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# EFFECT OF RICE RESIDUE MANAGEMENT OPTIONS ON SOIL PROPERTIES AND WHEAT YIELD UNDER RICE-WHEAT CROPPING SYSTEM: A REVIEW

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**ABSTRACT**

Soil health deterioration and depletion in soil fertility is the major concern linked with the rice-wheat cropping system sustainability. Adoption of new technology i.e., reduced/zero tillage and different straw management options are promising tools for conserving long run sustainability of the soil quality and health. Conservation agricultural systems that cause least soil disturbance and retain residue at the soil surface helps in refining fertility status of soil, soil aggregation, moisture conservation, nutrient availability and density of favorable microbes. Cultivation of long duration rice varieties and harvesting with combine harvester has maximized the rate of in-situ burning of rice residue in Indo-Gangetic Plains (IGP). Burning of crop stubbles not are only deteriorating soil health by causing loss of soil nutrients and organic matter but also causing environmental pollution by production of different harmful gases. Removal, in situ incorporation/retention of crop stubbles is better and viable option of residue management then burning. Crop stubble having significant quantity of plant nutrients and their judicious management will have several positive impacts on nutrient availability under rice wheat rotation. Long-term studies showed that residue recycling improved soil properties and becoming an essential part of ecologically sound sustainable agriculture.

***Keywords*** **:** Residue management, phytotoxicity, soil chemical and microbiological properties and wheat yield

## Introduction

Rice-wheat is most extensive cropping system occupies around 13.5 mha area in the Indo-Gangetic Plains of which 10 mha is in India and covers most of the cultivated area. Development of photo-insensitive, high yielding rice varieties and improvement in irrigation facilities, cultivation of rice has expanded to non-traditional areas of country where wheat was main crop in winter. Punjab, Haryana, Bihar, Uttar Pradesh and Madhya Pradesh are the state that followed rice-wheat cultivation on large scale and which counts to 75% of the total food grain production. The total annual crop residue load of india is 686 mt of which 368 mt comes from cereal crop. Around 234 mt crop residues are accounted as surplus that is available in India for variable management options (Hiloidhari *et al*., 2014). Residue of rice, wheat, maize, millet, cotton, sugarcane, jute, groundnut and rapeseed mustard are usually burnt on-farm, across the states. Among various crops, the major contribution in burning of residue is rice (40%) followed by wheat (21%) and sugarcane (19%). With respect to states, Uttar Pradesh (22.25 mt) has maximum crop residues burned followed by Punjab (21.32mt), Haryana (9.18 mt) and Maharashtra (6.82 mt) while, the maximum quantity of cereal crop remains are burnt in Punjab followed by Uttar Pradesh and Haryana (Jain *et al*., 2014). Characterization results showed that 84% of crop residues burnt is from rice-wheat rotation while remaining 16% is from other crop cycles (Shafie, 2016; Singh and Panigraphy, 2011). Ravindra *et al.* (2018) estimated that during 2017, about 116 mt crop residue was burnt in India, which emitted PM 10 (812 Gg), PM 2.5 (824 Gg), elemental carbon (58 Gg), organic C (239 Gg) and Green House gases (211Tg). During 2003-04, emissions of $SO_2$, CO, $NO_x$, and $NH_3$ were estimated to be 25, 6617, 209 and 218 Gg, respectively, which increased to 32, 8511, 268 and 281 Gg, respectively during 2016-17. Building upon this, Deshpande *et al.* (2023) estimated that greenhouse gas emissions from agricultural residue burning in India increased by approximately 75% between 2011 and 2020. The total $CO_2$-equivalent ($CO_2e$) emissions rose from ~19,340 Gg·yr$^{-1}$ in 2011 to ~33,834 Gg·yr$^{-1}$ in 2020. Most of these emissions occurred at the end of the Kharif season, followed by the Rabi season, primarily due to the burning of rice and wheat residues. Among Indian states, Punjab reported the highest crop residue burning activity, with 27% (2.0 million hectares) of its total cultivated area subjected to burning in 2020.

The primary reason behind burning of rice residue its lower digestibility, poor palatability, less protein (2-7%) and more silica content which makes it nutritionally inert in nature and cause aggressiveness in gastrointestinal tract of the cattle (Arora and Sehgal, 1999) and makes it poor animal feed like wheat straw. Besides the wide C:N ratio (80:1), high silica (12-16%) and lignin content (6-7%) of rice residue slows down the in-situ decomposition process and leads to nutrient immobilization when it directly incorporated in field (Bacon, 1990; Janssen, 1996; Yadvinder-Singh *et al.,* 2005). Multiple crop cycles, mechanized harvesting and the absence of cost-effective residue removal solutions have fuelled residue burning despite the Indian government's multilevel attempts to curb these activities (Liu *et al.,* 2021; Deshpande *et al.,* 2022a).

