**Crop residue and nutrient management effects on soil health**

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**ABSTRACT**

Natural resources such as crop residues can be recycled to improve the soil's physical, chemical, and biological properties. Most people consider crop residues to be a waste, but when they are used properly, they can greatly improve soil conditions. Many management options exists like burning, removal, incorporation, surface retention, and mulching. Farmer's usually burn residue in order to avoid interference with machinery when planting their next crops. A wide range of studies have documented the effects of incorporation, surface retention, and mulching on soil properties, and have shown these strategies to be very effective in improving physical, chemical, and biological qualities. Residues decomposition product promotes aggregation, improves soil bulk density, hydraulic properties, allowing more water to infiltrate. Further, Soil thermal properties and soil moisture near-surface are maintained, enhancing root and microbial activity, as well as nutrient transformation. All of these results in improved soil health thus helping to achieve economic, ecological, and socially sustainable agricultural production. The present chapter mainly focuses on the different on-field residue management options and their effect on soil properties and crop productivity through an array of already published literature.

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**Keywords-**Crop residue, residue management, soil health, crop productivity

**I. INTRODUCTION**

Crop residues (CR) are frequently regarded as having little or no value [1, 2], but they have the potential to improve the physical, chemical, and biological status of soil. When they are returned to the soil, they become valuable resources [3]. Intensive agriculture, with unscientific land management, depletes essential nutrients and reduces crop production potential. The soil must be physically good enough to support optimum crop growth and allow full utilization of its resources in order to produce the desired output from cultivated crops. As one of the most cost-effective ways to improve soil health, CR should be incorporated into the farming system. The total amount of CR produced in India is estimated at 350 x 106 kg Year-1. CR management is predominant in the Indo-Gangetic plains, especially Punjab and Haryana. In Indian Punjab, it is estimated that about 7-8 million metric tonnes of rice straw is burnt every year [**4**] which leads to almost complete loss of soil nitrogen (N), 25% of phosphorus (P) losses, 20% of potassium (K) losses and sulfur (S) loss to about 5-60% [**5**]. Moreover, it deprives soils of organic matter, deteriorates structural and hydraulic properties of soil, losses huge amounts of biomass, exhausts soil flora and fauna, and contributes largely to environmental pollution creating health hazard problems and deprivation of the agricultural environment. Other than burning, the residue management options available for farmers are removal of straw, surface retention and mulching, and incorporation into the soil. CR mulch acts as a natural blanket, protecting the soil surface from the insolation and erosive effects of raindrops and wind [6]. It protects the soil surface from excessive compaction, surface sealing, and crusting while reducing soil aggregate breakdown and dispersion. When used as surface mulch, CR improves soil structural properties by increasing the concentration of soil organic matter (SOM) [7].

Incorporation of CR into the soil helps to rebuild the biological activity and play a vital role in improvement and maintenance of soil physical condition for a long period of run. Moreover, it helps in building of SOM, improvement in soil aggregation and its stability, bulk density (BD), porosity and pore size, moisture holding capacity, hydraulic characteristics, penetration resistance [8], brings out modification in soil thermal and moisture regimes and contributes to nutrient pools of soil. It also reduces unproductive soil and water losses, helps to reduces soil temperature extremes and modifies microbial habitat for the proliferation of soil biota [6]. For sustaining the productive potential cropping systems, it is essential that the management practice should aim at improving soil physical condition via improving soil structural and hydraulic properties, that helps in reducing nutrient losses, providing favourable microbial habitat and controlling soil degradation by the ways that are effective and inexpensive [**9**]. One of the cost effective option for improving overall condition of soil is the build-up of SOM through incorporation of CR. On farm recycling of CR is the pre-eminent management practice for restoring the declined SOM content which is identified as the nucleus for improving soil physico-chemical and biological condition and sustaining agriculture production [**10**].

**A. Crop residue statistics in India**

The Ministry of New and Renewable Energy (MNRE), Government of India, estimates that approximately 500 Mt of CRs are generated each year. Uttar Pradesh generates the most CRs (60 Mt), followed by Punjab (51 Mt) and Maharashtra (46 Mt). Cereals produce the most residues (352 Mt), followed by fibres (66 Mt), oilseeds (29 Mt), pulses (13 Mt), and sugarcane (12 Mt) (Figure. 1). The production of cereal CRs is highest in Uttar Pradesh (53 Mt), followed by Punjab (44 Mt) and West Bengal (33 Mt). The state of Maharashtra produces the most pulse residue (3 Mt), while Andhra Pradesh produces the most fibre CR (14 Mt). Gujarat and Rajasthan produce most oilseeds CR (6 Mt).

