

Soil and Environmental Improvement in Intensive Cereal-Based Cropping Systems through Crop Residue Management

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ABSTRACT

The management of crop residue is a major challenge in intensive cereal-based cropping systems where two or more cereals are grown in a single year. This is mainly due to low turn-around period and less preference as animal feed. On the other hand, burning of cereal straw is common in north-western parts of India causing nutrient losses, and serious air quality problems affecting human health and safety. Conservation agriculture involving zero- or minimum-tillage and innovations in crop residue management to avoid straw burning could assist in achieving sustainable productivity and allow farmers to reduce nutrient and water inputs, and reduce risk due to climate change. Mulch is a good option for cereal residue management during the wheat crop, especially with no tillage. Mulch can increase yield, water use efficiency, and profitability, while decreasing weed pressure. Surplus residue from the previous crop can be incorporated into the fields of next crop with no adverse effect on yield. Crop residues can also be managed to maximize different input use efficiencies. Long-term studies of the residue recycling have indicated improvements in physical, chemical and biological health of soil. Since crop residues contain significant quantities of plant nutrients, their continuous application will have positive effect on fertilizer management in rice-wheat system. Other plausible option of crop residue management lies in utilizing a portion of surplus residue for producing biochar (and co-production of bioenergy) for using as soil amendment to improve soil health, increase nutrient use efficiency and minimize air pollution.

Key words : Cereal residue, Rice-wheat system, GHGs, Residue management.

Introduction

Crop residues, the by-product of crop production system, are most valuable natural resources in agriculture (Prasad *et al.*, 2020a). Residue generated along with economic plant part in cereal crops is

voluminous. Particularly cereals like rice and wheat produce huge quantities of crop residue. India has a gross agricultural residue potential of 696.38 million tonnes annually. Out of which, annual crop residue generation from cereal crops is

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roughly 364.27 million tonnes (Venkatramanan *et al.*, 2021). Crop residue generation is increasing globally due to the increase of cultivable area and cropping intensity (Cherubin *et al.*, 2018). Hence, effective management of cereal crop residues is the need of the hour, which is well-known and widely accepted practice under conservation agriculture also.

A large portion of the world's food is produced by cereal crops like wheat, maize, rice, and barley. Despite having the potential to enhance soil health, nutrient cycling, and sustainability, the management of agricultural residues after harvest is frequently disregarded. Crop residue burning is driven by factors like labour scarcity (Lohan *et al.*, 2018), short turn-around period, socio-economic constraints (Lopes *et al.*, 2020), ignorance of public health issues (Chawala and Sandhu, 2020) and low nutritive value of crop residues as animal feed. However, maintaining long-term productivity, minimizing negative effects on the environment, and boosting soil fertility all depend on proper management of cereal crop residues.

Crop residue availability in India

In south-east Asia the crop residue generation was the highest in India, followed by Bangladesh, Indonesia and Myanmar (Figure 1) as per the Reports of National Policy for Management of Crop Residues (NPMCR, 2014). Out of 500 MT total crop residues 92 MT were burnt in India during 2014 (NPMCR, 2014). Presently, 686 MT of gross crop residues are produced annually in India from 26 different crops including cereals (Singh *et al.*, 2020). Based on annual crop residue production, the states may be ranked in the order of Uttar Pradesh (60 MT) > Punjab (51 MT) > Maharashtra (46 MT). The percentage of dry surplus crop biomass generated in various states of India has been depicted in Figure 2 (Jain *et al.*, 2018). Nearly 500 MT of residue is recycled in various sectors like industrial, domestic and as livestock fodder. But, still a surplus of 178 MT is left without any single use (MoA and FW, 2019; Dutta *et al.*, 2022). Out of 178 MT, around 87 MT is burned and whereas, in Punjab alone 9 MT of paddy residue is incinerated (Datta *et al.*, 2020).

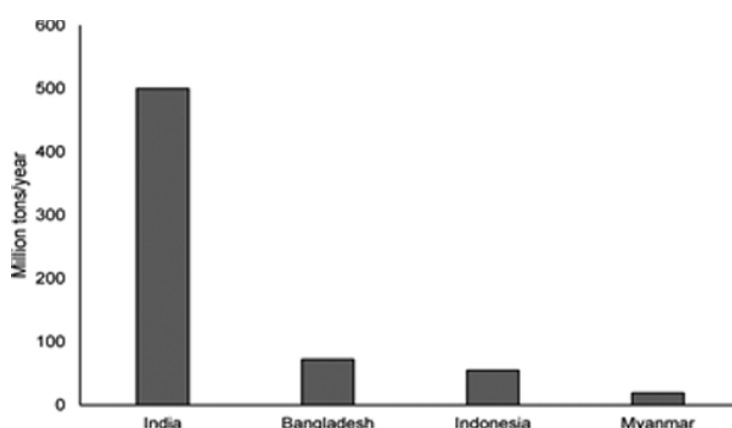


Figure 1. Crop residue generation in India compared to other select nations (source: modified from NPMCR, 2014)

