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REVIEW ARTICLE

Crop residue management solutions in the northwestern Indo-Gangetic plains: A review

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Abstract

In the northwestern Indo-Gangetic plains, the two major cereal crops, rice and wheat, are widely cultivated and these crops produce significant amounts of agricultural residue. Farmers often burn rice crop residues (RCRs) after mechanical harvesting due to low financial value, the lack of substitute applications and the narrow interval between paddy harvest and wheat sowing. Trends in the generation and burning of crop residues in Haryana and Punjab states are highlighted. This paper examines how RCRs burning affects soil health, human health and the environment. Burning crop residues causes declining soil organic matter and nutritional deficits in the soil. Post-harvest crop residues retain significant amounts of essential nutrients, highlighting an important role in nutrient replenishment and maintaining soil quality. The detailed literature reveals cost-effective *in-situ* residue management solutions, including mulching and incorporation techniques for wheat sowing. These solutions highlighted the benefits that enhance nutrient recycling, soil fertility, soil moisture conservation and crop yields. Happy Seeder, Smart Seeder, Super Seeder and the Super Straw Management system are technological interventions that enable residue management during wheat sowing. Timely sowing of wheat is intended to reduce cultivation costs and conserve natural resources by saving labour, fuel, water and fertilizer. Awareness, financial incentives and capacity building are the key points for large-scale adoption and making the rice-wheat cropping system sustainable in the northwestern Indo-Gangetic plains of India.

Keywords: crop residue; management solutions; residue burning; rice-wheat cropping system

Abbrevations: NW- northwestern; RCRs - rice crop residues; IGP- Indo-Gangetic plains; RW- rice-wheat; SOC- soil organic carbon; SOM- soil organic matter; PM- particulate matter; SMS- straw management system; HST- Happy Seeder Technology; SST- Super Seeder Technology; Mha- million hectares; Mt- million tonnes; t ha^{-1} - ton per hectare; Kg- kilogram; Tg- Teragram; Gg- Gigagram; kg ha^{-1}- kg per hectare; Kpa- kilopascal; SMRT - Smart Seeder Technology

Introduction

South Asia's burgeoning population, natural resource degradation and declining crop productivity are current issues and concerns regarding sustainable development and regional food security (1, 2). The continuous cultivation of the rice-wheat (R-W) cropping system has put its sustainability at risk, which is deeply related to the overuse of natural resources in South Asia. It has been estimated that the Indo-Gangetic Plains (IGP) account for about 85 % of South Asia's R-W cropping system and cover nearly 13.5 million hectares (Mha), which is a significant food crop production area for the Indian subcontinent (3, 4). In India, the R-W system produces nearly half of the food consumed in an area of 9.2 Mha, hence being essential to the country's food security (5, 6). For instance, the production of R-W crops increased considerably, from 46.85 million tonnes in 1963-64 to 248.28 million tonnes (Mt) in 2022-23 (7). Increasing food demand in India necessitates boosting cereal production in Haryana, Punjab and western Uttar Pradesh. These regions, collectively known as the "breadbasket" of the northwest (NW) IGPs, are becoming crucial for meeting the nation's cereal requirements (6).

In the NW IGPs, the conventional method of establishing rice is transplanting nursery plants in puddled soil, a technique of tillage during water ponding in the field (8). In contrast, the narrow time interval between rice harvesting and wheat planting enforces wheat establishment through seed drills or manual broadcasting after burning rice crop residues (RCRs) (9). Manually harvested scented rice varieties, the RCRs, are fed to animals as an alternative to wheat residue. Meanwhile, non-scented coarse rice and hybrid cultivars are mechanically harvested using harvesting combine machines, popularly known as combine harvesters. Due to the substantial silica concentrations, the RCRs of non-scented and hybrid rice cultivars are considered poor animal feed by farmers in Haryana and Punjab. Thus, farmers generally burn the RCRs over existing farmer fields to clear them for timely wheat planting because residues obstruct field preparation and planting implements. Haryana and Punjab collectively produce 28.10 Mt RCRs and more than 60 % burn yearly, causing severe soil, crops and local ecosystem hazards. Due to the prominent importance of animal feed, most wheat residues are removed using a straw reaper after mechanical harvesting.

It is essential to know that these current R-W cultivation practices in the NW IGPs for a long time may lead to soil structure degradation, inadequate aeration of the soil, development of a hard layer at a shallow soil depth that causes higher bulk density and decline in hydraulic conductivity (10-13). The hardpan inhibits the root growth of succeeding crops grown on upland (14). These practices may create serious sustainability issues such as stagnation in crop yield, declining water table, decreased total factor productivity in the system, loss of soil organic carbon (SOC), deficit micro-nutrients, extensive and frequent epidemics of insect-pests, inefficient usage of fertilizers and water (15-19). These traditional cultivation practices also reduce profit margins due to enhanced cultivation costs. The burning of RCRs emerged as a significant problem in the mechanically harvested R-W system practiced extensively in regions of Haryana and Punjab in NW India. Consequently, the depletion of soil nutrients in the region challenges farm profitability, sustainability, resilient production systems and nutritional security from future food requirement perspectives (20-22). Therefore, effective and efficient management of the RCRs is potentially a way forward in sustaining the ecological systems of local agriculture and maintaining the financial benefits of the farming community (23, 24).

In this modern farming era, conventional agricultural technologies are inefficient in preparing seedbeds for wheat planting under RCR scenarios. It had also been observed that the zero-tillage wheat sowing technology was adopted mainly in the areas where fine-grained rice varieties (Basmati) were extensively cultivated or in the partially burned (burning the loose straw) residue conditions. Partial burning was done to overcome the associated problems, such as RCRs buildup in front of the furrow openers, improper seed and fertilizer placement due to poor traction in the drive wheel mechanism and inconsistent depth of sowing because the drill is lifted repeatedly to remove residue clogs. To address these technological issues and make the R-W cropping system sustainable and profitable, we need to study the possible solutions for crop residue management to curb RCR burning. This review paper aims to investigate and synthesize existing research publications on the impact of RCRs, focusing on soil properties, crop yields and economic viability. Based on the findings, we can suggest suitable RCR management solutions to make the R-W cropping system sustainable and profitable.