Numerous reports suggest that burning of crop residues over the years have not only diminished total and potentially mineralizable nitrogen, but also burnt soil organic carbon, reduced bio-activity of beneficial microorganisms which help in cycling of nutrient and other vital ecosystem processes (Dobermann and Fairhurst, 2002; Yadvinder-Singh *et al.,* 2005; Bijay-Singh *et al.,* 2008; Chauhan *et al.,* 2012; Jain *et al.,* 2014). Regardless of some benefits such as killing of harmful pests and removal of heap before wheat sowing, burning causes heavy losses of N (up to 80%), P (25%), K (21%) and S (4-60%), air pollution ($CO_2$ @ 13 t ha$^{-1}$) and depriving the soils of organic matter (Mandal *et al.* 2004 and Singh *et al.* 2005). It was estimated that crop residue burning releases 505,968 Ggy$^{-1}$ of OC and 5992 Ggy$^{-1}$ EC, respectively (Lohan *et al.* 2018). Crop residue burning is the most common way to manage the crop byproduct, and it is the fourth largest contributor to biomass burning emissions globally (Sahu *et al.,* 2021). Removal, incorporation or retention of rice residue is the other substitutes to residue burning. On farm residue management alternatives are healthier and among them retention is highly beneficial than incorporation with respect to time, energy and cost effectiveness. Weed suppression, temperature control, moisture preservation and improvement in soil health are the additional benefits associated with the surface retention of rice stubbles. To adopt in situ crop residue management's options and maintaining sustainability of rice wheat cropping system there is a need to upgrade machinery involved in cultural operation, disseminated conservational techniques and divert the agricultural research work towards this approach.

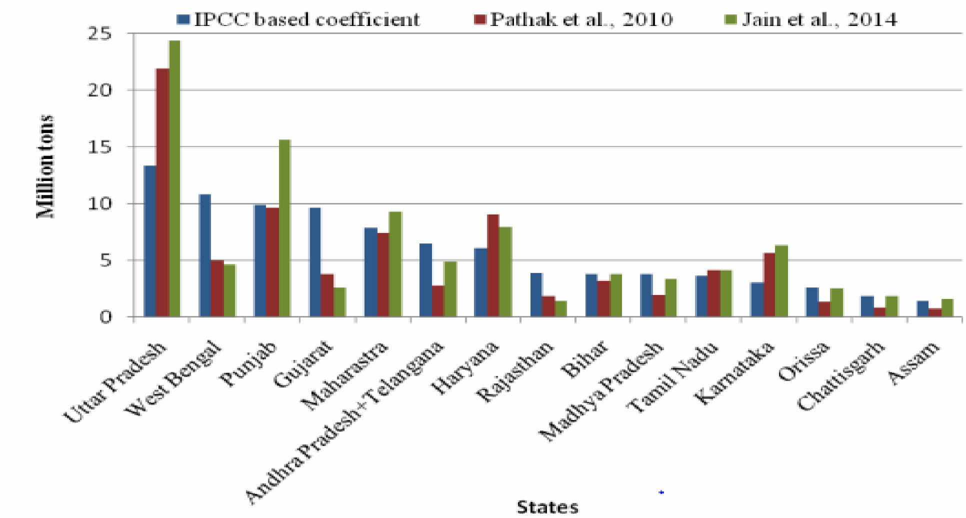


**Fig. 1:** State wise (top ten) scenario for annual burning of crop stubbles (mt/year) in India (Devi *et al.,* 2017)

**Options for paddy straw management:**

Crop residue used as animal food, mulch and cattle shed preparation is the traditional utilization method of crop stubbles. Some other alternatives such as fuel in thermal power generation, used as a substrate in mushroom farming, bio compost preparation, for bio-lubes extraction; manufacturing of paper and pulp can be integrated to minimize residue burning.

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**Fig. 2:** Crop residue management Alternatives

Biogas plant can also be employed as a sustainable approach for in situ disposal of crop residue which meet fuel and energy demands. Despite of all alternative, burning is the most common practice adopted by cultivar's which caused deleterious effect on soil as well as environment. By keeping environmental and soil health in mind, other effective or viable straw management is removal, retention and incorporation. Addition of 6-7 t $ha^{-1}$ of paddy residue whether incorporated/retained on soil surface is possibly influence the agronomic requirements of the succeeding crops such as sowing time, tillage, amount and time of nutrient application and irrigation scheduling. Seeding machineries (Happy seeder, spatial drill and rotary disc drill) are available for the direct seeding of wheat under full paddy straw load but still lacking of these kinds of machineries for other crops like potato and other vegetable. For *in-situ* management of enormous quantity of paddy straw, peasants have to do several tillage operations beginning from straw chopping using mulcher, followed by soil inversion using MB plough, preparatory tillage using rotavator and finally seed bed preparation using bed planter. Besides increasing cultivation cost this operation also delayed the sowing of next crop

**Table 1:** Pattern of disposal of rice residue adopted by the farmers:

| Sr. No. | Author and year | Usage pattern |
|---|---|---|
| 1 | Sarkar *et al.* (1999) | 75 % Mechanized harvested and 100 % burnt |
| 2 | Sidhu and Beri (2005) | In situ burning (Rice - 81% and Wheat - 48%), used for Animal feed (Rice- 7% and Wheat – 45%), Rope making (Rice- 4% and Wheat – 0%), Incorporate in soil (Rice- 1% and Wheat – 1%), Miscellaneous (Rice- 7% and Wheat – 7%) |
| 3 | Badarinath *et al.* (2006) | In situ burning of 75 % of straw and stubbles |
| 4 | Venkataraman *et al.* (2006) | 30-40 % straw is burned (Indo-Gangetic Plains ) |
|  | Average | Out of total straw yield 75% is burnt on farm |