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| **Figure 1: Crop residue generation by various crops in India** |

**II. CROP RESIDUE MANAGEMENT OPTIONS**

Farmers can manage residue in a variety of ways, including burning, incorporation, surface retention and mulching, and straw removal. The advantages and disadvantages of each management option must be considered. In general, the method to be used depends on the location, the soil, and the situation [7].

**A. Residue burning**

As a low-cost residue management practice, residues are traditionally removed from fields for animal feeding. Farmers have recently been burning large amounts of CRs left in the field in order to facilitate timely planting of the next crop, as CRs interfere with tillage and seeding operations. This practice depletes nutrients and SOM, causing a slew of environmental problems. The benefits of the practice include killing soil-borne deleterious pests and pathogens, clearing the land of residues quickly before the next crop is established, facilitating seed germination and establishment, and controlling residue-borne diseases [11], while the drawbacks include significant air pollution, eradication of beneficial soil insects and microorganisms, and soil SOM depletion [12].

**B. Surface retention and mulching**

Surface retention of previous CRs without incorporation protects the fertile surface soil from wind and water erosion. On the surface, residues slowly decompose, increasing OC (OC) and total N (TN) while protecting the soil from erosion and temperature fluctuations [13]. When compared to burning, residue retention on the surface increased soil NO3- concentration by 46%, N uptake by 29%, and yield by 37% [14]. The disadvantage of this method is that the machine fails due to the large volume of residue remaining on the surface, causing the seeding of the next crop to be delayed. It is commonly followed in areas where conservation tillage is common.

**C. Residue removal**

Removal of residues reduces the amount of organic binding agents required for aggregate formation and stability, which has a negative effect on aggregate stability. Furthermore, raindrop impacts close open-ended bio-channels, which decreases water infiltration rate (IR), hydraulic conductivity (HC), and air permeability, increasing runoff/soil erosion, and non-point source pollution transport (e.g., sediment and chemicals). Additionally, residue removal results in evaporation of surface soil moisture, increases diurnal temperature fluctuations, and reduces organic matter input required to improve soil water retention.

**D. Residue incorporation**

Residue incorporation has been shown to be very effective in improving soil’s physical properties. Ploughing is the most effective method of incorporating residue [15] [16]. Unlike removal or burning, straw incorporation increases SOM, N, P, and K content. However, the residue incorporation in soil particularly of cereals results in short-term immobilization of inorganic N, resulting in N deficiency and decreased crop yields by about 40% [**17**]. The research findings report that it is possible to overcome the N immobilization problem by applying 15-20 kg ha-1 of N as a starter dose with straw incorporation, which leads to a higher yield than burning straw [18].

**III. RESIDUE MANAGEMENT EFFECTS ON SOIL HEALTH AND CROP PRODUCTIVITY**

Many researchers around the world studied the effects of rice straw incorporation on soil physicochemical as well as biological properties under a wide range of soil and climatic conditions and reported positive effects on soil physical parameters such as soil porosity (SP), aggregation, BD, penetration resistance (PR), HC, soil chemical properties such as available nutrient content, and soil biochemical properties such as enzyme activities, and carbon fractions. All of this resulted in an improvement in overall soil health, which eventually leads to higher grain yields in the long run.