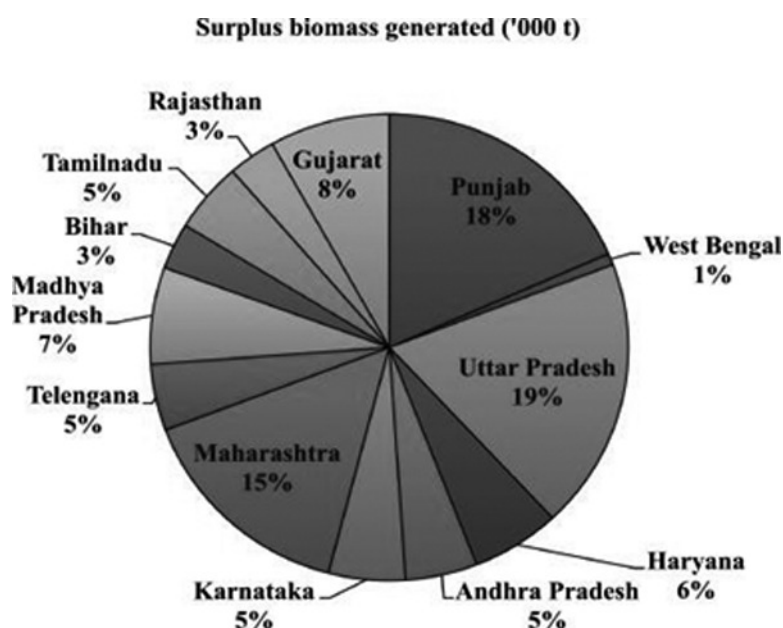


Figure 2 : Percentage of dry surplus crop residue generated in various states of India (Source : Adapted from Jain *et al.*, 2018)

Potential of cereal residues in India

In India annual residue generation from cereal crops is around 364.27 MT out of a gross agricultural crop residue potential of 696.38 MT (Venkatramanan *et al.*, 2021). A surplus of 178 MT is remained unutilized after recycling of about 500 MT in various sectors, including industrial, residential, and livestock feed (MoA and FW, 2019). Out of total unutilized residues, 87 MT are burned, whereas 9 MT of paddy residue are burned in Punjab alone (Datta *et al.*, 2020). The main cereal-based cropping systems in India include rice-wheat, rice-rice, pearl millet-wheat, soybean-wheat, maize-wheat, cotton-wheat and rice-maize. Over 10 million ha of the Indo-Gangetic plains (IGPs) are covered by rice-wheat, followed by rice-rice, pearl millet-wheat, soybean-wheat, maize-wheat, and rice-maize cropping

systems. Based on residue generation potential and surplus potential, crops may be ranked in the order of rice > wheat > maize > sorghum > pearl millet (Table 1). In India, the Indo-Gangetic plain region produces around one-third of the nation's total cereal production. Punjab and Haryana, two states in the IGP's north-west region, presently make up a highly productive rice-wheat zone that contributes around 69% of the nation's total foodgrain output (about 84% wheat and 54% rice) and is known as the 'food bowl of India' (Singh and Sidhu, 2014). By 2025, India's population is expected to reach 1.35 billion, which would require a 25% increase in agricultural production, particularly of wheat and rice. Under normal fertilization procedures, the continuous removal and burning of crop residues can result in net

nutrient losses, which will ultimately increase the cost of fertilizer input and decrease soil productivity. The long-term sustainability of various crops and cropping systems would increase with the

adoption of conservation agriculture involving crop residue management technique. This would also increase system productivity and overall resource-use efficiency

Table 1 : Residue generation potential and surplus potential of some cereal crops in India

Crop	Gross cereal residue potential (MT)	Surplus cereal potential (MT)
Rice	156.89	46.911
Wheat	149.05	48.27
Maize	43.22	12.83
Pearl millet	4.85	1.52
Sorghum	10.26	3.01

Source : Modified from Venkataramanan *et al.* (2021)