The review paper focuses on synthesizing existing research findings on the status of the generation and burning of crop residues and their harmful effects, including changes in soil properties, emission of harmful gases and crop productivity, to provide an extensive understanding. The key objectives of this review study are to identify the technological solutions and advantages associated with the efficient management of agricultural crop residues in the R-W cropping system.

Present status of crop residue generation

Over time, researchers estimated the residue generation from different crops and five significant crop contributions are listed in Table 1. It is reported that 146.50, 110.60, 13.80, 110.80 and 50.00 Mt residues of rice, wheat, oil seeds, sugarcane and cotton crops generated annually in India. Rice and wheat crops generated 192.82 and 120.70 Mt residue in 2014, while higher, i.e. 225.49 and 145.45 Mt in 2018 (26, 27). As per more recent estimates, the residue generation for rice is 145.51 and 162.99 Mt and for wheat, it is 149.45 Mt and 132.85 in 2021 (28, 29). However, rice is cultivated on 44.36 Mha in three seasons, where a large area is cultivated during the Kharif season, i.e., 28.597 Mha. This season generates 142.76 Mt of residue, of which 35.99 Mt is surplus. Another vital cereal crop, wheat, is cultivated on 30.838 Mha during the Rabi season, contributing to 145.449 and 25.07 Mt residue generated and surplus, respectively. Consequently, sugarcane's contribution in generation and surplus residue is 119.169 and 41.559 Mt, respectively. The combined residue generation of 11 crops is 682.62 Mt, of which rice and wheat contribute a significant share of 33 % and 21 %, respectively. However, sugarcane and cotton crops share about a quarter of the total crop residue produced annually in India, contributing 17 % and 10 %, respectively (Fig. 1) (27).

Earlier, maize, cotton, pearl millet and sorghum were cultivated during the Kharif season. However, with the introduction of submersible tubewells, assured production and favoured government policies, these were replaced by rice in Haryana. It is a severe matter to remember that the rice cultivation area expanded significantly, increasing from 0.192 million hectares in 1966-67 to 1.53 million hectares in 2021-22, an eightfold increase. In the same duration, the wheat area expanded from 0.743 to 2.56 Mha in Haryana (31). The cultivation area under rice (Kharif) and wheat (Rabi) crops increased significantly from 0.23 to 3.15 Mha (13-fold increase) and from 1.44 to 3.53 Mha (a 2.5-fold increase), respectively, from 1960-61 to 2020-21 in Punjab. A significant decrease in the area of cotton, pearl millet and pulses during the kharif season

Table 1. Residue generation (Mt) from major crops in India (2005 to 2021)

Crops	(25)	(30)	(26)	(27)	(28)	(29)	Average
Rice	146.50	154.00	192.82	225.49	145.51	162.99	171.22
Wheat	110.60	131.10	120.70	145.45	149.45	132.85	131.69
oilseeds	13.80	12.70	17.28	17.09	15.12	-	15.20
Sugarcane	110.80	110.60	107.50	119.17	133.72	152.06	122.31
Cotton	50.00	75.90	90.86	66.58	13.38	-	59.34

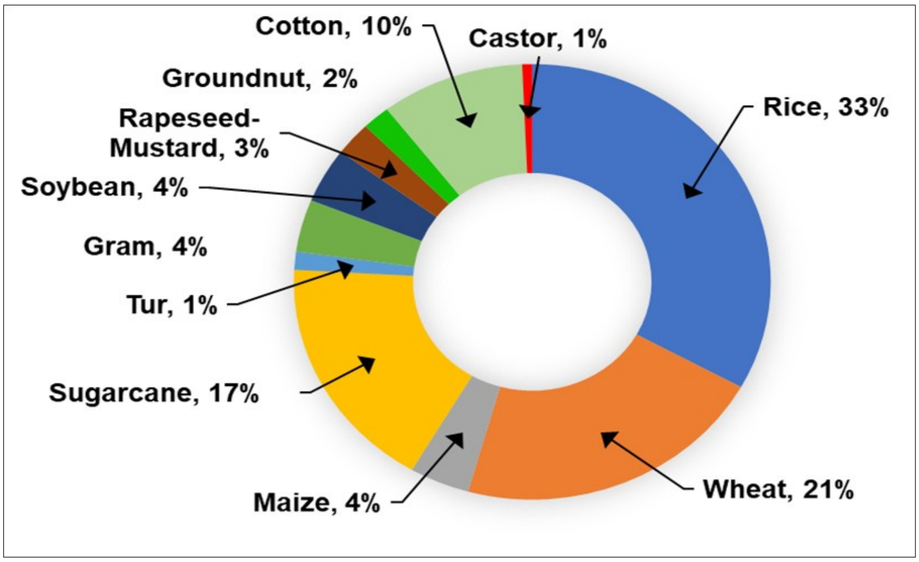

Fig. 1. Total annual dry biomass generated in India (27).

is the reason for the increase in rice cultivation in Punjab. The area under barley and oilseeds also decreased and was responsible for the rise in wheat area during the Rabi season (Fig. 2) (32). The dramatic rise in the area of paddy and wheat crops is directly linked to surplus residue and its burning in both the states of Haryana and Punjab. Currently, Haryana and Punjab generate about 7.0 Mt and 20 Mt residues from rice crops and jointly produce 28.1 Mt (33, 34).