**A. Effect on soil bulk density (BD) and porosity (SP)**

The incorporation of CR into soil reduces the BD of soil. CR incorporation in the soil increases the microbial activity and residue decomposition products favour more aggregation and thus reduce BD. Furthermore, because the residue is lighter than mineral matter, BD should decrease with dilution [19]. SP has a direct relationship with soil BD, so as BD decreases, porosity tends to increase. When aggregates form and grow in size, cavities form and expand within and between the aggregates. A conduit for fluid transport is created when these cavities are connected to each other (Shaver, 2010). In Punjab, India, “reference [20]” in a long-term experiment reported decrease BD in rice straw managed treatment over control. Among different treatments, treatments consisting of wheat straw + urea + rice straw incorporation resulted in a maximum reduction in BD (1.65 Mg m-3) because of the incorporation of the residue of both crops. Similarly in another study in the Philippines, “reference [21]” reported that all the plots receiving rice straw significantly decreased the soil BD. BD under control and straw burnt plot were statistically at par, but straw incorporation had resulted in lowering of soil BD over burning and control mainly because of increase in SOC storage. While studying the long-term effect of CR incorporation on two different soil types, “reference [22]” reported lower BD with CR incorporation in both soil types. However, the magnitude of decrease was highest in Shahpur soil (coarse silty in texture and low SOM) as compared to Awagat soil (fine loam texture). Similar results were also reported for the SP. This was mainly attributed to the property of CR in improving soil structure mainly in the soil with a light texture and low SOM content. “Reference [23]” studied the long-term effect of different levels of wheat straw mulch (0, 8, and 16 Mg ha-1 Year-1) on a silt loam soil of Central Ohio and reported that in 0-3 cm soil depth, 16 Mg ha-1 Year-1 treatment lowered the BD by 58% (0.84 Mg m-3 ) and 8 Mg ha-1 Year-1 treatment by 19% (1.11 Mg m-3 ) than BD under 0 Mg ha-1 Year-1 (1.32 Mg m-3). Similarly, SP was also affected by wheat straw mulch. The SP under 0, 8, and 16 Mg ha-1 Year-1 of wheat straw mulch was 0.50 m3m-3, 0.64 m3m-3, and 0.72 m3m-3, respectively and it increased by about 28% and 44% under 8 and 16 Mg ha-1 Year-1 of wheat straw mulch over control treatment. However, “reference [24]” in Lithuania did not find any significant effect of chopped straw incorporation on soil BD in the upper 3-13 cm and lower 15-25 cm depth soil layer. They reported a BD of 1.25–1.49 Mg m-3 in the upper soil layer without straw and 1.29–1.47 Mg m-3 in the plot with straw incorporation. In a three-year study with different tillage practices and eight levels of CR management under the wheat (w)-mungbean (m)-rice (r) cropping system, “reference [10]” in Bangladesh reported that BD under the Swrm (where the residue of all three crops were incorporated) was found to be the lowest (1.38 Mg m-3) followed by Smr (1.40 Mg m-3) and Smw (1.40 Mg m-3) having incorporation of two CRs. S0 (Plot without incorporation of CR) showed the highest BD (1.44 g cm-3). Similarly, Swrm showed the highest SP (43.2%) while the lowest was in S0. However, “reference [25]” in Canada did not find any significant effect of CR on BD. However, when averaged across CR, BD was higher for No-tillage than tillage by about 15% in black Chernozen and 18% in gray Luvisol. Similar results have been reported by “reference [26]” in Vertisol soil type of Australia where the effect of residue management on BD was non-significant. While studying the effect of conservation tillage on the productivity of wheat for 15 years (1992-2006) in Northern China, “reference [27]” reported that for the first six years, BD was significantly less for CT (conventional till). It was statistically uniform for CT and NTSC (no-till and residue cover) in the next five years, afterwards, NTSC resulted in the lowering of soil BD. The SP increased with the increasing mulch rate [28]. However, lower mulching rates up to 5 Mg ha-1 Year-1 did not show any significant difference in SP. Up to 5 Mg ha-1 Year-1, the mean SP was 0.3% and it increased by about 173% under 10 and 15 Mg ha-1 Year-1 of mulch rate. “Reference [7]” reported that CR management significantly affected the SP of soil. It was 49.4, 48.8, 51.9, and 54.6% under control, straw burning and removal, straw incorporation, and straw incorporation plus FYM treated plot, respectively. Similar results have been reported by [29] [30]. The SP was lower for low mulch rate and it increased by about 95% with 8 Mg ha-1 of mulch rate. In a short-term study in Western Nigeria, “reference [31]” reported decreased BD with increasing mulch rate in 0-5 cm soil layer i.e. 1.17 Mg m-3 under control to 0.97 Mg m-3 with 8 Mg ha-1 of mulch treatment. Similarly, “reference [32]” observed 58% lower BD under the high-mulch treatment and 19% lower under the low-mulch treatment as compared to the BD under the no-mulch treatment for the 0-3 cm depth.