Burning of crop residues : A national problem

The highest incidence of residue burning is seen in the states of Uttar Pradesh, followed by Punjab and Haryana (Jain *et al.*, 2014). According to the recent reports this trend has been shifted as Indian Council of Agricultural Research (ICAR), satellite remote sensing detected 1,357 active stubble-burning events across Punjab (345), Haryana (22), Uttar Pradesh (128), Rajasthan (79), Madhya Pradesh (783) and Delhi (0) — accounting for 8 percent of the season's cumulative fires (<https://indianexpress.com/article/cities/chandigarh/stubble-burning-punjab-haryana-improve-up-rajasthan-worsen-9665797/>). The data collected in India showed that over 25% of the total crop residues were burnt on the farms, as depicted in Intergovernmental Panel on Climate Change (IPCC) national inventory

preparation guidelines (Jain *et al.*, 2014; Bhubaneswari, 2019). More than 90% of households in rural areas and 32% of households in urban India used biomass as the primary energy source for cooking and heating (Singh *et al.*, 2015), of which agricultural residue contributed about 16–20% to the total indoor solid biomass burning (Saud *et al.*, 2011). Burning crop residue in India, particularly in the Indo-Gangetic Plain (IGP) or 'Cereal basket of South Asia', led to poor air quality (Bikkina *et al.*, 2019) and negative health effects for the local population. Polycyclic aromatic hydrocarbons (PAHs) refers to a family of organic pollutants that are widely present and have hazardous effects on both ecological safety and human health. Such PAHs, produced by burning biomass, are another major source of emissions (Muir and Galarneau, 2021). Needless to say that, India rank second (after China) in

terms of global PAH emissions (Rajput *et al.*, 2014). Crop residue burning significantly increases the quantity of air pollutants such as CO₂, CO, NH₃, NO, SO₂, non-methane hydrocarbon (NMHC), volatile organic compounds (VOCs), semi volatile organic compounds (SVOCs) and PM (Zhang *et al.*, 2011). An estimate of emissions from open burning of rice straw

in India has been given in Table 2. It was predicted that cumulative CO, CO₂, N₂O, and NO_x emissions from rice and wheat straw burning are 0.11, 2.306, 0.002 and 0.084 MT, respectively (Hayashi *et al.*, 2014). In India, the overall carbon-di-oxide (CO₂) production from residue burning during 2000-2017 and its future estimate has been depicted in Figure 3.

Table 2 : Emissions from open burning of rice straw and other crop residues in India

Name of Pollutants	Rice straw		Other crop residues	
	EF* (g kg ⁻¹ dm)	India (Gg)	EF (g kg ⁻¹ dm)	India (Gg)
CO ₂	1,515	127,260	1,460	16,253
CH ₄	2.70	227	1.20	13
N ₂ O	0.07	5.88	0.071	1
CO	92.00	7728	34.70	386
NMHC	7.00	588	4.00	45
NO	3.38	588	3.10	35
SO ₂	0.40	34	2.00	22
Total particulate matter (TPM)	13.00	1092	13.00	145
Fine particulate matter (PM 2.5)	3.90	328	12.95	144

*EF= Emmission factor

Source : Adapted from Chaudhury *et al.* (2016)

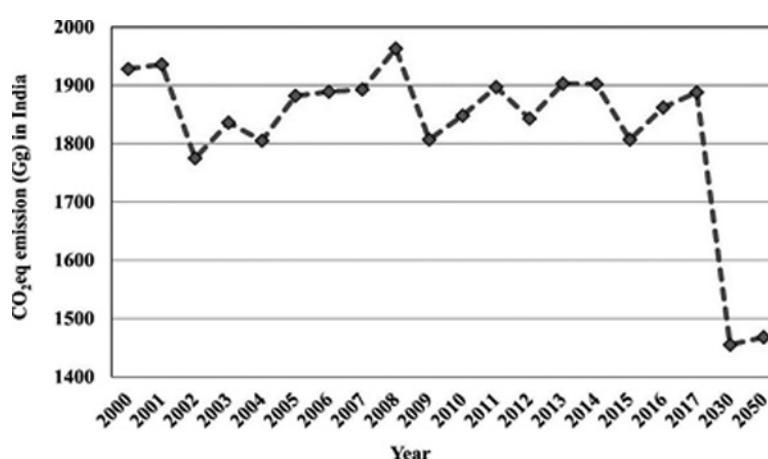


Figure 3 : Carbon-di-oxide (CO₂) production from residue burning during 2000 to 2017 and its future estimate in India (FAOSTAT, 2019).