Crop residue burning in Haryana and Punjab

Farmers in the N-W region of India have high-yielding animals, popularly Murrah buffalo. Wheat residue is extensively utilized in animal feeding and is not a primary concern for management. As stated earlier, RCRs (6-8 t ha^{-1}) are unsuitable for feeding animals and hinder field preparation and sowing for the subsequent crops (35). Therefore, farmers commonly opted to burn the RCR because they were concerned about the timely sowing of following winter crops such as wheat, field peas and potatoes (36). Earlier research calculated the amount of residue burned in 20 states of India, as shown in Table 2 (37). For RCRs burning, Punjab is in first position (10.39 Mt), followed by Haryana (3.75) and Uttar Pradesh (3.57 Mt). Meanwhile, Uttar Pradesh ranks first (13.59 Mt), Maharashtra (8.03 Mt) and Karnataka (4.11 Mt) for sugarcane trash burning in India. Rice, wheat and sugarcane crops contribute 41.52 Mt, 19.67 Mt, 35.27 Mt of residue burning in India. However, a total of 116.27 Mt, including 32.74, 33.63 and 30.09 Mt residues of rice, wheat and sugarcane crops, were burned annually in India (28). Approximately 1.24 Mt and 9.8 Mt RCRs are burned yearly in Haryana and Punjab, with 23 Mt in N-W India (33, 38). The emergence of the most recent problem of RCRs infield burning is a severe issue for the sustainability of the R-W cropping system.

Harmful effects of RCR burning

Deterioration in soil properties

Maintaining soil quality for prolonged sustainability in agricultural production is essential and it depends on various ecosystem elements such as chemical, physical and biological properties. The vital soil properties, chemical (pH, soil organic matter (SOM) and cation exchange capacity), physical (texture, water holding capacity and infiltration rate) and biological (N mineralization, soil respiration and bacterial diversity) that contribute to the healthy soil. These soil

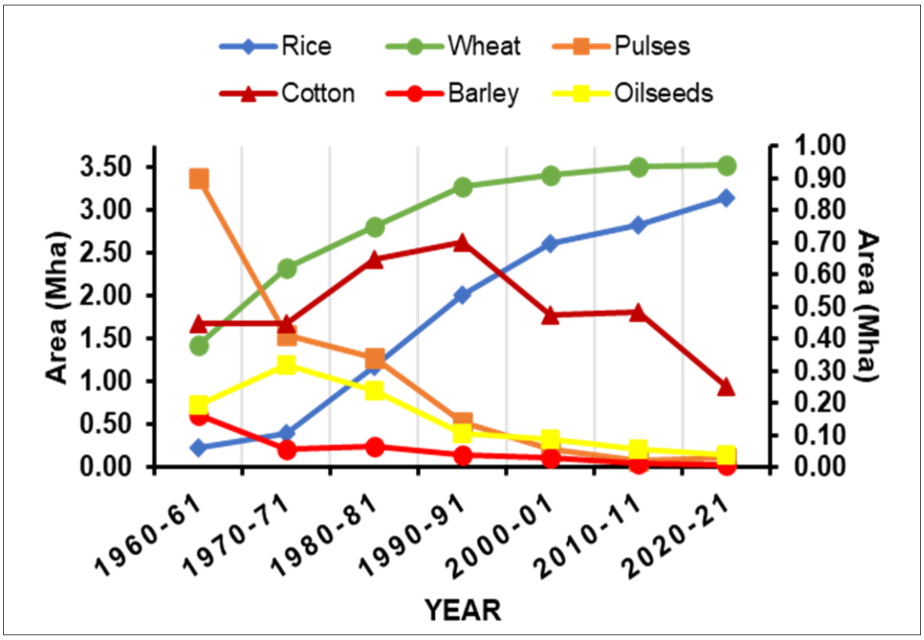

Fig. 2. Area under different crops in Punjab (32).

Table 2. Crop residue burning in major states of India (Mt Yr^{-1}) (37)

S. No.	State	Rice	Wheat	Sugarcane	Total for all Crops
1	Uttar Pradesh	3.57	7.20	13.59	24.36
2	Punjab	10.39	4.50	0.69	15.64
3	Maharashtra	0.86	0.15	8.03	9.27
4	Andhra Pradesh	3.38	0.00	1.29	4.89
5	West Bengal	4.30	0.12	0.19	4.61
6	Karnataka	2.14	0.03	4.11	6.35
7	Haryana	3.75	3.38	0.75	7.96
8	Madhya Pradesh	1.06	1.76	0.45	3.32
	India	41.52	19.67	35.27	97.62

properties help germinate seeds, develop roots, store and supply water and nutrients and grow crops. However, soil organic carbon (SOC) is a particularly significant marker for soil health, which regulates several characteristics of soil, like recycling nutrients, soil structure protection, pesticide and water conservation (39, 40). SOM is the crucial carbon source in the soil that regulates microbial activities and provides the chemicals needed for microorganism breakdown, critical to the soil's continued sustainability (41). The continuous decrease in SOM and multiple nutrient deficiencies are directly related to over-mining of soils and burning crop residues (42, 43). The status of nutrient mining is increasingly concerning in the critical and higher agricultural productivity region of the IGP of India, where extensively practised R-W is supplied with inadequate and imbalanced nutrient application strategies, contributing to stagnated crop productivity and vastly decreasing factor productivity (44).