Source: Singh *et al.*, 2018


**Fig. 3 :** Machineries used for sowing crop under paddy residue.

**Phytotoxic effect of residue management**

The phytotoxic effect of crop residues hinders their use as sources of biological modifications to improve soil fertility. The allelochemicals from crop residue may be released into soil possibly either through direct secretion from crop wastes or by the microbes which used these residues as substrate (Kruidhof, 2008). Different bioassay tests were conducted to find out the phytotoxic effect of straw, showed that incubation of aqueous extract of soil straw mixture was more than twice phytotoxic at constant temperature as the extract from soil incubated alone. The temp. range of 20-25°C reported highest phytotoxicity. The rise in temp above 25°C will not only increased the rate of straw decomposition but also tarnished the phytotoxic substances more quickly. Healthy decomposition is the most suitable ways to decrease the phytotoxic effect of crop residues. Alternate rewetting and dehydrating may be resulted into increased in rate of decomposition of residue. Chou *et al.* (1981) evaluated the effect of temperature on production of phytotoxin during rice straw decomposition in soil and found that the amount of the phenolic was likely higher in the samples which were incubated at 25°C than at either 15°C or 35°C, decomposition of rice residue in soil released maximum amount of toxins after incubation of six weeks and then it start decreasing and after twelve week it slowly disappeared. Farooq *et al.* (2018) examined the integrated effect of allelopathic residues and NPK fertilizer by conducting two year field and pot study with the treatments including $T_0$ (control), $T_1$ (200-150-100 kg NPK ha $^1$), $T_2$ (100-75-50 kg NPK ha$^{-1}$ + mung bean straw 4 t ha$^{-1}$), $T_3$ (100-75-50 kg NPK ha$^{-1}$ + rice straw 4 t ha$^{-1}$), $T_4$ (mung bean straw 8 t ha$^{-1}$) and $T_5$ (rice straw 8 t ha$^{-1}$) and reported that application of mung bean and rice straw residue significantly inhibited germination and growth traits in wheat whereas minimal phytotoxic effect was noticed when straws were integrated with NPK fertilizer both under lab and field conditions, particularly under 14 days of alternate wetting and drying cycles.

**Impact of different straw management practices on soil properties and wheat crop Bulk density**

Incorporation of organic materials in soil results in reduction of the bulk density reported by several researchers (Bhatia and Shukla, 1982; Sharma *et al.*, 2000). Regar *et al.* (2005) reported that residue incorporation or FYM decreased bulk density of soil (1.42-1.27 Mg m$^{-3}$) and the effect was more noticeable when residues were applied @10 t ha$^{-1}$. Singh *et al.* (2005) reported lower bulk density with residue incorporation at 0-5 cm soil layer than either residue burning or removal. Similarly, Gangwar *et al.* (2006) studied the effect of three tillage practices with two levels of nitrogen as main and three crop residue management practices (removal, burning and incorporation) as sub main plot in wheat under rice wheat rotation and recorded that zero tillage had highest (1.69 Mg m$^{-3}$) and residue incorporation had lowest (1.59 Mg m$^{-3}$) soil bulk density. Singh and Yadav (2006) reported that residue incorporation and retention significantly lowered value of bulk density than residue removal. Sah *et al.* (2014) also recorded lower value of bulk density under zero-tillage combined with residue retention treatment. Chaudhary *et al.* (2017) found that the straw incorporation + NPK reduced bulk density up to 0-15 cm soil depth over the 100% NPK treated plots. Gathala *et al.* (2017) observed significantly higher value of bulk density with no residue than the residue retention treatment (wheat residue incorporated and rice residue retained as mulch). Kumari *et al.* (2018) studied the effect of long-term crop residue and zinc fertilizer application on soil physical properties and observed significance reduction in bulk density with increasing level of residual starter Zn and residue incorporation whereas the highest reduction was reported with 100% crop residue incorporation and Zn@ 10 kg ha$^{-1}$. Kumar *et al.* (2018) observed that zero tillage with residue or without residue retention significantly decreased the soil bulk density. Zhao *et al.* (2019) reported that straw incorporation significantly decreased soil bulk density by an extant of 6% over straw removal. Prasad *et al.* (2025) investigated the impact of rice residue management on soil bulk density in a rice-sunflower cropping system reported that incorporating rice straw with an adjusted carbon:nitrogen:phosphorus (C:N:P) ratio of 30:1:0.3 prior to incorporation resulted in the lowest soil bulk density (1.34 Mg m$^{-3}$) whereas residue removal and burning treatments exhibited higher bulk densities (1.38 Mg m$^{-3}$).

**pH and EC**

Soil pH is the main factor that influence fertility of any kind of soil by affecting availability of nutrient through nutrient cycling and strongly influenced by crop residue management. There are several reports which indicate different result for soil pH, regardless of whether crop residues have been burned, incorporated, or used as a mulch/retained. Dhar *et al.* (2014) concluded that soil pH and EC was non-significantly affected by addition of straw along with green manure. Kabirinejad *et al.* (2014) reported that addition of crop residues significantly decreased soil pH and increased EC. While Kharia *et al.* (2017) reported that tillage and rice residue had non-significant effect on soil pH as well as EC. Similarly, Saikia *et al.* (2017) concluded that soil pH was affected non-significantly at all the growth stages of wheat when different wheat straw and green manure practices applied in rice and tillage and rice straw management practices in succeeding wheat. Kaur *et al.* (2019) observed that burning of crop residue significantly increased mean pH and EC. Singh *et al.* (2019) reported that different residue management treatment had non-significant effect on soil pH but significant on EC and higher value were recorded under residue incorporation + green manuring followed by incorporation, burning and minimum values recorded under removal. Vinay *et al.* (2020) reported that happy seeder significantly increased soil pH by extent of 3.82 % than the initial value followed by CM (Conventional Method) which was at par with HS. While significantly minimum pH value was observed with RMBP (Reversible Mould board Plough). Zahid *et al.* (2020) concluded after 6 year study that retention of both rice and wheat residue and only rice residue incorporation and retention having statistically lower pH and EC as compared to rice straw removed+burnt. Huang *et al.* (2021) reported that burned straw return significantly reduced soil pH as compared to straw removal and straw return. Singh *et al.* (2023) recorded that incorporation of rice straw over two years resulted in lowering of both pH (0.2 unit) and EC (0.1 dS/m). Kumar *et al.* (2023) reported an increase in soil pH by 0.5 units and EC by 0.3 dS/m immediately following residue burning. Gupta *et al.* (2024) observed significant improvement in bulk density under residue management (retention/ incorporation) treatments compared to residue removal or residue burning.

