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Crop Residue Generation, Recycling and its Management for Agricultural Sustainability

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Abstract

Large number of studies show adverse effects of crop residue burning on soil organic carbon (SOC), soil fertility and soil health, and long-term sustainability of crop production. In India, enormous quantities of crop residues are produced annually whose improper management creates unsustainability in the production systems. Crop residues as a crucial source of carbon (C) and plant nutrients can be a boon for sustainable agriculture and their ploughing back into the soil will help protect soils against soil erosion, improve water conservation, enhance SOC and recycle nutrients. Returning crop residues back in the soils follows the principle of taking whatever you want and plowing rest back to the soil for sustainability. Several technologies available for handling residues of crops include mushroom cultivation, composting, biochar formation, manufacturing of non-woven composites, and *in-situ* mechanical intensification management using crop management techniques focused on agricultural conservation. Due to large-scale residue production in Indo-Gangetic Plains, *in-situ* management is the more sustainable and practical method for recycling of residues.

Key words: Crop residue, recycling, sustainability, *in-situ* management, mushroom cultivation, composting, biochar formation

Introduction

India is primarily an agrarian country with a total geographical area of 329 million hectares (Mha), which includes 140 Mha area under farming with a cropping intensity of 136%. The cropping intensity in the country has witnessed an increase of 25% since independence. The area under wheat increased significantly and now it is the predominant crop of *rabi* season owing to assured irrigation. Rice-wheat cropping system, mostly practised in Northern India *viz;* Haryana, Punjab, Uttar Pradesh and Madhya Pradesh, contributes maximum to the national food grain production. Due to enhanced rice-wheat production, the stover production also enhanced significantly, especially in the non-traditional areas. Plant parts, left after crop harvesting called crop residues, are a good source of soil nutrients. It is not a waste material but a good natural resource and it is the largest part of agricultural harvests which contains a huge amount of carbon and other nutrients such as nitrogen (N), phosphorus (P), potassium (K), sulphur (S), etc.

There is generation of a huge amount of rice residue in North-West India and wheat residue in central and Eastern India. Crop residue management is the emerging challenge for sustainable growth in agriculture and environmental protection mainly in Haryana, Punjab, Uttar Pradesh and Delhi.

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Burning of crop residue is contributing to huge atmospheric pollution that has serious implications on the environment, soil, and human health as well as economic conditions due to the release of large amounts of air pollutants. One tonne stubble burning along with 199 kg ash releases 3 kg of particulate matter, 60 kg of carbon monoxide (CO), 1460 kg of carbon dioxide (CO_2) and 2 kg of sulphur dioxide (SO_2). This is also a potential source of harmful greenhouse gases (GHGs) and other chemically and radiative important trace gases and aerosols. Heat generated by burning of the crop residues increases the soil temperature which causes the death of beneficial soil microbial population and reduces the level of N and C in the topsoil layer. Crop residue is highly rich in nutrients. For example, one tonne of paddy straw contains approximately 2.3 kg P_2O_5, 5.5 kg N, 25 kg K_2O, 1.2 kg S, 50-70% of micro-nutrients absorbed by the rice crop and 400 kg of carbon which are lost during burning. Apart from this colossal nutrient loss, some of the soil properties like temperature, pH and moisture are adversely affected due to burning.

All the above-mentioned losses can be managed using various straw management technologies such as using Happy Seeder for sowing seed in standing stubbles of crop residue. *In-situ* retention of crop residues can improve the water retention of soils and benefit the crop. This practice of *in-situ* incorporation of crop residues can alleviate the harmful effect of residue burning. Crop residues can help in reducing soil erosion, maintaining soil moisture, improving soil tilth and quality, and reducing the nutrient runoff.

Generation of Crop Residues in Indian Agriculture

Crop residue is a plant material remaining in the field after harvesting of economic produce. This includes leaves, stalks, roots, etc. According to the estimates made by Ministry of New and Renewable Energy, Government of India, about 500 million tonnes (Mt) of crop residues are generated annually in the country. There is wide variability in the generation of crop residues and their use across different regions of the country depending on the crops grown, cropping intensity and productivity of these crops. Generation of crop residues is highest in Uttar Pradesh (60 Mt) followed by Punjab (51 Mt), and Maharashtra (46 Mt). Among different crops, cereals generate maximum residues (352 Mt), followed by fibres (66 Mt), oilseeds (29 Mt), pulses (13 Mt) and sugarcane (12 Mt). The cereal crops (rice, wheat, maize, millets) contribute 70% while rice crop alone contributes 34% to the crop residues. Wheat ranks second with 22% of the crop residues whereas fibre crops contribute 13% to the crop residues generated from all the crops.