The leftover crop residues after harvesting the crops are an essential nutritional resource as they retain substantial quantities of nitrogen (N) and phosphorus (P), potassium (K) and sulphur (S) by 25 %, 25 %, 75 % and 50 % respectively, absorbed by cereal crops during their growth period (45). It is important to know that RCRs generally contain a significant amount of primary and secondary nutrients, i.e. N, P, K, S, calcium (Ca), magnesium (Mg) and silica (Si) by 5-8 kg, 0.7-1.2 kg, 12-17 kg, 0.5-1 kg, 3-4 kg, 1-3 kg and 40-70 kg respectively on a dry weight basis per ton of straw (46). The burning one-ton RCRs results in the loss of about 5.5 kg of nitrogen, 2.3 kg of phosphorous, 25 kg of potassium, 1.2 kg of sulphur, 400 kg of organic carbon and 50-70 % of micronutrients (47). By considering the availability of residue from various agricultural plants, including rice, wheat and sugarcane, residue burning causes annual nutrient mining of about 0.45 million tons (Mt), 0.144 Mt and 0.84 Mt of NPK in India (26). In NW India, it has been estimated that burning of agricultural residue results in nutrient loss, equivalent to INR 2000 million annually (45). Consequently, the agricultural system requires an extra investment of almost $50.5 per hectare to replenish only three major plant nutrients caused by residue burning (48). The current agricultural scenarios of removal and burning of RCRs and nutrient application approaches can deplete soil nutrients. These practices may raise fertilizer costs for similar crop production in the short term. In the long-term, the productivity of the crops and quality of the soil could be reduced, thus affecting the cropping system sustainability. Therefore, by considering the detrimental impacts of RCR burning on soil quality and crop productivity, farmers should be made aware by showcasing the available RCR management technologies to curb residue burning and maintain soil quality.

Emission of harmful gases and human health concerns

Crop residue burning in agricultural fields releases air pollutants, including greenhouse gases, which can substantially affect atmospheric chemistry (49). Open infield burning of leftover RCRs is the primary source of releasing air pollutants comprised of carbonaceous materials that significantly contribute to global climate change, potentially elevating aerosol levels, acid deposition, increasing tropospheric ozone and depleting the stratospheric ozone layer (50, 51). RCR burning affects the environment due to inadequate smoke dispersion and dilution. Following the onset of the winter, the burning smoke cloud from RCR lingers near the earth's surface, exacerbating ambient air quality deterioration and impacting human health. The burning of agricultural residues can release substantial quantities of air pollution emissions like carbon dioxide (CO_2), nitrous oxides (N_2O), methane (CH_4) and air pollutants such as carbon monoxide (CO), ammonia (NH_3), nitrogen oxides (NO_x), sulphur dioxide (SO_2), volatile organic chemicals (VOCs) and coarse particulate matter ($PM_{2.5}$) and (PM_{10}) (52, 53). Using agricultural statistics data on total crop production, the burning of 116.3 Teragram (Tg) crop residues released about 176.1 Tg of CO_2, 313.9 Gigagram (Gg) of CH_4 and 8.14 Gg of N_2O in India. It was also estimated that the burning released 453 and 935.8 Gg of particulates $PM_{2.5}$ and PM_{10} during 2017-18. However, it was 190.7 and 393.8 Gg during 1980-81, which shows a 137 % increase in particulate emissions during the study period (28).

Burning open field residue has also resulted in several health-related issues for humans and animals. In India, premature mortality and morbidity have risen due to air pollution in the past decades (54). Black carbon is a constituent of fine particulate matter ($PM_{2.5}$) associated with respiratory and cardiovascular illnesses in humans (55). Elevated pollution emissions in Delhi, Haryana and Punjab have resulted in respiratory ailments, chest constriction, ocular irritation and xerophthalmia (56). Due to the sudden rise in particulate matter fractions resulting from RCR burning, school children are most susceptible to life-threatening diseases such as pulmonary function tests and severe lung infections (57, 58). It was observed that a three-fold higher risk of acute respiratory infections, which is the main reason for lost disability-adjusted life years during periods beginning from harvesting of rice to post-sowing of wheat in 2014 (59). Due to high levels of air pollution, Delhi (India) faced a public health emergency in 2016 as the coarse particulate matter ($PM_{2.5}$) was 25 times higher than the World Health Organization suggested target of 10 micro gm^{-3} (60). It has been commonly noticed that wind direction towards Delhi raises ecosystem contamination due to the burning of RCRs in Haryana and Punjab (61).

Benefits of RCR management

Soil chemical properties

Researchers conducted an extensive trial to investigate the impact of *in-situ* decomposition and N release dynamics on incorporated RCRs. They found that incorporating RCRs increased the accessible soil K concentration from 50 to 66 mg K kg^{-1} and RCR also added 175 kg K ha^{-1} annually in all straw-amended methods. The wheat yield was significantly higher when RCRs were incorporated than in the fields. A significant increase in SOC was also observed (12.20-17.62 %) (62). It has been found in a six-year-long experiment that higher crop productivity was mainly due to 29-30 % higher total organic carbon in conservation agricultural practices as compared to traditional field preparation-based sowing techniques along with keeping residue at the soil surface. It is necessary to consider that keeping residue treatment increased the availability of soil available N, P, K, S and Zinc by 10, 16, 12, 6 and 11 %, respectively. The results reveal that keeping residue techniques enhances the soil quality, mainly SOC level, which helps in soil health restoration, specifically SOC in the soil near crop root zone (0-0.2 m) (63).

On average, SOC increased by 31 % in zero-tillage sown wheat with surface retention of RCRs using Happy Seeder Technology (HST) in the upper 0-15 cm soil during a two-year experiment conducted at the regional investigation facility of the state agricultural university in Haryana. In particular, organic carbon increased by 23.8 % in zero tillage sown wheat, with all RCRs keeping compared to the traditional wheat sowing method. Zero tillage wheat sowing prevented the direct contact of microbes with the soil surface, which was the best way to limit C mineralization and SOC (64). In a two-year experiment, the primary, zero and conventional tillage practices were compared with and without RCR management. However, the SOC (g kg^{-1}) was statistically at par in three plots of primary and conventional tillage, i.e., 6.79, 6.58 and 6.45, but a significantly higher value of 7.40 in zero tillage fields with residue retention based on two two-year averages. On a two-year average, the SOC in zero-tillage by keeping residue field was 8.24, 11.08 and 12.83 % higher than in primary and conventional field preparation fields (65).