**B. Effect on soil aggregation and aggregate stability**

The greater the amount of CR returned to the soil, the greater the surface coverage and protection of soil structure from natural and anthropogenic perturbations [33]. Soil is protected from heavy raindrop impacts and surface sealing and runoff is restricted, allowing water to penetrate down the profile, insulating soil from high temperatures and reducing SOM loss, thereby improving structural stability. In northwest India, while studying the effect of CR and manure application on soil aggregation in the rice-wheat cropping system, “reference [34]” reported that application of rice straw and FYM resulted in an increase in aggregation especially macro-aggregates, a decrease in micro-aggregates, and the effect was not significant for the application of nitrogenous fertilizers. They further reported that at 0-5, and 5-10 cm soil layer, the macro-aggregate formation was enhanced significantly with the application of rice straw and FYM. However, at 10-15 cm, the improvement in > 2 mm fraction was the least. When assessed across different nitrogen rates, an abundance of macro-aggregates was found with the incorporation of rice straw at 0-5 cm soil layer. Similarly, in the arid lands of the Loess Plateau of China, “reference [35]” reported that aggregate stability was high in 0-10 cm soil depth and decreased with an increase in soil depth. In the two years of experimentation, aggregate stability in 0-10, 10-20, and 20-30 cm soil layer were 5.0-23.2%, 10.3-32.1%, 10.6-47.9% respectively, and significantly higher for straw incorporation treatments over control plot receiving only inorganic fertilizer. In another short-term study, “reference [36]” reported that straw incorporation resulted in a reduction of 2.0-0.25 mm aggregate fraction as compared to control plots. However, no significant influence of straw incorporation on aggregates in the size range >2.0 mm or < 0.25 mm has been reported. “Reference [37]” reported that compared with no residue treated plots, soil aggregation was improved in CR treated plots and had a higher proportion of large macro-aggregates than the small macro-aggregates. The CR treated plot had 14% higher water-stable macro-aggregates as compared to the no residue treated plot. While studying the effects of different mulching rates, “reference [29]” found that water-stable aggregates were higher in 16 Mg ha-1 year-1 mulch rates, ranging from 38% to 67%, and lowest under plot receiving 0 Mg ha-1 year-1 mulch rate. Similar results have been reported for mean weight diameter (MWD) which was highest for mulch rate no mulch. “Reference [25]” in Canada reported a higher value of MWD under no-tillage and residue retention and least under tillage without residue. Similarly, “reference [38]” showed that CR incorporation was the most effective measure for increasing the aggregate stability of the rhizosphere. “Reference [39]” and “reference [40]” also found that straw application improved the aggregate stability and other soil properties.

**C. Effect on surface sealing and soil penetration** **resistance**

Surface seals are commonly found in bare soil when raindrops strike the surface, causing soil aggregates to break down and disperse. Finer particles moved down with the percolating water and oriented themselves, clogging the pores near the soil surface. Surface sealing has a negative impact on the physical properties of soil, which ultimately affects soil productivity [6]. It reduces saturated/unsaturated HC and IR while increasing runoff rate and amount. Because crusts have a higher density and lower HC than the underlying soil layers, they limit seedling emergence, water, air, and heat fluxes, and increase soil erosion. Maintaining a complete and continuous cover of CR on the soil surface is critical for reducing surface seal formation [41]. A soil surface protected with heavy CR does not seal or crust even in soils of high silt and low SOM. Soil penetration resistance (SPR) is caused by cohesive forces between individual soil particles as well as frictional resistance encountered by particles forced to slide over one another or ride out of interlocking positions to make way for growing roots. Except for cracks and macropores, root elongation in soils is possible only to the extent that root pressure exceeds soil penetration resistance [42]. In Bangladesh, “reference [43]” reported that SPR was significantly reduced by retention of a higher amount of CR as compared to a lower amount. SPR in 0-5 and 5-10 cm soil layer under the low amount of residue retention was 80, 152 and 69, 134 N cm-2 under a high amount of residue retention. However, at lower soil layers i.e. 10-15 cm, the effect was not significant. Similarly, “reference [44]” in Norway reported that straw management treatments significantly improved the modulus of rupture (a test used to characterize soil penetration). However, “reference [24]” did not find any significant influence of straw incorporation on PR. At depth of 1.5-9.0 cm, PR was highest and changed drastically from 223 to 1115 kPa in straw removed plot and from 208 to 1053 kPa in straw incorporated plots, respectively. At depth 9.0-22.5 cm, PR changed from 1115 to 1175 kPa in straw removed plot and from 1053 to 1211 kPa in straw incorporated plots. In another study, “reference [31]” observed significantly lower PR under different rates of mulch treatments. At soil depth 0-5 cm, PR under control was 1.54 Kg cm-2 and reduced to 1.07 Kg cm-2 under 8 Mg ha-1 of mulched treatment. They also reported that PR tends to decrease with an increase in soil depth up to 40 cm. Lower PR under a higher mulch rate was attributed to the wetness of the soil profile because of a reduction in soil evaporation and runoff [45]. Conversely, while working on silt loam soil of Central Ohio, “reference [23]” did not find any significant effect of different mulch rates on cone index at 0-5 cm soil layer.

