain 6.1 kg N, 0.8 kg P, and 11.4 kg K [11,116–118]. Burning of paddy straw causes a intact loss of about 79.38 kg ha^{-1} N, 183.71 kg ha^{-1} P and 108.86 kg ha^{-1} K [118]. In Punjab state alone, the burning of paddy straw residue causes loss of 3.85 mt of SOC, 59,000 t N, 20,000 t P and 34,000 t K [30,107,119]. A researcher [120] documented 26.1 mt of C, 0.35 mt of N is emitted per year due to burning of crop residues. Plants and trees standing on bunds, road sides and canal sides of 2–3 m height are adversely affected due to straw burning. Micro flora and fauna present in the soil are also destroyed due to burning which leads to loss of biodiversity [83,107].

3.7. Technologies available to manage paddy crop residues

3.7.1. Retention of residue on soil surface

Mulching with crop residues increases the least soil temperature in winter through reducing upward heat flux from soil and declines soil temperature during summer due to shading effect. The crop residues play a significant role in betterment of soil acidity by releasing bases such as hydroxyls during the decomposition of crop residues with higher C: N, and soil alkalinity through application of residues from lower C:N crops such as legumes, oilseeds and pulses [121]. The crop residues also help in carbon sequestration in the soil [27]. Crop residues, particularly from wheat and rice crops, have a wide C:N ratio of 70:1 to 100:1. About 30–40% of C supplemented through crop residues becomes decomposed in about 2 months [122]. As long as added C remains in the soil, it causes immobilization of applied N [44].

The benefits of retention of crop remains on soil surface are 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 next successive crops. Residues turns as pool of plant nutrients, prevention of nutrients leaching, increased cation exchange capacity (CEC), provision of amiable environment for biological N-fixation, increase in microbial biomass, enhanced enzymes activities such as dehydrogenase and alkaline phosphatase. Moreover, residue retention on soil surface helps in soil moisture conservation by reducing evaporation losses up to 45 mm and increasing water holding capacity by 5–10% during wheat growing season. Residue retention also decreases soil temperature due to shading effect of residues in summer season and in raises the least soil temperature due to decline in upward soil heat flux. It also increases infiltration, reduces formation of soil crust and runoff.

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 [76,82,101,123–126]. 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) has been developed [40,56,82,102,127–129]. 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 [40–42,118,129,130]. Happy seeder consists of a straw managing unit and a sowing unit in one composite machine (Fig. 6). The hinged flails mounted on the rotating shaft cuts the standing stubbles and loose straw coming in front of the furrow opener with simultaneous tyne cleaning (for proper seed placement) and places the residue in between the sowing tynes. This PTO operated machine functional with 50 hp tractors (Double clutch) and can cover 0.3–0.4 ha h^{-1}. Total energy use for crop establishment using the happy seeder technology, (1602 MJ ha^{-1}) was only upto 15% of that used for conventional sown wheat (10,415 MJ ha^{-1}). The key source of energy used with the happy seeder technology was sowing, which consumed about 97% of the total energy input for crop establishment (Table 4).

Fig. 6. Sowing of wheat seed by happy seeder in paddy residue retention.

Recent reports suggests the happy seeder technology has encroached area from 8, 100, 370 and 952 ha in 2006–07, 2007–08, 2008–09 and 2009–10 respectively [48,113]. In 2012–13, the number of happy seeder machines in India was 350 which have been increased to 600 in 2014–15. Considering the effective field capacity (EFC) of happy seeder machine, 0.3 ha h^{-1} and working period of 30 days in a season, a total of 37,298 machines are required for direct drilling of wheat in paddy harvested field. About 31,511 and 5788 happy seeder machines are required to cultivate 1.9 mha and 0.35 mha field in Punjab and Haryana respectively. Similarly, considering the cost of one machine $2083, the estimated total amount of $65.63 million and $12.05 million are required for NW India to cover the paddy residue burnt area by direct drilling of wheat in paddy residue mulched fields.