The HST sown wheat plots with residue mulching had significantly higher SOC (7.57-9.03 g kg^{-1}), available-P (20-32 kg ha^{-1}) and available-K (7 kg ha^{-1}) contents than the without residue plots sown with conventional and zero tillage techniques in the four-year experiment (66). Higher SOC was obtained in retaining RCR on the soil surface than without residue plots. The study results indicated that wheat sown using HST with RCRs mulching increased the SOC by 0.80 to 1.13 times compared to the plots without residue and conventionally tilled. The nitrogen availability was 214.42, 205.61, 193.95 and 134.47 kg ha^{-1} in the full residue retention, partial residue retention, no residue under zero-tillage and conventional tillage sowing, respectively. This enhancement was 60 % higher in residue retention against conventional till no residue conditions. Phosphorus and potassium were also approximately 100 % higher from 19.15-38.73 kg ha^{-1} and 153.31-302.76 kg ha^{-1} in residue retention against no residue plots (67). The comparatively slow rate of crop residue degradation in zero tillage techniques is expected to limit residue exposure to soil microbiota, which enhances the availability of the SOC and nitrogen. The benefits of RCRs retention in the soil's chemical properties are depicted in Table 3. In addition to the above, phenols were found abundantly in RCRs and decreased the phalaris minor germination due to their inhibitory effect (68, 69). Thus, *in-situ* retention of the RCRs strengthens the recycling of soil nutrients, which helps in soil health improvement by enhancing organic material amounts, decreasing fertilizer requirements (nitrogen and phosphorus) and reducing chemical input in the management of weeds (70-72).

Soil physical properties

The RCR mulching on the soil surface using residue management techniques prevents evaporation losses and conserves the soil moisture for longer. The residue management techniques resulted in higher soil moisture content, i.e., 17.93 and 20.37 %, in both years of the experiment. By surface mulching of the RCRs, higher soil moisture, i.e. 23.60 % and 16.94 %, was observed than in no-residue conventional tillage wheat sown plots in 2018-19 and 2019-20 at 75 days after sowing. Consequently, HST sown plots observed 13.44 % and 16.20 % higher soil moisture than in no-residue conventional tillage wheat sown plots at harvest in both the years of study (64). Low and equal soil bulk density was recorded in soils at 0-15 and 15-30 cm depth in HST and conventionally sown wheat with residue mulching conditions. Lower bulk density was attributed to reduced sub-soil compaction in HST sown wheat. Comparatively higher bulk densities of 1.56 and 1.53 Mg m^{-3} were observed in Super Seeder Technology (SST) with incorporated

Table 3. Benefits of RCR retention in the soil properties

SN	Key result points of the study	References
	Chemical properties related parameters	
SN	**Key result points of the study**	**References**
1.	Increase in SOC (12.20-17.62 %), soil K contents from 50 to 66 mg K kg^{-1} and wheat yield	(62)
2.	Not only higher 29-30 % but also higher N, P, K, S, Zn by 10, 16, 12, 6 and 11 %, respectively	(63)
3.	SOC in zero-tillage with residue retention plot was 8.24, 11.08 and 12.83 % higher than in primary and conventional till fields.	(65)
4.	Higher SOC (7.57-9.03 %), available-P (20-32 %) and available-K (7 %) in residue mulching than non-mulched treatments.	(66)
5.	RCR retention increases SOC by 105.45 %. Phosphorus and potassium were also approximately 100 % higher from 19.15-38.73 kg ha^{-1} and 153.31-302.76 kg ha^{-1}	(67)
6.	SOC increased by 31 % in HST sown wheat with surface mulching of RCR in the upper 0-15 cm soil	(64)
	Physical properties related parameters	
	Key result points of the study	
7.	Saturated hydraulic (k_s) for 0-7.5 and 7.5-15 cm depth was higher (1.82 and 1.36) in residue and lower in conventional tillage (1.12 and 0.78), respectively.	(83)
8.	Significantly higher water use efficiency of 1.45 kg m^{-3} (60 KPa), 1.95 kg m^{-3} (80 KPa) over 1.11 kg m^{-3} (critical growth stages) thus saving 30 % water.	(81)
9.	Average water productivity decreased from 12.31 to 10.98 kg ha^{-1} mm^{-1} and 13.90 to 10.91 kg ha^{-1} mm^{-1} in $I_{0.9}$ to $I_{1.2}$ irrigation regime.	(76)
10.	A higher infiltration rate of 36 cm hr^{-1} was recorded, significantly higher (36 %) in residue retention against 23 cm hr^{-1} in residue removed plots.	(74)
11.	Lower bulk density, higher infiltration rate and soil moisture content were observed in HST and deep-ploughed fields.	(73)
12.	Higher soil moisture conservation, i.e. 16.94-23.60 % in residue retention and 13.44-16.20 % at 75 DAS in RCR burning and removal plots.	(64)

and conventionally sown without residue conditions. Higher water infiltration rates and cumulative water infiltration were also observed in conventional deep ploughs, followed by HST sown wheat under residue mulching. The wheat plots sown with HST had more soil moisture at 0-15 cm depth than those without residue plots (73).