**D. Effect on hydraulic properties of soil**

One of the most sensitive parameters to CR management is soil water content. Keeping the soil surface covered with CR reduces evaporation rates and lengthens the first-stage drying period [7]. Thus, residue-covered soils retain more soil moisture within the crop rooting zone than soil without CR and keep an extra inch of water available for growing plants in late summer. Mulching with CRs improves soil water storage by (i) increasing IR as SP improves, (ii) decreasing runoff losses as residue retards surface sealing and crust formation, allowing more water to infiltrate, and (iii) reducing evaporation and abrupt fluctuations in soil surface temperature, and thus aiding in the maintenance of plant available water. (iv) increasing SOM concentration, which increases the soil's water retention capacity. SOM derived from residue interacts with the soil matrix, increasing the specific surface area required to adsorb and retain water molecules. As a result, as residue incorporation increases, so does soil water content and plant available water capacity [23]. Soil erosion can be reduced by up to 90% compared to an unprotected, intensively tilled field, depending on the amount of CRs left on the soil surface. The hydraulic properties of soil viz. IR, HC, and soil moisture have been reported to be affected significantly by CR incorporation. “Reference [46]” reported the reduced BD in 0-15 cm soil depth with incorporation of rice and wheat straw with associated increase in saturated HC because of increase in macro-porosity of soil. Incorporation of residue of both wheat and rice crop increased the IR of soil. Initial IR was maximum (7.0 mm hr-1) where residue of both crops incorporated, after five hours, it varied from 2.0 mm hr-1 under less intensive tillage without CR to 4.0 mm hr-1 where residue of both crop where incorporated. In another study, “reference [22]” reported the favourable effect of residue incorporation on infiltration because of presence of greater proportion of maco and mesopores and lowered soil BD in both Awagat and Shahpur soil. While studying the effect of different tillage treatments, “reference [47]” reported that sorptivity of straw retained treatment was significantly lower than straw burnt treatment at lower potential (-40 mm). HC under straw-retained direct- drilled treatments was 4.1 times greater than that of straw-burnt conventional tillage treatments. This was mainly because of improvement in more transmitting macropores under straw retained direct drilled treatment. Significantly higher amount of available soil moisture was detected in straw retained direct drilled treatment as compared to straw burnt conventional till system. Similarly, “reference [48]” on a sandy loam soil also reported that total as well as final infiltration were significantly higher with zero tillage in combination with CR retention as compared to conventional tillage. While studying the effect of three types of CRs, “reference [10]” reported higher soil moisture content by 31% in the plot receiving residues of all three crops (wheat, rice and mungbean) than plot without CR incorporation. In contrast, “reference [28]” in Spain did not find any significant difference in water content at mulching rate of 1 and 5 Mg ha-1 year-1 over control. At higher mulching rates of 10 and 15 Mg ha-1 year-1, there were about 18% higher soil moisture for all suction intensities. They also reported about 7.6% higher HC with mulching rate of 10 and 15 Mg ha-1 year-1 as compared to control and low mulching rates and no any benefit was found beyond 10 Mg ha-1 year-1 of mulch rate. “Reference [49]” in Japan studied the effect of rice straw mulch and nitrogen fertilization on soil moisture content during wheat growth and found that in the surface soil, moisture content was reduced at faster rate in the plot without rice straw mulch i.e. from 33.2% at sowing to 14.1% after 20 days of sowing. The moisture content under 4 Mg ha-1 of rice mulch retained highest percentage of soil moisture i.e. 21% after 20 days of sowing. They reported significantly higher amount of soil moisture even after removal of rice straw from previously mulched plot. With increasing nitrogen fertilizer rate, soil moisture content decreased due to more crop growth and enhanced transpiration.