**Available macronutrient**

Crop residues not only compensate for soil organic matter, a major determinant of soil quality and also supply essential plant nutrients (macro and micronutrients) when mineralized. The quality and quantity of residues applied affect C and N mineralization rates. Plants with high quality (high N content, low C:N ratio, low content of lignin, cellulose, polyphenol and low lignin / N) show high C decomposition and N mineralization rates. Gupta *et al.* (2007) reported that incorporation of crop residue increased inorganic and organic P, reduced P sorption, and P release over straw burning and straw removal. Sharma *et al*. (2010) and Davari *et al*. (2012) also observed that incorporation of rice and wheat residues significantly increased N, P and K contents of soil. Wei *et al.* (2015) reported that the high and medium amount of wheat straw incorporation had significantly increased available soil N, P and K content by 9.1–30.5%, 9.8–69.5% and 10.3–27.3%, respectively over control up to 0–40 cm soil layers. Saikia *et al.* (2017) recorded that PTR+RR+GM (puddled transplanted rice with residue retention and green manuring) and ZTW+R100 (zero tillage wheat with 100% residue retention) significantly increased available N, P and K in both surface (0-7.5 cm) and sub-surface (7.5- 15 cm) soil layer. Kurmvansi *et al.*(2018) after 38 years rice-wheat crop cycle with no residue addition and chemical fertilizer treatment consisted of three levels of N (40, 80 and 120 kg N/ha), three levels of P (0, 40 and 80 kg $P_2O_5$ /ha) and two level of K (0 and 80 kg $K_2O$ /ha) in rice and wheat crop reported that available nitrogen status in soil was almost same as initial, Phosphorus reduced by 9.28 % as compared to initial, maximum reduction of 41.6% was observed in available potash as compared to initial status. Ali *et al.* (2019) recorded that residue management and tillage significantly affected the soil available nutrient content and higher Soil $NO_3$-N and $P_2O_5$ contents associated with residue incorporation followed by zero tillage as compared to residue removed and brunt. While Soil $K_2O$ contents were significantly higher with residue brunt followed by incorporated, zero tillage and removed. Nandan *et al.* (2019) reported that residue retention increased available N, P and K content by 10, 16 and 12%, respectively, over residue removal. Singh *et al.* (2019) found that residue management practices significantly and favorably affected macronutrient content and higher value were recorded under residue incorporation + green manuring followed by incorporation alone then burning and lowest under removal. Available N, P and K content increased by 29.21 and 15.17 %, 88.89 and 77.78 % and 40.96 and 40.43%, respectively, under crop residues incorporation with green manuring and incorporation alone in comparison to burning. Zhao *et al.* (2019) reported that straw incorporation increased 15% more soil available N, P and K in the 0–20 cm soil layer as compared to straw removal. Vinay *et al.* (2020) reported higher available P and K content (37.9 and 12. 28%, respectively) as compared to initial P and K under HS was followed by RMBP, M, ZTD and minimum values of P and K was reported under CM. Zahid *et al.* (2020) concluded that retention of both rice and wheat crop residue, only rice crop residue incorporation and retention having significantly higher concentration of total N, available P and K at 0-15 cm soil depth as compared to rice residue removed+burnt. Singh *et al.* (2023) observed a 20% reduction in soil available N and 10% reduction in P and K following residue burning over two years. Chen *et al.* (2023) reported a decline of 8-12% in available N, P, and K over five years in fields where rice residues were removed. Patel *et al.* (2024) found that rice straw incorporation increased available N by 15%, P by 10% and K by 12% after three cropping cycles. Gupta *et al.* (2024) also reported significantly higher available nutrient content (N, P, and K) in conservation tillage and residue-treated plots than without residue/burning treatments.

**Available micronutrient**

Among other factors, maintaining or incorporating a substantial amount of crop residues on the soil surface is key to manage depletion of micronutrients in the soil and restoring soil fertility (Abrol, Gupta, and Malik 2005). However, most farmers without recognizing potential importance of residue either indulge in burning the crop residue or disposing it off (Malik, Yadav, and Singh 2005). Approximately 50–80% of the micronutrients (Zn, Fe, Cu and Mn) taken by rice and wheat crops can be recycled through the residue incorporation. Long term incorporation of crop residues resulted in increased the DTPA-extractable Zn, Cu, Fe, and Mn content in the soil (Yadvinder-Singh *et al.,* 2000). Availability of micronutrients (Zn and Fe) influenced by crop residue in rice also reported by Singh *et al*. 2005 and Gupta *et al*. 2007. Kharia *et al.* (2017) recorded significantly higher content of micronutrients (Zn, Fe, Mn and Cu) in the surface soil layer under ZTW+R (zero tillage wheat with rice residue retained as surface mulch) compared with ZTW/CTW-R(zero/ conventional tillage in wheat without rice residue) and micronutrient Fe and Cu (12-14%) had higher increase in availability compared to Zn and Mn (3-6%). Nandan *et al*. (2019) after the end of 6 year reported that residue retention treatment significantly increased DTPA–extractable Zn by 11% over removal. Sharma and Dhaliwal (2020) reported that N@120 kg $ha^{-1}$ and incorporation of rice straw @7.5$tha^{-1}$ significantly increased micronutrients cations and all micronutrient transformations compared with no residue incorporation. Zahid *et al.* (2020) found that residue of both rice and wheat; retention and incorporation of only rice residue significantly had higher concentration of DTPA-extractable-Cu, Mn, and Zn at 0-15 cm soil depth over rice straw removed+ burned treatment. Whereas DTPA extractable Fe was significantly higher when only rice residue retained over the other residue management treatment.