The mean initial infiltration rate of 36 cm hr^{-1} was significantly higher (36 %) in residue retention against 23 cm hr^{-1} in residue-removed plots (74). The RCRs retention improved soil water retention significantly compared to no mulch treatments. Stable aggregation, higher SOC and enhanced soil physical properties help in higher soil moisture in residue retention plots (75, 76). Higher initial infiltration rate may be attributed to increased surface-connected macropores due to increased earthworm activity (77). Substantial increase in soil infiltration rate was observed by adding residues in tilled or no-tilled fields (78). Irrigation scheduling has a significant contribution to improving water productivity in agriculture. During a multi-year investigation, the average water productivity decreased from 12.31 to 10.98 kg ha^{-1} mm^{-1} and 13.90 to 10.91 kg ha^{-1} mm^{-1} in $I_{0.9}$ to $I_{1.2}$ irrigation scheduling. The decline in water productivity is due to a comparatively small increase in crop yield for increased irrigation water use in the field (79). Conserving residue delayed irrigation scheduling due to less soil evaporation and saving irrigation. Therefore, in two years of a three-year experiment, the irrigation biomass water productivity was considerably increased in the first year, from 6.2 to 8.4 kg m^{-3} and 5.0 to 6.8 kg m^{-3} in the third year (80).

Precision irrigation scheduling by tensiometer at 60 KPa and 80 KPa had increased water use efficiency compared to scheduling based on critical growth phases in wheat. The data of a four-year investigation reveals that tensiometer-based scheduling saved 30 % water, leading to significantly higher water use efficiency of 1.45 kg m^{-3} (60 Kpa), 1.95 kg m^{-3} (80 Kpa) over 1.11 kg m^{-3} (critical growth stages) (81). Multilocation on-farm experiments have been conducted to assess different sowing techniques in different districts of Punjab. Overall, the mean bulk densities were higher in rotavator and farmer practice than in HST sown wheat locations at all three depths. The results indicated larger compaction in rotavator and farmer practice, subject to more farm operations than just one field pass in the wheat planting with HST. Similarly, root mass density values were increased in HST and current agricultural practice compared to rotavator-sown wheat (Table 4) (82). Repeated farm operations in conventional tillage without mulch affect the soil's physical parameters. Higher saturated hydraulic conductivity (k_s, cm hr^{-1}), i.e. 1.82 and 1.36, was recorded at 0-7.5 and 7.5-15 cm soil depth under residue retention conditions. However, it varied from 1.12 to 0.78 in conventional tillage no-residue practices. Comparatively, less organic carbon, compaction and more soil disturbance were the reasons for lower k_s values in no-mulch conventionally tilled plots (83). Hence, residue retention helps increase water infiltration, conserves soil moisture for extended periods and decreases irrigation water by 20 % and labour requirements (84, 85). Similar results were also reported i.e. 25-30 % irrigation water saving in HST sown wheat compared to the traditional sowing method (86).

Crop yield

In a two-year study, the data reveals that RCRs management promotes the growth parameters of the crop. The higher crop yield (8.12 %) was recorded in RCRs plots, i.e. 3804.21 kg ha^{-1}, compared to 3518.46 kg ha^{-1} without residue plots. The straw yield under RCR and control treatment was 5433.10 and 5228.63 kg ha^{-1}, respectively, which was 3.9 % higher (87). The RCR retention substantially elevated the wheat grain and straw productivity by 16.9 % and 6.3 %, respectively, compared with control treatments without residue retention (88). During the long-term study at the regional research institute in eastern India, the residue retention practices increased the productivity of wheat crops by 7-10 %, rice by 3-8 % and maize by 7-10 % under zero-tillage based crop sowing techniques (Table 5) (63). Furthermore, it was observed that wheat crop yield under residue mulched conditions sown with HST was significantly higher (10.42 %) than no residue conditions under zero tillage (66). However, mulching RCRs by these machines also controls the weeds due to mechanical impedance effects during sowing, reduces weeds and crop growth competitions and increases crop yields (59).

The wheat crop yield in RCRs retention plots with zero tillage HST sowing, no residue zero tillage and conventional tillage without residue plots were 56.8, 51.5, 52.9 and 43.6 q ha^{-1}, respectively. It was 30.27, 21.33 and 18.11 % higher in HST than conventional tillage without residue practices. Similarly, the straw yield was also 27.98, 21.19 and 15.84 % higher in HST than conventional tillage without residue practices. The higher yield in HST was attributed to relatively higher soil moisture available throughout the development phases of crop growth (67). Due to significantly higher ears m^{-2} 595 and 592 in residue retention and 589 in no residue plots and grains ear^{-1}, the crop productivity was significantly higher in fields by keeping residue, i.e., 12.90 and 12.60 t ha^{-1} in comparison to 5.61 t ha^{-1} in without residue. Precision irrigation scheduling by tensiometer at 60 KPa and 80 KPa had better water use efficiency than scheduling based on development phases in wheat (81).

Economic viability of residue management practice in R-W cropping system

The mulching of RCR during wheat sowing exhibits a higher wheat yield over no residue mulching (Table 5). The higher yield leads to ₹5746 ha^{-1} higher gross return and net returns, which is responsible for the higher benefit: cost ratio (B: C

Table 4. Impact of sowing practices on bulk density (g cm^{-3}) (82)

District	Rotavator			HST			Farmer practice		
	0-15	15-30	30-45	0-15	15-30	30-45	0-15	15-30	30-45
Jalandhar and Kapurthala	1.27	1.42	1.37	0.90	1.18	1.15	1.10	1.15	1.25
Fatehgarh Sahib	1.25	1.38	1.30	1.21	1.29	1.25	1.28	1.35	1.38
Patiala	1.57	1.50	1.61	1.29	1.42	1.30	1.39	1.42	1.45