**E. Effect on soil organic carbon**

In the 11 years of continuous rice-wheat rotation, “reference [54]” reported that SOC content improved by 34% with the incorporation of rice straw and application of FYM. “Reference [55]” reported that sandy loam soil with low initial OC had great potential for increasing OC content as evident by a 29.6% increase as compared to 11.6% in silt loam soil, in straw retained treatments compared with straw burning. Likewise, In NW China, “reference [8]” reported that maize straw incorporation resulted in an increase in SOC storage. SOC storage for straw incorporation @ 4500 Kg ha-1 was 7.71% in 2008 and it increased to 21.40% in 2010 over control. As compared to control, straw incorporation @ 4500 kg ha-1 showed a significant increase in SOC storage, but no significant difference was found between straw incorporation @ 9000 and 13,500 Kg ha-1. In another study, “reference [56]” in the USA also reported higher SOC stock where CR was retained and incorporated as compared to complete and partial residue removal. In long-term research, “reference [57]” showed that the OC content of soils was significantly increased with the application of rice straw at the rate of 12 t ha-1 and wheat straw at the rate of 6 t ha-1. Similarly, in the cotton wheat system, “reference [22]” reported a significant increase in SOM with straw incorporation as compared with straw removal. This effect was more pronounced in coarse silty soil as compared to fine loamy soil. However, “reference [58]” in Nepal did not find any significant effect of CR incorporation to increase SOC in a conventionally tilled rice-wheat system. However, SOC content was 11% higher under no-tillage and residue added treatments than under conventional tillage and no residue added treatments. In Southern Spain, while working with mulched treatments, “reference [28]” also did not find any significant difference in SOM content between mulching rates of 1 Mg ha-1 year-1 and control. Increasing mulching rates from 5 Mg ha-1 year-1 resulted in an increase in organic matter ranging between 3.1-4.4% and the highest increase was reported for mulching rates of 10 and 15 Mg ha-1 year-1. In a long-term experiment at China, “reference [59]” reported that the mean SOM for no-till with straw was 18.8 g kg-1 in the 0-0.05m soil depth which was significantly greater than conventional tillage plots i.e. 14.3 g kg-1. “Reference [60]” reported that the incorporation of CR increased the SOC content by about 4.8% but did not find a significant difference in SOC content between residues returned and removed treatments. Similarly, “reference [61]” reported increased SOC with residue retention along with nitrogen inputs. “Reference [62]” found that with rice straw incorporation, SOM increased from 6.4% in 2008 to 12.2% in 2010.

**F. Effect on soil available nutrients**

In a long-term study at Ludhiana, Punjab, “reference [17]” found that the incorporation of CR resulted in a higher concentration of TN as compared to treatments with residue removal or burning. Similarly, AP content was also greater in plots with residue incorporation as compared to its removal or burning. The burning of CR resulted in decreasing AP content because of its loss to the atmosphere. “Reference [63]” and “reference [64]” also reported that TN content was significantly improved with rice straw incorporation as compared to the burning of CR. In Vertisol soil type, “reference [65]” reported that TN and mineralizable nitrogen in 0-10 cm soil depth was significantly higher in treatment with no-tillage residue retention and increasing level of fertilizer nitrogen. Similarly, “reference [60]” reported 29.2% increase in N with the incorporation of CR. Similar results also have been reported by “reference [66]”. In Philippines, “reference [21]” reported that all the plots receiving rice straw treatment showed significantly highest AK ranging from 375 Kg ha-1 in 50% straw incorporation to 495 Kg ha-1 in residue burning over control (355 Kg ha-1). In NW china, “reference [67]” reported that different nutrient management treatments had significantly improved the soil nutrient status as compared to control. Treatment comprising of Straw + NP, and FYM showed significantly higher nutrient content over control and other treatments. Similarly, “reference [27]” in NW China reported that no-tillage in combination with residue retention showed significantly higher TN and AP by about 25.6% and 4.4% respectively.