On-farm crop residue management methods

Residue management in the farmer's field can be accomplished by residue retention or residue incorporation. Surface retention can be achieved through partial or complete residue burning, anchored stubbles following loose straw removal, or full straw retention. Similarly, Zero-till (ZT) seed drill, turbo seeder, happy seeder, special drill chopper and spreader, rotavator, and disc harrows can be used to perform residue incorporation in the soil (Table 3). On the other hand, after the crop

harvest residues are collected, stored and subsequently used for a variety of purposes including animal feed, power generation, ethanol production input, fuel for brick kilns and boilers, paper/board manufacture, packing material, and others. Due to its high lignin and silica content (8– 14%), rice straw has low nitrogen and phosphorus levels and causes delayed and incomplete ruminal digestion of CHO (Sarnklong *et al.*, 2010). Therefore, it is essential to select proper residue management strategies that must be beneficial to the environment, besides increasing farm productivity.

Table 3 : Machineries used for retaining crop residues on soil surface

Machinery	Description	Advantages	Limitations
Zero-till Drill	Passive type seeding machine with/without a fertilizer drilling mechanism; Usually fitted with inverted T-type furrow openers	Used for seeding the crops in an untilled field with/without anchored residue.	Clogging of furrow openers with loose residue; Poor traction of seed metering drive wheel due to the presence of loose straw; Non-uniform depth of seed placement due to frequent lifting of the implement under heavy residue conditions; Higher infestation of dicots weeds
Mulcher	Active type residue chopping machine, which cuts the residue into small pieces.	After mulching operation, chopped stubbles can be incorporated into soil using rotavator or disc harrow followed by crop sowing with zero-till drill	Requires additional field operation
Happy Seeder Straw Management	Active type seeding machine having flails at the front and seeding attachment at rear.	Used for seeding the crops in untilled field with anchored and loose residue.	Does not work efficiently under moist residue condition; Low operation window of the machine; Low field capacity compared with conventional seed drills
System (SMS)	Optional attachment, which can be integrated with a combine harvester; Chops the crop straw into small pieces and distributes it on the soil surface.	In SMS operated field, chopped residue can either be retained on the surface or mixed with soil easily. Chopping crop straw into small pieces reduces the clogging of blades / furrow openers of seeder or planter.	Not suitable for small land holding; Increased fuel consumption of about 2.5–3 l h ⁻¹ during combine operation

Machinery	Description	Advantages	Limitations
Rotary Disc Drill	Active type seeding machine having Soil Razor discs at the front and seeding attachment at rear.	Used for seeding the crops in untilld field with anchored and loose residue in rice-wheat and sugarcane- wheat cropping systems; Works on wet residue.	Seed covering issue under dry soil condition

Source : Adopted from Kumar *et al.* (2023)

Around the world, a variety of crop residue management strategies are being used in actual field settings. These strategies include conservation tillage with or without residue retention, soil moisture conservation methods, ZT and residue mulching, besides their use as animal feed and vermicomposting. In addition to that, crop residue management include biomass energy production (Porichha *et al.*, 2021),

biofuel generation (Prasad *et al.*, 2020b) and crop residue-based biorefinery. Current use and potential of crop residue in various *in-situ* and *ex-situ* application along with advantages and limitation has been listed in Table 4. However, due to its higher silica content, rice leaf reduces feed digestibility and become indigestible for animals (Singh *et al.*, 2020).

Table 4 : Current use and potential of crop residue in various *in-situ* and *ex-situ* applications

Crop residue management option	Suitability / priority of method	Advantages	Disadvantages	References
Surface retention	Residue of cereal	↓Soil erosion ↓Soil compaction ↓Input cost ↓Environmental pollution ↑Soil organic matter ↑Microbial population	↑Weeds ↑Rodent problem ↑Insect-pests ↓Herbicide efficacy	Venkatramanan <i>et al.</i> (2021); Kassam <i>et al.</i> (2022)
Composting residue	All crop	Faster composition with kitchen and other wastes	NA	Mandpe <i>et al.</i> (2020)
Biochar	Rice	Use of crop residue as feedstock in a sustainable way rather than burning; Multiple applications of biochar such as soil amendment and solid fuel	Need of drying and densification of crop residue prior to application	Venkatramanan <i>et al.</i> (2021)

Bioenergy (liquid and gaseous fuel)	All crop residue	Reduced coal burning in power plants; Utilization of crop residue as feed stock as per availability in local area; Reduced fossil fuel demand with lesser noxious impact on the environment	Need of pretreatment of crop residue	Datta <i>et al.</i> (2020)
Industrial application	Rice	Partial substitution of wood by residue in paper industry for reduced deforestation; Potential application in bioplastic and multifunctional carbon materials	Requires pretreatment of crop residue	Venkatramanan <i>et al.</i> (2021)
Value addition	Rice	Extraction of value- added components prior to use in gasification and thermal power plants, thereby enabling dual benefits	Low component yield, costly pretreatment process High	-