Table 5. Effect of RCR retention on yield and economics of wheat cultivation

SN	Key result points of the study	Reference
	Effect of residue management on yield	
1.	Grain yield was significantly higher in residue retention plots, i.e. 12.90 and 12.60 t ha^{-1} in contrast to 5.61 t ha^{-1} without residue.	(81)
2.	Higher wheat yield by 7-10 %, rice by 3-8 % and maize by 7-10 %.	(63)
3.	Crop and straw yields were 8.12 % and 3.91 % higher in RCR incorporation than without residue plots.	(87)
4.	HST sown had a significantly higher (10.42 %) yield than no residue conditions under zero tillage.	(66)
5.	HST has a higher wheat yield, i.e., 30.27, 21.33 and 18.11 %, than traditional tillage operations without residue.	(67)
	Economic viability of residue retention	
	Key result points of the study	
6.	Lesser cost of cultivation (₹4825 ha^{-1}) ₹22013 ha^{-1} in HST compared to ₹26838 ha^{-1} in conventional wheat sowing.	(89)
7.	Higher returns in HST ₹35980 acre^{-1} compared to ₹29450 acre^{-1} in conventional wheat sowing practices	(91)
8.	₹5746 ha^{-1} higher gross return and net returns lead to the higher benefit-cost ratio (B: C ratio), i.e. 2.02 and 1.79 mulched over non-mulched plots.	(87)
9.	Higher net return by 23398, 19167 and ₹32314 ha^{-1} on average basis in zero tillage, HST and mulcher HST over conventional wheat sowing.	(67)
10.	Monetary benefits worth ₹5000 ha^{-1} can be gained through conserving RCRs in the field for wheat sowing.	(92)

ratio), i.e., 2.02 and 1.79 in mulched over non-mulched plots (87). The higher gross return by ₹21566, 18005 and 30433 ha^{-1} was observed over conventional wheat sowing as zero tillage, partial residue mulching and full residue mulching practices. Similarly, the net returns were also higher by ₹23398, 19167 and 32314 ha^{-1} on a two-year average basis. Due to the monetary benefits gained in zero tillage and HST, the average benefit: cost ratio was in the order of 2.99, 3.83, 3.64 and 4.11, respectively in conventional, zero tillage, partial residue mulching and full residue mulching plots (67). Due to less irrigation number and lesser labour cost, the cultivating expense was less (₹4825 ha^{-1}) in HST, i.e. ₹22013 ha^{-1} over ₹26838 ha^{-1} in conventional wheat sowing. Higher gross and net return in HST exhibit a higher B: C ratio of 4.5 compared to 3.6 in traditional practices (89). In a three-year study, savings of ₹4583 ha^{-1} and higher yield, resulting in a higher three-year average B: C ratio of 3.87 in residue management plots as compared to 2.89 in the traditional wheat sowing method (90). Higher returns were observed in HST ₹35980 acre^{-1} compared to ₹29450 acre^{-1} in conventional wheat sowing practices (91). Conservation of the RCRs in the field can save ₹5000 ha^{-1} during wheat sowing (92).

In a detailed comparative study, the comparative economic performance was evaluated of the latest wheat sowing interventions such as conventional tillage, zero tillage, HST and Super Seeder Technology (SST). In the former case, the investigation was carried out in two districts, Kaithal and Karnal districts and the pooled results are as follows. The variable cultivation cost in traditional farming practices (₹36650 ha^{-1}) was more than HST and zero tillage (₹31363 and ₹28567 ha^{-1}), respectively. Because of the lower cultivation expenses with almost similar yield, the net return in zero tillage and HST (₹73657 and 81800 ha^{-1}) was higher than in conventional sowing techniques (₹70866 ha^{-1}) of wheat. However, the conventional sowing technique was compared to the SST sowing technique in wheat in the latter case and pooled results are given in Table 6. The variable cultivation cost in SST was observed to be ₹6233 ha^{-1} less, i.e., ₹34988 ha^{-1}, than ₹41221 ha^{-1} in traditional seeding techniques. Reduced cost of cultivation leads to higher net return by ₹10382 ha^{-1} in SST technology in contrast to ₹74959 ha^{-1} in traditional wheat seeding techniques in Haryana (93, 94). Cost-effective RCR management solutions for wheat sowing using *in-situ* techniques are displayed in Fig. 3.

Management solutions and perspectives to curb RCR burning

The farmers burn RCR after conventional combined harvesting followed by wheat sowing using the zero-tillage technique in parts of Haryana. Zero-tillage wheat sowing technology has some added benefits, such as reduced cultivation costs and timely sowing, which enhance the capacity of wheat in competing Phalaris minor*,* an important weed and potential yield benefits (95, 96). However, partial burning of RCRs is a prerequisite to adopting zero-tillage sowing in the areas where farmers grow coarse rice varieties and hybrids. Nevertheless, in conventional wheat sowing, the RCRs were completely burned using the shrub master, usually known as the stubble shaver, following combine harvesting. Continuous efforts by the researchers developed the Turbo HST and the recent Combo HST, which can sow wheat using zero-tillage and simultaneously mulching the RCR on the field surface (97, 98). The HST enables to plant wheat provided loose straw was uniformly spread, which was not a feature of conventional combine harvesters. For efficient and uniform distribution of loose straws, a straw management system (SMS) was developed and equipped for conventional combine harvesters and mandatory for the new combine harvesters (61). More recently developed, another machine is popularly known as Smart Seeder Technology (SMRT), which partly incorporates RCRs into soil and mulching of the remaining on the surface using strip-till technology, SST for full incorporation and surface seeding cum mulching technique (99, 71).