**Organic carbon and its fraction**

Rice straw is an important source of organic C and having plant nutrients that required for the optimum growth of crop (Beri *et al.,* 1995; Yadvinder-Singh, 2014). It has been the most viable management option for improving productivity of crop and soil fertility (Huang *et al.,* 2013; Wang *et al.,* 2015a). Significant information regarding to the quality and persistence of soil organic carbon provided by the liability graded fraction of TOC (Ghosh *et al.,* 2012; Venkatesh *et al.,* 2013). Management practices influenced TOC but these changes are challenging to detect, as they occur slowly and are comparatively small compared to the its huge background, which are temporally and spatially different (Blair *et al.,* 1995; Purakayastha *et al.,* 2008). In contrast, water soluble C, easily oxidizable C and microbial biomass C are some more sensitive soil labile organic C fractions indicators and help in explaining SOC change at initial stages of changes in soil management practices and land use (Haynes 2000; Purakayastha *et al.*, 2008; Gong *et al.,* 2009). Several studies reported that incorporation/ retention of crop residue enhance the yield of crop and TOC under different cropping systems (Sidhu and Beri, 1989; Singh *et al.,* 2005; Wang *et al.,* 2015a; Zhu *et al.,* 2015). Liu *et al.* (2014) reported that rice straw incorporation increased pool of TOC by 13% and its labile fractions by 42%, over the application of chemical fertilizers alone. Similarly, Benbi *et al.* (2015) also found that long-term addition of FYM and rice straw caused build-up of labile and recalcitrant pool of SOC as well. Bendi *et al.* (2015) investigated effect of different organic and inorganic nutrient sources on TOC and SOC pools under rice-wheat system and reported after the end of 11 years of experiment, WEOC, HWOC, and $KMnO_4$-C pools of TOC were 0.32%-0.50%, 2.2%-3.3%, and 15.0%-20.6%, respectively. The easily-oxidizable, oxidizable, and weakly-oxidizable fractions were 43%–57%, 22%–27%, and 10%–19% of TOC, respectively. WEOC, HWOC, $KMnO_4$-C, easily oxidizable fraction were enhanced with application of FYM and straw and greatest increase was greatest for WEOC and lowest for $KMnO_4$-C while, WEOC showed a comparatively higher sensitivity to management than TOC. Ghosh *et al*. (2016) investigated from their seven year of research with four residue treatment i.e. no residue/removal, rice residue, lentil residue and both rice + lentil residue and three levels of fertilizer in lentil (0, 50, 100 % of RDF) under rice- lentil system and observed that very labile, labile and less labile fractions significantly increased under residue incorporation over residue removal and the quantitative increase in C-fractions with residue inclusion followed the sequence Cfrac2>Cfrac3>Cfrac1. Nandan *et al.* (2019) reported that residue management treatments significantly affceted TOC and soil C-fractions. C*frac*1, C*frac*2, C*frac*3, C*frac*4, and TOC increased by 18, 24, 5, 10, and 12%, respectively, under residue retention over residue removal. Sharma *et al.* (2019) also observed that Zero tillage in wheat + rice residue significantly enhances non-labile, less labile, labile, very labile pools of carbon. Zahid *et al.* (2020) recorded significantly higher amount of soil organic matter under retention of both rice and wheat crop residue followed by when only rice residue incorporation and retention and lowest under rice straw removed and burning practices.

**Dissolved organic carbon (DOC)**

On a short-term basis DOC, and most active pool of organic carbon, functions as source and sink for organic substrate and mineral nutrients and help in conversion of stable organic form of carbon to plant nutrients by acting as a catalyst over a longer period therefore influencing nutrient cycling and crop productivity. Naresh *et al.* (2018) observed that irrespective of tillage practices i.e. ZT and CT, residue retention resulted in 22.56% and 25.61% higher DOC as compared to the non-residue treatments in both surface as well as sub-surface soil, respectively. Yan *et al.,* 2020; Chen *et al.,* 2017b; Benbi *et al.,* 2015 and Zhu *et al.,* 2014 also observed that return of rice straw significantly increased the soil DOC. Huang *et al.* (2021) recorded that straw burning had significantly improved DOC as compared to straw removal and straw return in a double-cropped rice cropping system. Yan *et al.* (2020) reported that low and high amount of straw return and abandoned farm having significantly higher DOC as compared to no straw return.