Source : Adopted from Kumar *et al.* (2023)

Crop residue management for improvement of resource use efficiency in rice – wheat cropping system

Rice–wheat cropping is considered as one of the major food security systems in South Asia, supplying food for 400 million people from an area of 13.5 M ha (Kumar *et al.*, 2018). The primary concern in the IGPs is the irrational use of natural resources like soil, water, and energy to maintain higher production together with massive residue burning (Choudhary *et al.*, 2018). A combine harvester is used to harvest almost two-thirds of the IGP's rice fields, which results in loose rice residue that limits future field preparation and sowing of succeeding crops. As a result, *in-situ* residue burning is the only option left with the farmers, as practiced widely

in northwest India. No doubt, it is inexpensive and hassle-free technique. Almost 25 MT of rice and wheat residues are being burned in the Haryana and Punjab states only. This residue burning results in approximately 31,250,000 million MJ of energy loss along with 37 MT of CO₂ emissions (Singh *et al.*, 2015). Residue burning contributes 0.05% to the total GHG emissions of India, which is detrimental for soil microorganisms and causing a huge loss in biomass, organic C, surface water, and soil temperature (Gadde *et al.*, 2009). Therefore, there is a serious need for adoption of well-managed residue management systems with good potential for resource use efficiency. Few promising benefits of crop residues management have been discussed below.

i) Improvement of soil resources

Both the soil carbon stocks and the labile pool of soil organic matter are improved by continuous incorporation of rice wastes into the soil. As exhaustive feeders, rice-wheat systems extract more soil nutrients than those supplied by fertilizer or recycling. This residue has a remarkable contribution to nutrient conservation, and checking the nutrient loss through either leaching or volatilization. Higher organic matter improves soil microbial colonization (Piccoli *et al.*, 2020). Better nutrient availability depends on microbial biomass and its activities in soil. Interestingly, it was found

that the microbial population is positively correlated with the phyto-biomass present in soil (Verhulst *et al.*, 2011). Microbial activities strongly reflect the soil nutrient storage capacity and nutrient recycling (Table 5). High organic matter also stabilizes the soil aggregation. Rice straw in soil reduces soil erosion and subsequent major nutrient removal. Residue retention positively influences the soil physical resources, such as porosity, bulk density, and aggregate formation. Singh *et al.* (2010) proved that continuous application of 16 t rice residue ha⁻¹ resulted in lowering bulk density from 1.20 to 0.98 g cm⁻³ in sandy loam soil (0-5 cm).

Table 5 : Effect of residue management on soil chemical properties under rice-wheat cropping system

Soil parameter	Unit	Rice		Wheat	
		CT*	ZT+R	CT	Z+R
pH	-	7.44	7.38	8.9	8.9
Total OC	g kg ⁻¹	1.90	2.29	0.52	0.56
Available N	kg ha ⁻¹	185.8	195.7	-	-
Available P	kg ha ⁻¹	29	30.6	10	11
Available K	kg ha ⁻¹	236.2	250.6	206	208

*CT = Conventional Tillage, ZT+R= Zero tillage with residue. Source: Modified from Korav *et al.* (2022)

i) Enhancement of water resources

Conserving water resources is the main difficulty in modern agriculture. After harvesting of *kharif* (wet) rice, retention of straw in the field efficiently conserves the residual soil moisture for subsequent crops, mainly in dry tracts (Chavan *et al.*, 2009). Utilizing rice straw as a mulch not

only helps to keep the soil moist but also controls weed growth, lowers soil temperature, and most importantly, increase the wheat yield. An estimate showed that 84% of the residues are wasted from rice-wheat systems (Singh and Panigrahy, 2011). Keeping rice straw in zero-till wheat in IGPs increases the

wheat yield, monetary return, and resource use efficiency (Erenstein and Laxmi, 2008; Ladha *et al.*, 2009). Retention of rice residues lowers the crop water use by 3–11% and increases the water use efficiency (WUE) by 25% as compared to no-mulch situation (Chakraborty *et al.*, 2010). In addition, rice straw increases wheat root length by 40% as a result of better soil moisture retention.