To shun residue burning in N-W India, the Indian government launched the important scheme in the year 2018 with primary emphasis on the encouragement of mechanization in agriculture for the conservation of RCRs in the regions of NW Indo-Gangetic plains with ₹11520 million financial provisions. The three primary components of the plan were Information, Education and Communication (IEC). Regional agricultural officers, universities and institutions are the major stakeholders in this project. The key objective of this initiative was to improve knowledge of the management of crop residues by motivating young brains and developing the

Table 6. Comparative economic analysis of wheat sowing techniques in Haryana

Author Details	(93)			(94)	
	Conventional	Zero- Tillage	HST	Conventional	SST
Variable cost	36650	31363	28567	41221	34988
Fixed cost	64295	63008	63116	67270	66616
Total cost (A+B)	100945	94371	91683	108490	101604
Production (qtl ha^{-1})	55	54	56	49	51
Grain return	95351	93744	97708	98414	102495
Straw return	12165	11276	12659	17765	17834
Gross Return	107516	105020	110367	116179	120329
Returns over variable cost	70866	73657	81800	74959	85341
Net returns	6571	10649	18684	7689	18724
B:C Ratio	**1.07**	**1.11**	**1.20**	**1.07**	**1.18**

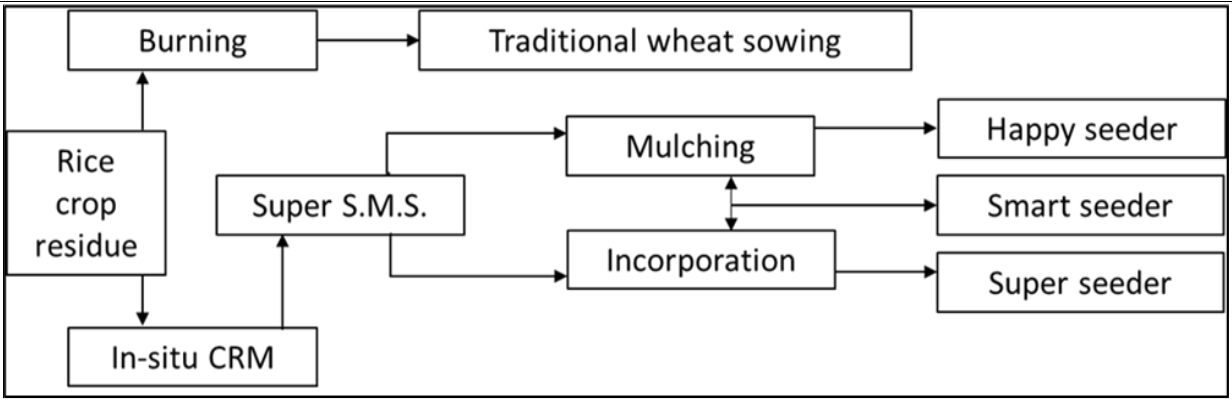

Fig. 3. Cost-effective rice crop residue management solutions for wheat sowing.

capacity of focused farmer groups (100). The responsibility of organizing capacity-building programs at the field level was given to Krishi Vigyan Kendra's for technical knowledge upgradation of new machinery among farmers. In 2018, national and international agencies' combined approach focused on harnessing agricultural residues' power through innovative technologies and reviving the green revolution raised funds to provide innovative residue management machinery in Haryana and Punjab (101).

Limitations

The recent wheat sowing machines are specially designed to work under residue management situations and require comparatively high horsepower tractors. Therefore, the farmers must have high-horsepower tractors, necessitating extra investment to replace other farm implements required for different farm operations. For the efficient operation of these machines, harvesting the paddy using an SMS fitted combine harvester is mandatory, but farmers report the unavailability issues of these combines. In HST sown wheat fields, loose residue had been retained as a surface layer. This surface layer may facilitate pest infestation due to the high moisture content of surface soil. Generally, we apply the first irrigation at the crown root initiation stage, which may occur 20-25 days after sowing in the conventional sown wheat. However, applying irrigation at the crown root initiation stage in HST sown wheat, where the soil may have higher soil moisture, can damage roots and enhance the chances of insect pest attack in the crop. Poor or low wheat germination issues in SST sown wheat have also been reported. This situation may arise due to comparatively less soil moisture content at the time of sowing or deeper placement of the seed. Thus, the new wheat sowing methods require separate practice packages for sowing, irrigation scheduling and controlling insects and pests under residue management conditions.

Conclusion

The rice-wheat cropping system in NW IGPs poses numerous issues, like deteriorating soil health, decreasing crop yields and higher cost of cultivation due to RCR burning. Farmers often burn RCRs after mechanical harvesting, which exhibits air pollution and leads to respiratory problems among the local population due to increased particulate matter during October and November. Effective residue management strategies are crucial to address these challenges, focusing on *in-situ* residue management solutions. The solutions include mulching and incorporation, which enhance nutrient recycling, soil organic matter, soil fertility and soil moisture conservation, collectively leading to better growth and crop yields. Mulching has been found to increase wheat crop yields significantly and reduce frequent irrigations, making it particularly beneficial in rainfed and limited canal water irrigated areas. Technological interventions such as the HST, SMRT, SST and SMS must be introduced to farmers to improve their understanding of the ability of these machines to manage residue and shift traditional practices. These revolutionary RCR management machines provide efficient ways to handle without burning. The HST, for instance, reduces the need for extensive field preparation and enables direct wheat drilling into RCRs, thus saving human labour, time, fuel, water and fertilizer applications. Demonstrated technologies achieve a higher benefit-cost ratio than conventional tillage, making it a financially viable option for farmers. This economic advantage is crucial for encouraging the widespread adoption of residue management techniques. However, the cost of purchasing these technologies can be a barrier for many farmers, requiring financial incentives and supportive policies for widespread adoption. In conclusion, while incorporating and mulching RCRs, large-scale awareness and capacity-building are essential to achieve widespread adoption and sustainable agricultural development. Promoting these residue management solutions will also contribute to the broader goals of environmental conservation and sustainability of the R-W cropping system in the NW IGPs of India.

Authors' contributions

GP and NK conceptualized and designed the study. GP, NK and VS collected the literature. GP and ARM reviewed and wrote the draft of manuscript. NK and AP reviewed and edited the manuscript. GP, ARM and ANY participated in the sequence alignment along with overall correction of the manuscript. All authors have read and approved the published version of the manuscript.

Compliance with ethical standards

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Ethical issues: None

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