**Microbial biomass carbon (MBC)**

Among the overall amount of soil organic carbon microbial biomass carbon is most active part of SOC, suggested as a beneficial and highly delicate portion of a change in SOC status (Powlson *et al.,* 1987; Friedel *et al.,* 1996). Sharma *et al.,* 2020 reported that conjoint application of fertilizer-N and straw incorporation (RS10.0 & N150) significantly increased MBC. Chen *et al.* (2017b) and Benbi *et al.* (2015) also reported that returning of rice straw significantly increased MBC of soil. Bera *et al.* (2018) reported that value of MBC increased progressively from sowing of wheat and reached to a maximum at flowering stage and then declined at maturity of wheat crop. At flowering, MBC content was 15.1 and 23.1% higher in 0-7.5 cm layer in ZTW-R(zero tillage without residue) and ZTW+R ( zero tillage with residue) compared with CTW-R, (conventional without residue) respectively. Hao *et al.* (2019) observed long-term returning of straw significantly improved MBC content in the 0-15 cm soil layer. Zhao *et al.* (2019) recorded that incorporation of straw significantly improved the MBC by 21.5% and 96.5% at 0–10 and 10-20 cm soil depth, respectively, over straw removal. However straw incorporation had non-significant effect at 20-30 cm depth. Sharma *et al.* (2020) evaluated the effect of four levels of fertilizer-N (0, 90, 120, and 150 kg N $ha^{-1}$) and rice straw incorporation (0, 5.0, 7.5, and 10 $Mgha^{-1}$) on soil microbiological properties and reported that conjoint application of fertilizer-N and straw incorporation (RS10.0N150) significantly increased MBC. Priyanka *et al.* (2024) reported that rice residue retention with 4tonn/ha and 6 tonn/ha with zero tillage in barley increased MBC.

**Table 2:** Impact of different quantities of straw returned on the soil organic carbon pools in the rice–wheat cropping system (source: Jin *et al.,* 2020).

| Study | Depth (cm) | Amount of straw returned | TOC (g/kg) | LOC (g/kg) | DOC (mg/kg) |
|---|---|---|---|---|---|
| Hu et al. (2015) | 0~20 | 0 kg/ha rice straw, 0 kg/ha wheat straw | 15.32 b | 235.18 c | 235.18 c |
| | | 2,250 kg/ha rice straw, 1,500 kg/ha wheat straw | 16.25 a | 376.92 a | 376.92 a |
| | | 4,500 kg/ha rice straw, 3,000 k/ha wheat straw | 16.37 a | 314.03 b | 314.03 b |
| | | 6,750 kg/ha rice straw, 4,500 kg/ha wheat straw | 15.64 ab | 232.40 c | 232.40 c |
| | | 9,000 kg/ha rice straw, 6,000 kg/ha wheat straw | 16.10 ab | 336.25 ab | 336.25 ab |
| Xu et al. (2016) | 0~21 | 0 kg/ha rice straw, 0 kg/ha wheat straw | 14.81 b | — | 172.57 b |
| | | 2,250 kg/ha rice straw, 1,500 kg/ha wheat straw | 15.53 ab | — | 190.65 a |
| | | 4,500 kg/ha rice straw, 3,000 kg/ha wheat straw | 15.49 ab | — | 197.34 a |
| | | 6,750 kg/ha rice straw, 4,500 kg/ha wheat straw | 15.63 a | — | 199.73 a |
| | | 9,000 kg/ha rice straw, 6,000 kg/ha wheat straw | 15.40 ab | — | 189.38 a |
| Chen et al. (2017) | 0~20 | 0 k/ha rice straw, 0 kg/ha wheat straw | 15.64 b | — | 445.50 b |
| | | 8,000 kg/ha rice straw, 5,000 kg/ha wheat straw | 17.70 a | — | 654.58 a |

*Note:* Different lower case letters within a column indicate significant differences at the 5% level.

Abbreviations: DOC, dissolvable organic carbon; LOC, labile organic carbon; TOC, total soil organic carbon.

**Table 3:** Effect of different methods of straw management of soil chemical properties under rice–wheat cropping system

| Author name | Duration of experiment | Treatment details | Soil properties | | | |
|---|---|---|---|---|---|---|
| | | | OC (%) | Nitrogen | Phosphorous | Potassium |
| | | Initial soil status | 0.337 | 131 | 16.5 | 133.7 |
| Khrab *et al.,* 2004 | 5 year | Straw removal | 0.317 | 124.8 | 16.7 | 132.7 |
| | | Straw removal+GM | 0.366 | 139.5 | 17.9 | 135.9 |
| | | Straw Burning | 0.335 | 128.2 | 16.8 | 144.3 |
| | | Straw incorporation | 0.392 | 141.4 | 18.1 | 148.8 |
| | | Straw incorporation+GM | 0.427 | 153.1 | 18.6 | 153.0 |
| | | | | | | |
| Yadvinder *et al.,* 2009 | 3 year | Initial soil status (**sandy loam**) | 0.36 | - | 10.9 | 37.5 |
| | | Burned CT | 0.35 | | 4.65 | 32.4 |
| | | Burned ZT | 0.36 | | 4.58 | 33.4 |
| | | Incorporation CT | 0.44 | | 5.48 | 39 |
| | | Mulch ZT | 0.48 | | 5.96 | 39.9 |
| | | Initial soil status (**silt loam**) | 0.56 | - | 16.3 | 65.4 |
| | | Burned CT | 0.60 | | 8.83 | 70.6 |
| | | Burned ZT | 0.61 | | 8.52 | 67.6 |
| | | Incorporation CT | 0.65 | | 9.69 | 76.8 |
| | | Mulch ZT | 0.68 | | 10.02 | 77.4 |
| | | | | | | |
| Kumar *et al.,* 2019 | 1 year | Before burning | - | 313 | 68.39 | 193.76 |
| | | After burning | - | 269.98 | 76.31 | 225.12 |
| Singh *et al.,* 2019 | 4 year | **Initial soil status** | - | - | - | - |
| | | Removed | 0.40 | 175 | 20 | 190 |
| | | Burned | 0.38 | 178 | 18 | 188 |
| | | Incorporated | 0.58 | 205 | 32 | 264 |
| | | Incorporated +GM | 0.62 | 230 | 34 | 265 |