For uniform spreading of paddy straw after harvesting of paddy by combine harvester, a Straw Management System (SMS) had been developed by Punjab Agricultural University. Straw spreader is attached to the rear side of combine harvester just beneath the straw walkers and behind the chaffer sieves (Fig. 7). The loose residues falling from the harvester straw walker is spread behind the harvester by the spinning discs. Afterward in 2015–16, a new version of SMS known as super SMS was developed and evaluated jointly by PAU and CIMMYT, BISA. Super SMS is mounted at the rear of the self-propelled combine harvester having 4.27 m cutter bar and engine power of 110 hp. The straw coming out of the straw walkers of the combine harvester is fed to the unit from one side and is discharged from the outlet of the housing. The chopped material is blown off tangentially and deflected using a deflector for uniformly spreading the residues in the entire width of combine harvester [131].

Table 4
Saving in energy consumption and cost of operation in Happy Seeder Technology as compared to Conventional Practices.

Farm operation	Machine/ Technology used	Energy consumption,	Cost of operation,	Saving in Energy consumption over conventional, %	Saving in
		MJ ha^{-1}	Rs ha^{-1}		Cost over conventional, %
Happy Seeder Technology					
Residue management	Straw Spreading	49	0.0	93.53	100.00
Land preparation	None	0	0.0	100.00	100.00
Sowing	Happy Seeder	1551	2620	−110.27	−78.23
Irrigation	Submersible pump	0	0	100.00	100.00
Total		1600	2620	84.64	72.57
Conventional Practice					
Residue management	Stubble Shaver + Burning residues	758	1463	–	–
Land preparation	Harrowing (Twice) +	1264	2520	–	–
	Cultivator (Twice) +	1260	2385	–	–
	Planker	622	1626	–	–
Sowing	Seed cum fertilizer drill	738	1470	–	–
Irrigation	Submersible pump	5773	87	–	–
Total		10,415	9551	–	–

Fig. 7. A view of super straw management system attached behind the combine harvester and direct drilling of wheat seed by happy seeder.

3.7.2. In-situ incorporation

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 [21,30,132]. It increases hydraulic conductivity, cation exchange capacity (CEC), and reduces bulk density of soil by modifying soil structure and aggregate stability, surface crust formation, water evaporation from the top few inches of soil and prevents leaching of nutrients. It also increases the microbial biomass and enhances activities of enzymes such as dehydrogenase and alkaline phosphatase [133]. 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 [134]. On a long-term basis escalations 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 conducted studies to [122,135] reveal that soil treated with crop residues held 5–10 times more aerobic bacteria and 1.5–11 times more fungi than soil from which residues were either burnt or removed. 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 phosphorous (6 g of Nitrogen and 0.8 g of phosphorous 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 [136]. One of the study revealed a 10 years of continuous residue addition with no-till results in 25% higher SOC compared to conventional tillage (CT) [51]. In that same time frame, the SOC content was 17% greater with minimum tillage than CT.

On the contrary, due to immobilization of inorganic N and its adverse effect due to N deficiency, a significantly decline in wheat yield was reported by some researchers [21,43,96,123,137], but this trend could be off-set by additional N application [50]. Moreover, residue incorporation impacts denitrification rate, abundance of denitrifier, and N_2O emissions in soil [138].

3.7.3. Collection of residues for off farm uses

The residue generated from the paddy-wheat cropping system can be laid to many uses as discussed in Section 3.6., 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 (Fig. 8). 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 combine 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 8.5–11.0 l ha^{-1} [83,139]. Thus baler provides a solution for straw management in an environmental friendly way. The energy requirements vary widely from 0.6 to 1 kW h ton^{-1} and cost of operation is $ 88.13 per hectare.

3.8. Government policies on paddy residue management

India is a legislation rich country with reference to pollution. This issue has been debated comprehensively at numerous forums by scientists, engineers, environmentalists and the Governments officials are also conscious of the harmful consequences of the practice on human health, soil health, soil fertility as well as environment. Eleven major laws exist to control pollution in India and many forums for their implementation in various ways [86]. Under these laws, provisions were

Fig. 8. Straw bailer for bailing of paddy straw in combine harvested paddy field.

made to protect the environment from all categories of pollution associated to industrial and agricultural activities. However, to prevent the burning of straw, Government invoke Section 144 of the Civil Procedure Code (CPC) to ban the burning of paddy, but it is hardly implemented, and there is petite effort to sensitize farmers on the concern.