**G. Effect on enzyme activities and soil carbon pools**

Soil enzymes are vital components of the soil and can serve as the indicator of soil quality and portray the potential soil fertility under different management interventions. The activity of enzymes in the soil is governed by the different management practices and ameliorative measures which affect the soil properties of biologically most active surface horizons. In the rice-wheat cropping system, “reference [68]” reported the highest activity of dehydrogenase (DHA) in rice straw incorporated treatment as compared to rice straw removal. “Reference [69]” in the rice-wheat system, also reported that DHA activity was 2 times higher in rice straw compost incorporated treatment as compared to no compost incorporated treatments. Similarly, significantly higher activity of DHA was observed in 0-30 cm soil depths with the incorporation of wheat residue than its burning “reference [70]”. “Reference [71]” reported the higher microbial biomass and enzyme activities following rice straw incorporation as it acts as a source of food and energy for microbes. In the maize-wheat cropping system, “reference [72]” reported 14.6% higher activity of fluorescein diacetate (FDA) enzyme in 0-5 cm soil depth under 75% CR retention as compared to without retention. In the rice-wheat-mungbean cropping system, “reference [73]” reported an 18% increase in FDA activity after 9 years of CR and vermicompost incorporation than no straw and vermicompost incorporation. “Reference [74]” under the wheat-fallow cropping system reported that the activity of the acid phosphate (acid P) enzyme decreased by straw burning as compared to straw incorporation. In another experiment, “reference [75]” reported that the incorporation of maize residue at the rate of 7.5 t ha-1 increased the activity of alkaline phosphate (alk P) by about 80% as compared to no residue. Similarly, “reference [76]” reported a significant improvement in alk P activity after the incorporation of wheat straw. Soil labile carbon pools are considered the soil quality indicators and are influenced by CR management practices [77] [78]. While working in the rice-wheat cropping system, “reference [27]” reported that water-soluble carbon (WSC) increased by about 71-109% in rice straw incorporated treatments as compared to without rice straw incorporation. Similarly, “reference [79]” in China reported that the incorporation of 50% and 100% CR has significantly increased WSC content as compared to straw removal. It increased by 34 and 71% under 50 and 100% CR incorporation [79]. In another study, “reference [73]” in the rice-wheat and rice-wheat-mung bean cropping system reported higher basal soil respiration (BSR) in FYM and CR amended plot. “Reference [58]” also reported higher cumulative CO2 under incorporation of CR at the rate of 10 t ha-1 as compared to control. Similarly, “reference [80]” in an incubation study observed that BSR was significantly higher in rice straw incorporated treatments. Rice straw incorporation increased the BSR by 2.7-2.8% over no straw incorporation. “Reference [79]” in China reported that the incorporation of 50% and 100% rice straw increased the microbial biomass carbon (MBC) as compared to control. The magnitude of increase was higher after ten years of rice straw incorporation than after two years. However total organic carbon (TOC) was not affected significantly by rice straw incorporation as compared to control after two years of experimentation, but after ten years significant increment was reported. However, “reference [81]” reported the minimal effect of CR retention on TOC content, but MBC was affected significantly in CR retained treatments.