**Table 4:** Effects of Different method of straw management Techniques on overall Soil Health

| Author Name | Treatment details | Soil properties | Effect on soil properties |
|---|---|---|---|
| Kaur *et al.* (2022); Singh *et al.* (2021); Kumar *et al.* (2023) | Residue burning | Loss of soil organic carbon and nutrients (N, P, K) Deterioration of soil microbial biomass and enzyme activities Increased risk of soil erosion due to surface exposure | Negative |
| Sharma *et al.* (2023); Ramesh *et al.* (2022) | Residue incorporation | Increases soil organic carbon, moisture retention Enhances microbial diversity and activity Improves soil structure and fertility | Positive |
| Prakash *et al.* (2021) | Use as Animal Feed | Removes biomass that could improve soil Low digestibility limits feed value Minimal direct soil impact | Neutral to slight negative |
| Patil *et al.* (2023); Gupta & Singh (2022) | Composting | Converts residues into stable organic matter Adds humus and improves nutrient availability Promotes soil microbial health | Positive |
| Sharma & Thakur (2023); Joshi *et al.* (2021) | Biochar Production from Residues | Biochar improves nutrient retention and cation exchange capacity (CEC) Enhances soil water-holding capacity and microbial habitat | Highly Positive |
| Singh & Rathore (2020) | Mechanical Removal for Bioenergy | Removes residues from field, potentially depleting SOC Needs balanced harvesting to avoid soil degradation | Varibale |

## Soil Enzymes

Enzymatic activity are the potential indicator and measures of change in soil quality that induced by change in management and environment (Mohammadi, 2011). Alkaline and acid phosphatases are associated with the release of inorganic phosphates from organic materials, and serve as a main connection among biologically unavailable and mineral phosphorus by catalyzing hydrolysis of organic phosphate esters to orthophosphate. Urease is an enzyme that hydrolyzes urea and urea type substance to $CO_2$ & $NH_3$. Different straw management conditions significantly affect enzymatic activities depending on climate, soil type, and conditions available for experiments (Wang *et al.*, 2015a; Zhao *et al.,* 2015). No tillage and retention of crop residues on surface significantly increased enzymatic activity by improving microbial biomass had been reported by researchers (Hok *et al.,* 2018 and Saikia *et al.,* 2019). Chaudhury *et al.* (2005) reported dehydrogenase (DHA) as an effective indicator of soil quality in rice–wheat–jute and other cropping systems. Zhang *et al.* (2016) also reported increase in activity of urease with the increase in amount of straw application. Kharia *et al.* (2017) recorded significantly higher activity of enzymes at upper soil layer (0-5 cm), activity of DHA increased by 6 and 14%, ALP by 9 and 13% and Urease by 8 and 13%, respectively under ZTW+R as compared with ZTW/CTW-R. Wei *et al.* (2015) reported that incorporation of wheat straw with three level ((H: 9000 kg $hm^{-2}$, M: 6000 kg $hm^{-2}$, and L: 3000 kg $hm^{-2}$) significantly affected enzymes activities and high straw incorporation increased activities of urease and phosphatase by 24.4–31.3% and 9.9–36.4% in 0-40 cm soil depth, respectively over the control. Kaur *et al.* (2019) recorded that burning of residue significantly decreased the activity of dehydrogenase as compared to pre burning soil sample. Kumar *et al.* (2019) investigated the effect of burning of rice residue on soil microbial dynamics and reported that burning of straw caused significant decline in population of most important groups of microorganisms-bacteria, fungi, actinomycetes, phosphate and potassium solubilizing microbes and cellulose degraders immediately after burning over residue removed and retained. Singh *et al.* (2019) found that incorporation of crop residue with GM and without GM increased the activity of phosphatase by 43.55 and 38.71 % and dehydrogenase by 124.14 and 89.66%, respectively over residue removal and burning. Ming *et al.* (2019) reported that winter cover crop residue incorporation in a double-cropping rice system had significantly higher soil, enzyme activities than in the R-R-Fa(rice-rice fallow) system and after application of residue in soil activities of alkaline phosphatase reached maximum at the booting stage and gradually reduced after this. Zhao *et al.* (2019) observed that full straw incorporation significantly improved the activities of urease, invertase and catalase in the 0–15 cm soil depth by 11.4%, 41.0%, and 12.9%, respectively over straw removal. Sharma *et al.* (2020) reported that conjoint application of fertilizer-N and straw incorporation (N@150 & RS@10) significantly increased dehydrogenase and alkaline phosphatase activity. Chaudhary *et al.* (2024) reported that in their field experiment, conservation tillage combined with full rice residue retention significantly enhanced dehydrogenase enzyme activity compared to partial residue retention (anchored stubbles) and conventional tillage (residue incorporated with chopping). The study evaluated four rice residue management practices as the main factor, with two nitrogen levels (150 and 180 kg $ha^{-1}$) and two nitrogen split levels (two vs. three splits) as sub-treatments.