A National Policy for Management of Crop Residue (NPMCR) has also been formulated and disseminated to all the States for implementation and also to ensure prevention of crop residue burning by providing incentives on the purchase of modern machineries to minimize left over crop residue in the field proportion, multiple uses of crop residue and formulation of fodder pellets as briquettes for gasification. Some of the laws are in operation to regulate the pollution viz. (i) Air Prevention and Control of Pollution Act, 1981; (ii) The Environment Protection Act, 1986; (iii The Environment (Protection) Rules, 1986; (iv) The National Environment Tribunal Act, 1995; (v) The National Environment Appellate Authority Act, 1997. Haryana State Pollution Control Board (HSPCB) has also taken various measures to limit the amount of industrial pollution in the state but not much has been done to address agricultural pollution. As per the direction from National Green Tribunal, a suitable coercive and penal action should be taken by the state government, including launching of prosecution, if persistent residue burning by the defaulters [30,124]. On the direction of Hon'ble High Court of Punjab and Haryana regarding imposition of burning residue, the Government of Punjab Imposed mandatory of SMS attachment on all the existing and new production of combine harvester. During 2016–17, Haryana Government commenced action against 1406 violators, and recovered a fine of 20,522$ to the farmers who continue to disobey orders on burning paddy residues [140].

3.8.1. *Suggestions and recommendations for future strategies*

Following suggestions and recommendations are required to halt prevalent practices leading to pollution and wastage of potential resources.

i. Provision of incentives to farmers for not incinerates paddy residues in the open.
ii. Anticipation of assistance (seeds, fertilizers, pesticides, electricity, diesel etc.) provided to the farmers if they persist with the defaults.
iii. Maximum land cover facilitation using conservation agriculture (CA) practices. Enforcement of rice-wheat cropping system intensification through relaymoong-bean crop.
iv. Targeting crop residue to generate renewable energy for improvement of air, soil quality, mitigating climate change effects and global warming.
v. Establishment of energy plants encouraged to utilize the surplus crop residue for energy generation in a sustainable, environment friendly and cost effective way.
vi. Crop residues should be categorized as recycling/ amendments i.e. lime or gypsum. Their use in agriculture field should draw subsidy like any other mineral fertilizers or amendments.
vii. Endowment of higher subsidy rate to farmers who retain their residue in the field as crop residues are a supplement to chemical fertilizers.
viii. Free electricity should not be provided as the same policy has led to installation of high powered tube wells that are responsible for over drawing of water from deep inside the earth.
ix. *In-situ* management in the field, fast decomposition by chemical or biological means and straw mulching by mechanical means must be promoted.
x. The machines like use of double disc coulters, zero tillage and happy seeder would help in mulching the crop stubble.
xi. Paddy residue could be collected from the fields and may be used for formulating useful products viz. making compost, organic manure and bio-char to improve soil health, soil fertility and gasification as an alternate fuel for power generation.
xii. During harvesting of paddy crop, the crop stem may be cut from the root level itself. This practice would require a suitable reaper cum harvester that should be developed using indigenous techniques.
xiii. Use of high horse-power segment of tractor for deep cutting may be facilitated to small farmers on cooperative basis.
xiv. Intimating small farmers to understand the prominence of chaff making out of the paddy residues is of greater advantage.

4. Conclusions

In conclusion, residues are of great economic value as livestock feed, fuel and industrial raw material. Contrariwise, complications with managements of crop residues remain diverse in different regions and associated with the socio-economic needs. Legally inflicting forbidden incineration of crop residues is success restricted due to lack of proper education to farmers about its implications on soil, human and animal health. Even though the farmers are aware of the adverse effects of paddy straw burning at the farm level but they are constrained by the lack of economically viable and acceptable machineries and alternatives for disposal of paddy residues. 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. Availability of RCT machinery is the first limitation to manage the crop residues in-situ and other limitations are unavailability of residue based power plants, biochar units for ex-situ residue management. Government should promote and provide need based support alternative options to stop residue burning instead of strict law enforcements.

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