ii) Environmental improvement

In rice-wheat systems, rice residues burning, which is thought to be a practical approach to get rid of stubble, has become a major problem. For example, 50–60% of all post-harvest rice residues are burned in open fields in Punjab state only (Singh *et al.*, 2015) but recently there is a drop in residue burning in Punjab. Burning residue has terrible impacts on the soil and airborne environments, as well as on people's health and visibility. For greater C sequestration, soil C stock, and low global warming potential, machine-based residue integration with the aid of microbial spray or bailing of residue for animal feeding may be a viable choice. Alternatively, rice-wheat system residue may be utilized effectively as agricultural compost, livestock feed, surface mulching agents, biochar, and biofuel, as well as for *in-situ* integration. One hectare of rice straw can produce over three tons of nutrient-rich compost when used as farm yard manure (FYM). Compost that has been enriched with phosphorus using low-grade rock phosphate contains 1.5% N, 2.3% P₂O₅ and 2.5% K₂O (Sidhu and Beri, 2005). The growing of *Agaricus bisporus* (white button mushroom) and *Volvariella volvacea* (straw mushroom) has also shown

excellent utilization of rice and wheat straw. Crop residues are being used more frequently as biochar recently because it has the capacity to store carbon for a long time, preventing microbial degradation and reducing greenhouse gas emissions (Zhang *et al.*, 2012). As previously indicated, *in-situ* residue integration provides a number of benefits for soil physicochemical and biological characteristics as well as crop yield.

Therefore, it is important to properly and efficiently manage the residues produced by the dominant rice-wheat cropping systems in order to improve carbon sequestration and maintain sustainable production. Upgraded and modern technologies should be incorporated to maintain the distance from residue burning with the consideration of farmers' economic viability. Location- and soil-specific residue conservation practices would be a great researchable issue in future also.

Government Initiatives

Strict laws have been implemented in various times to lessen the pollution and protect our biodiversity (Vikaspedia, 2020). Some of them includes – The Environment (Protection) Act (1986), The National Environmental Tribunal Act (1995, Amendment 2010), The National Environment Appellate Authority Act (1997), The Environment (Siting for Industrial Projects) Rules (1999) and National Green Tribunal Act (2010).

One of the remarkable steps taken by Ministry of Agriculture and Farmers' Welfare (Govt. of India) with implementing National Policy for Management of Crop

Residue (NPMCR) in 2014 with the following major objectives:

- i) Develop and advocate sustainable management of crop residues through advancement in machinery or in multiple industrial sectors.
- ii) Creating awareness within farmers via capacity building and extension activities.
- iii) Provide financial support to the farming sector for feasible management of crop residue.
- iv) Developing and implementing suitable laws/acts/policies for managing crop residue.

The National Pollution Control Board (CPCB), New Delhi and the National Remote Sensing Agency, Hyderabad (NRSA) started pilot projects under NPMCR in collaboration with the respective states to justify the goals and actions such as the development of farm machinery, the modification of combine harvesters to collect straw with higher grain recovery, and the use of remote sensing to monitor crop residue management (NPMCR, 2014). But not much progress has been achieved except satellite-based monitoring of crop residue in the states of Punjab and Haryana (Datta *et al.*, 2020). Cabinet Committee for Economic Affairs on March 2018 approved Rs. 1152 crores for promoting farm mechanization to efficiently manage surplus residue and knock down pollution level in the NCR region, but still 17% and 50% of the rice straw have been converted into ashes in Haryana and Punjab respectively (MoA and FW, 2019; Datta *et al.*, 2020). Like, Govt. of India, each state government has

established a pollution control board and passed a number of legislations. The same is true for Haryana and Uttar Pradesh also. In Punjab, the Punjab Pollution Control Board (PPCB), Punjab State Council for Science and Technology (PSCST), State Department on Environment and Forestry, Punjab Energy Development Agency (PEDA), and Punjab Biodiversity Board have been established to handle various aspects of pollution and its control.

Constraints of crop residue management in rice – wheat cropping system

The rice-wheat cropping system is widely used in India, from the vast area of Punjab in the west to West Bengal in the east. However, in recent years, questions have been raised about the sustainability of this cropping system due to improper crop residue management (Busari *et al.*, 2015). According to the farmers' understanding, the traditional methods of growing rice and wheat require a lot of labor, water, fertilizer, and other inputs in addition to capital. Additionally, this resource-intensive system releases a lot of GHGs. Traditionally, rice fields are prepared by using several wet tillage operations, and then seedlings are transplanted into puddled soil. On the other hand, the preparation of wheat fields involves drilling or distributing seeds following deep ploughing the ground (Bhatt *et al.*, 2016). In this cropping system, preparing the seed bed causes the soil's organic carbon to be oxidized, and this is detrimental for the environment. In addition, the conventional tillage process is not suitable and environment-friendly, as it makes the soil a source rather than a sink of environmental pollutants (Busari