## Yield and yield attributes

Crop residues are source of plant nutrients. Addition of residue into soil either directly or indirectly affected the crop performance and yield in many ways and results are varied according to the practices involving for residue management. Different residual management practices such as burning, removal, or incorporation showed similar yields of rice and wheat reported by several researchers (Walia *et al.,* 1995; Singh *et al.,* 1996; Bijay-Singh *et al.,* 2001). While Beri *et al.* (1995) recorded significantly lower yields of both rice and wheat with the incorporation of crop residues as compared to removal or burning of residues. Davari *et al.* (2012) reported that combinations of FYM + RR + B and VC + RR + B improved growth, grain yield and yield attributing characters of wheat over the control by 81% and 89%, respectively. Dotaniya (2013) recorded that residue incorporation increased the yield by 4.2 and 2.3% over removed and burnt, respectively. Residue burns recorded significantly higher (1.9%) grain yield of rice than residue removed. Wheat grain yield was increased by the extent of 33.1% under residue incorporation and 31.4% under residue burnt over the residue removed. Verma and Pandey (2013) reported that different rice residue management practices significantly affected the plant height and number of tillers per meter row length of wheat and maximum was reported with 30% additional NPK + recommended NPK as compared to without residue incorporation+ recommended NPK and residue incorporation + recommended NPK. The yield and yield attributes characters were also recorded maximum with the same treatment. Usman *et al.* (2014) recorded higher number of grains per spike, 1000-grain weight and yield of grain in tillage includes either straw retained/incorporated than tillage methods includes brunt straw. Kumar *et al.* (2016) observed that zero tillage along with residue retention recorded significantly higher yield (grain and straw) and yield attributes of wheat over other management practices. Kharia *et al.* (2017) recorded significantly higher yield of yield and yield attributes viz., 1000 grain weight, spike length, grain weight per spike and grains per spike under ZTW+R than ZT/CT with no straw. Ali *et al.* (2019) reported significantly higher total yields of rice and wheat under residue incorporation over removal and burning of residue. Zhao *et al.* (2019) recorded that full straw incorporation significantly increased the wheat yield over straw removal and increased is in yield by an average of 58%. But for rice yield difference was non-significant. Meena *et al.* (2020) also reported that rice residue retention significantly increased wheat grain yield, above-ground biomass, tillers per square meter and grains per meter square. Sharma and dhaliwal (2020) reported that application of N@120 kg N $ha^{-1}$ and rice residue incorporation @7.5 t $ha^{-1}$ significantly increased crop yield compared with no-residue. Crop grain yield under residue incorporation was significantly higher than no residue incorporation irrespective of N application.

## Nutrient content and uptake by both crops

Crop residue management significantly affected the total nutrient (NPK) uptake of both rice as well as wheat. Incorporated residue of either rice or wheat released nutrients slowly after decomposition during the crop growth period and resulted in better crop establishment and dry matter production. Das *et al.* (2003) observed that highest nutrients uptake was found in plot where rice-straw incorporated which was at par with wheat-straw incorporated plot. Dotaniya (2013) investigated the effect of three crop residue management practices (incorporation, burning and removal) with two levels of nitrogen (100 and 150 kg N $ha^{-1}$) and three levels of potassium (0, 30 and 60 kg $K_2O$ $ha^{-1}$) fertilization on nutrient uptake and recoded that residue incorporation caused higher uptake of N and K in both the crops over the other treatments. Burning of residue had response at par in both crops. N @ 150 kg $ha^{-1}$ and K @ 60 kg $K_2O$ $ha^{-1}$ resulted into higher N and K uptake over other treatment. Verma and Kumar (2013) reported highest N uptake by grain and straw when rice residue incorporated with 30% additional N+P+K + recommended NPK over without incorporation of rice residue + recommended NPK and rice residue incorporation + recommended NPK. Kharia *et al*. (2017) recorded significantly higher uptake of macro and micronutrients under ZTW+R compared with ZT/CT without rice straw. Ali *et al.* (2019) also reported that significantly higher uptake of NPK in rice and wheat with residue incorporation than residue burning and removal. Sharma and Dhaliwal (2020) recorded higher micronutrients uptake in grain as well as straw for both wheat and rice crop under RS (rice residue) incorporated over the RS0 (no rice residue) treatment. Among the N application, total Zn, Fe, and Mn uptake was significantly higher in N@120compared with N0 (no nitrogen). The difference in total Cu uptake was non-significant for wheat.

## Conclusion and recommendation

Long-term residue management practices and adoption of conservation tillage practices resulted in improvement of soil properties and increase nutrient availability as compared to conventional farmer's practice. Among all options, residue retention emerges as the most soil- and environment-friendly strategy. It builds soil organic carbon, supports microbial life, and minimizes pollution. Burning and removal offer short-term convenience but are ecologically unsustainable. To foster healthy soils and a sustainable future, rice-based systems should transition toward residue retention and minimal tillage, supported by biological and nutrient management tools. From the above discussion it can be concluded that crop residue has a potential to emerge as a one of important sources of nutrient owing to availability in huge amount and plays important role in improving soil properties over long-run and thereby sustaining production system and eco-services. Use of surplus residue for energy generation instead of on-farm burning is a better option to cope up with increased air pollution due to residue burning. Sustainability of rice wheat cropping system is the biggest challenges and introduction of conservational agricultural practice like adoption of reduced and no tillage along with residue retention and incorporation are helpful in maintaining soil health and sustainability of this system. Crop diversification under rice wheat rotation is also result in development of sound management practices. More research evaluating effect of burning and residue removal on soil health is required; they can also help in creating awareness among cultivators. There is need to stop the current pattern of removal or burning of paddy as long run of these practices may leads to loss in soil fertility and soil nutrient and use residue for other purposes such as electricity generation, ethanol production, bio-gas, mushroom production and bio-char production *etc.* It needs to focus and upgrade the location specific technologies practices to encourage *in-situ* residues management and their synchronization/ compatibility with on-going system for sustainable utilization of crop residue without affecting crop production.

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