**H. Effect on crop productivity**

In Eastern India, “reference [46]” reported that the grain yield of rice and wheat significantly improved with the application of rice straw and wheat straw either separately or in combination as compared to without CR treatment. This was mainly attributed to improvement in SOC levels, reduce evaporative loss of water, and improved water infiltration, which improved the soil’s physical condition and reduced the nutrient losses. Similarly, “reference [62]” showed a significant increment in grain yield with rice straw incorporation and nitrogen fertilization. In another study, “reference [83]” observed that the grain yield of corn and soybean could reduce by about 0.10 Mg ha-1 with the removal of each Mg ha-1 of residue. “Reference [60]” in Pakistan reported that the incorporation of CR increased the grain yield of maize by 23.7% as compared to residue removal treatments. Similar results have been reported by “reference [84]” about a 37% increase in grain yield of cereals with CR incorporation as compared to without incorporation. “Reference [85]” reported increased maize yield with an increasing amount of CR. The highest yield (4900 K5g ha-1) was found under a plot that received 150% of CRs from the previous crop as compared to the control. While a number of studies reported the higher grain yield with residue management, there are few studies that reported the decrease or variable effect of CR on crop productivity. “Reference [61]” reported that lentil grain yields during 1995- 96 were 0.82 and 1.17 t ha-1, 0.28 and 0.35 t ha-1 in 1996-97, and 1.63 and 1.24 t ha-1 in 1997-98 under residue removal and residue retained treatments. When averaged over all years, no significant effect of residue retention and residue removal on the grain yield of lentils was reported. In sandy clay loam soils of the Philippines, “reference [21]” did not find any significant effect of residue treatments on grain yield in the first and second cropping cycle, however in the third and fourth cropping cycle, 100% straw treated plots showed significantly higher grain yield as compared to 50% straw incorporation and control. In the last cropping cycle, burning of residue recorded the highest grain yield of about 18.5% over control followed by 100% straw + green manure (16.8%) and 100% straw (15.4%). Similarly, “reference [86]” in a long-term experiment, reported that some years showed higher grain yield while some not. However, the overall effect was found to be non-significant. Such variable reports have also been presented by “reference [44]” who reported that in the first year of experimentation, the different straw management treatments did not show any significant effect on grain yield. In the second year, the grain yield was significantly improved with the incorporation of normal and double amounts of straw. However, in the fourth year of experimentation, straw-managed treatments showed a significant negative impact on grain yield. On average, the incorporation of normal and double amounts of straw increased the mean grain yields by 0.29 Mg ha-1 as compared to other treatments. “Reference [87]” in Kenya did not find any significant effect of CR management in combination with tillage practices on the grain yield of maize and soybean. In Punjab, India, “reference [17]” found that residue burning resulted in the highest yield of rice and wheat as compared to incorporation or residue removal. The reduction in yield with residue incorporation was mainly due to the immobilization of N and P. Residue incorporation together with the application of N @ 60, 120, and 180 Kg ha-1 resulted in a depression of wheat yield by 0.54, 0.27, and 0.08 t ha-1, respectively. However, the positive effects of residue incorporation were reported after 13 years when residue management practices were discontinued. A simplified mechanism of how crop residue improves soil health and crop productivity is depicted in Figure 2.

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| **Figure 2: Simplified mechanism of how crop residue improves soil health and crop productivity** |

**IV. CONSTRAINTS OF USING CROP RESIDUES IN THE FIELDS**

Using CRs in the field presents a number of challenges. These include difficulties in sowing and applying fertiliser and pesticides, as well as pest infestation issues [88]. The zero-till seed-cum-fertilizer drill system has been greatly improved to provide farmers with trouble-free technology. The other bottleneck is weed control, particularly in the rice-wheat system. Excessive use of chemical herbicides may be unsuitable for a healthy environment. Because of higher residue levels and fewer options for nutrient application, particularly through manure, nutrient management may become more complex. It is possible for fertilisers, particularly N, applied entirely at the time of seeding to lose their efficacy and cause environmental pollution. The adoption of residues incorporation systems is further limited by additional management skills, an expectation of lower crop yields and/or economic returns, negative attitudes, and institutional obstacles. Furthermore, farmers prefer clean, well-maintained fields over shabby fields that have been tilled.

**V. CONCLUSION**

Farmers have several residue management options, including burning, incorporation, surface retention and mulching, and straw removal. Burning, on the other hand, is effective in terms of facilitating timely planting of the next crop because crop residues interfere with tillage and seeding operations, but this practice causes nutrient and SOM loss, resulting in a variety of environmental pollution. Another option is to remove straw, which reduces aggregate stability and accelerates runoff and soil loss. The incorporation and surface retention of straw is the most cost-effective and has been proven very effective by researchers. This helps in maintaining agronomic productivity by enhancing SOM, quantity, and availability of essential nutrients and soil moisture, promoting soil biotic activity thus soil aggregation as well as reducing soil erosion and non-point source pollution. Crop residue recycling has the potential to return a significant amount of plant nutrients to the soil. The stagnation of yields caused by declining soil organic carbon is a major threat to the majority of India's cropping systems. As a result, it is a massive obstacle for growers to manage crop residues effectively and efficiently in order to improve the physical condition of the soil and maintain production sustainability. If crop residues are managed scientifically, then it can affirm the improvements in soil health and sustain the productivity of cropping systems.

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