et al., 2015). It is estimated that around 10–14 Mg ha⁻¹ crop residues were produced from rice-wheat cropping systems in the IGP (Jagir *et al.*, 2015; Sarkar *et al.*, 2020). Before initiation of mechanized harvesting, all of the residues were taken away from the field for alternative uses. A large portion of residues was leftover in the field after the introduction of mechanized harvesting using combine harvesters. Removal of these crop residues is labor and capital intensive. Though both crop residue burning and removal are the primary cause of soil degradation in some developing countries, they have some positive impact on improving soil health status (Jagir *et al.*, 2015).

The major concern for the rice-wheat cropping systems is residue management. A limited amount of crop residues in rice-wheat cropping systems are used for domestic and industrial purposes. The burning of rice residues is one of the major problems that adversely affect soil as well as the environment (Bhatt *et al.*, 2016). Amongst rice and wheat residues, wheat straw is used in the dairy sector, but due to the high silica content, rice straw is not used as cattle feed in different regions across the country. In addition, boosting productivity is also a major concern of rice-wheat cropping systems in order to respond to the pressure of population growth in India. Incorporation of rice straw causes immobilization of nitrogen due to the wider C:N ratio of rice straw, and it decreases grain yield. Therefore, farmers usually burn rice residues in their fields to get rid of them, and thus assure timely sowing of wheat crops. Delayed sowing of wheat often decreases grain yield. Thus, to avoid the burning of rice residues,

numerous alternative strategies have been suggested by different experts, and one can choose the most efficient option depending on their socioeconomic and cultural status for the judicious application of rice residues (Singh and Sidhu, 2014).

Benefits of crop residue management

i) Source of plant nutrients

About 40% of N, 30–35% of P, 80–85% of K and 40–50% of S uptake by rice remains in the vegetative parts at maturity. Similar to this, 25–30% of N and P, 35–40% of S and 65–75% of K absorption are preserved in wheat residue (Maurya *et al.*, 2020). Recently, Kumar *et al.* (2023) has given a specific idea about the major nutrient content of rice, wheat and maize straw (Table 6). Crop residues, which are a carbon-rich biomass, contain potassium (14%–23%), phosphorus (0.45%–2%), nitrogen (0.6%–1%) and carbon (40–45%), all of which are essential for crop growth (Wang *et al.*, 2020). They help in balancing out nutrient imbalances in agricultural soil and making up of inorganic fertilizers' deficiencies. The release rate and content of nutrient are related to the properties of crop residues (C/N ratio and chemical composition), the climate (temperature and moisture), the soil conditions (pH and water content) and the method of applying crop residues into soil (Grzyb *et al.*, 2020). It is typically believed that a C/N ratio greater than 25:1 causes inorganic nitrogen to quickly immobilize, whereas a lower C/N ratio causes mineralization. The decomposition of agricultural wastes and nitrogen release may be facilitated by warm temperatures and adequate soil moisture.

Table 6 : Major nutrient content of rice, wheat and maize straw

Nutrient	Concentration of different nutrients (%)		
	Rice straw	Wheat straw	Maize straw
C	40–47	40–55	41–47
N	0.5–0.8	0.5–0.8	0.6–1.5
P ₂ O ₅	0.07–0.12	0.13–0.21	0.04–0.22
K ₂ O	1.16–1.66	0.93–3.90	0.1–1.5
S	0.05–0.1	0.04–0.6	0.01–0.22

Source : Modified from Kumar *et al.* (2023)

i) Improvement of soil structure

Specific surface area, pore volume and pore size distribution are the three main pore structure parameters (Chen *et al.*, 2017). Pore structures in residue vary depending on the types of crop. The internal structure of the rice straw is composed primarily of porous tissue with low specific surface area ($0.77 \text{ m}^2 \text{ g}^{-1}$) and pore volume ($0.0059 \text{ m}^3 \text{ g}^{-1}$), including a significant number of vascular bundle sheaths, medullary cavities, intercellular canals and other porous tissue (Xu *et al.*, 2016). The linear multi-cavity structure of wheat straw can act as a bridge between the pores, adding complexity to the connection of the porous network structure (Kuang *et al.*, 2021). The average pore size and cumulative pore volume of wheat straw are 13.90 nm and $0.01 \text{ cm}^3 \text{ g}^{-1}$ respectively (Zhang *et al.*, 2018). Nanometer-sized pores ($5\text{--}100 \text{ nm}$) are the main pores in corn stalks. The total pore area is $31.88 \text{ m}^2 \text{ g}^{-1}$ and the porosity is 73.33% (Li and Chen, 2014). Cotton stalks mainly consist of macrospores and have a very low specific surface area ($1.95 \text{ m}^2 \text{ g}^{-1}$)

and total pore volume ($0.0115 \text{ m}^3 \text{ g}^{-1}$) (Rizwan *et al.*, 2020).

ii) Improvement of pH and cation exchange capacity (CEC)

Crop residues, particularly in soils with low buffering capacity, may have significant effects on soil pH. Rotary tillage and straw coverage dramatically lowered soil pH from 7.7 to 7.4 and 7.2, respectively (Cao *et al.*, 2022). In another study, it was observed that the application of crop residues to soil increased the pH of topsoil ($0\text{--}10 \text{ cm}$) and sub-soils, and the effects can persist over 26 months (Butterly *et al.*, 2013). The changes in pH are related to the excess cation concentration, C and N cycles, types of crop residues and soil (Shen *et al.*, 2015). Crop residue management highly and significantly influences the cation exchange capacity (CEC) of soil. Accumulation of soil organic matter (SOM) in crop residues can produce more negative charges to increase CEC (Rezig *et al.*, 2013). In sweet sorghum cultivation, 30% crop residue retention (based on total harvested fresh biomass) produced 11.3% and 27.32% higher CEC

than that of 15% crop residue retention and crop residue removal, respectively (Malobane *et al.*, 2020).

iv) Increased microbial activity

Crop residue recycling can increase the content of organic matter in soil and provide good environment for the growth and proliferation of microorganisms (Table

7). It was found that compared with wheat straw return, lower fungal community diversity and higher fungal pathogenic risk were observed in soil with corn straw return. Lower relative abundance of bacteria and fungi, but higher relative abundance of actinomycetes was observed in double-season straw return (Su *et al.*, 2020).

Table 7 : Effect of crop residue management in rice-wheat system on soil microbial activities

Indicators	Crop residue management practices		
	Removed	Burned	Incorporated
Bacteria ($\times 10^6$)	14.5	2.6	28.36
Fungi ($\times 10^3$)	58	11	105

Source : Modified from Singh *et al.* (2019)

v) Improvement of soil productivity

Judicious crop residue management is very helpful for maintaining the soil productivity and recycling of soil nutrients (Rusinamhodzi *et al.*, 2016). Successful management of crop residue was not only beneficial for the improvement of soil productivity and nutritional status, but also helped to improve the overall health status of farm animals. Long-term application of crop residues along with conservation tillage was reported to boost the soil productivity, C-pool and earthworm population (Frazão *et al.*, 2019).

Conclusions and future directions

Around the world, a huge portion of populations depend heavily on agriculture. The population of the globe has been increasing at an alarming rate during the last two to three decades. The agricultural

system is under pressure to produce more food at this rising rate. Furthermore, less natural resources available due to their indiscriminate destruction. This emphasizes the need for the universal adoption and expansion of improved conservation technologies. Conservation technologies in agriculture are regarded as the most useful technology since they help preserve food production and resource conservation. Due to uneven depletion of numerous natural resources, modern intensive agriculture systems are particularly input-sensitive, and their shortage affects many regions of the world. Crop residue management enhances the physical, chemical, and biological state of the soil in addition to assisting in preventing nutrient loss from the soil surface.

In terms of their economic value, crop residue is sometimes viewed as waste

materials, although they actually provide soil with elemental carbon and a number of mechanisms for nutrient recycling. It provides food for soil microorganisms by supplementing additional soil organic matter. In addition, crop residues offer multiple ecosystem services to the environment when retained in the field after harvest. Crop residues as natural resources help to develop soil stability and maintain soil fertility. Good management practices with crop residues reduce soil erosion. Growing more food for an ever-increasing population brings the opportunity for fast residue generation. Crop residues provide ecosystem services that enhance soil health and supplement essential components for plants. Moreover, proper management practices can be useful for imparting the beneficial roles of these elements. In addition, the fuel crisis in developing countries who wish to maintain the pace of development must be addressed properly through the generation of renewable energy. Intensive use of fossil fuel produces huge GHG emissions and a series of associated environmental problems. Therefore, the alternate source of renewable energy derived from biomass in the form of crop residues will gain importance as a sustainable technique for energy generation in near future.

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