Extent of Crop Residue Burning

Extent of the utilization of crop residues varies across different states of the country. Traditionally, crop residues have numerous competing uses such as animal feed, fodder, fuel, roof thatching, packaging and composting. The residues of cereal crops are mainly used as cattle feed. Rice straw and husk are used as domestic fuel or in boilers for parboiling rice. Farmers use crop residues either themselves or sell it to landless households or intermediaries, who further sell these to industries. The remaining residues are left unused or burnt on-farm. In states like Punjab and Haryana, where crop residues of rice are not used as cattle feed, a large amount is burnt on-farm. Sugarcane tops are either used for feeding the dairy animals or burnt on-farm for growing a ratoon crop in most parts of the country. Residues of groundnut are burnt as fuel in brick kilns and lime kilns. The residues of cotton, chilli, pulses and oilseed crops are mainly used as fuel for household needs. The shells of coconut and stalks of rapeseed and mustard, pigeon pea and jute and mesta, and sunflower are used as a domestic fuel (Pathak et al., 2010).

Surplus residues *i.e.*, total residues generated minus residues used for various purposes, are typically burnt on the farm. Total amount of crop residues surplus in India is estimated to be 91-141 Mt. Cereals and fibre crops contribute 58% and 23%, respectively **(Figure 1**) and remaining 19% are from sugarcane, pulses, oilseeds and other crops. Out of 82 Mt surplus residues from the cereal crops, 44 Mt is from rice followed by 24.5 Mt from wheat, which is mostly burnt on-farm. In case of fibre crops (33 Mt of surplus residue) approximately 80% of the residues are from cotton and are subjected to on-farm burning. It is worth mentioning here that large uncertainties, as well as variability, exist in the estimates of generation, utilization and on-farm burning of crop residues. Pathak B.S.. (2004) had estimated that annually 523 Mt crop residues were generated in India, out of which 127 Mt was surplus. According to the Ministry of New and Renewable Energy Resources (MNRE, 2009), the amount of crop residue generated was 500 Mt and surplus was 141 Mt. Crop-wise, the annual surplus crop residues of cotton stalk, pigeon pea stalk, jute and mesta, groundnut shell, rapeseed and mustard and sunflower were estimated to be 11.8 Mt, 9.0 Mt, 1.5 Mt, 5.0 Mt, 4.5 Mt, and 1.0 Mt, respectively. Based on the estimates about 72 Mt crop residues are burnt on-farm. Pathak et al. (2010) estimated that about 93 Mt of crop residues are burnt on-farm in the country.

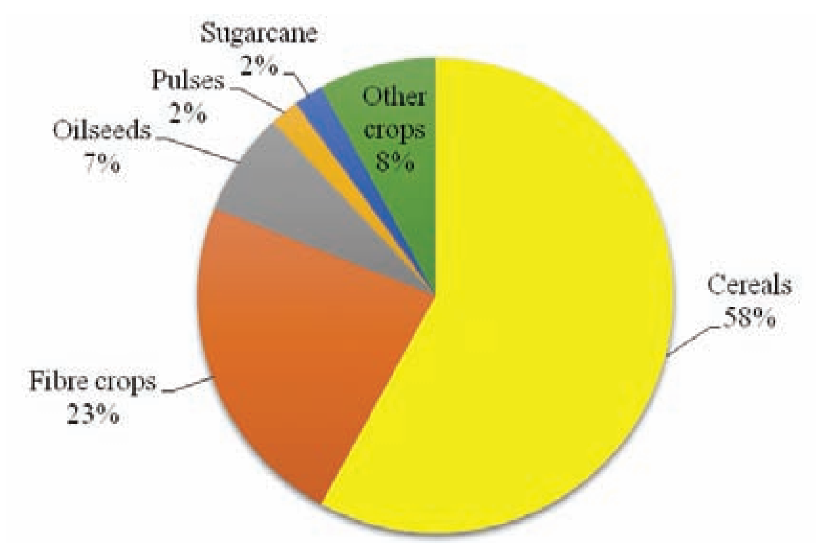

Figure 1. The share of unutilized residues in total residues generated by different crops in India (calculated from MNRE, 2009)

Reasons for Burning of Crop Residues at the Farmer's Field

Main cause of paddy residue burning is very narrow window of time (20-30 days) available between the harvesting of rice and sowing of wheat. Paddy is a water-intensive crop and there is high usage of water in its cultivation. Paddy cultivation can legally begin only around mid-June when the monsoons typically arrive in North India. During the harvesting of paddy crop with combine harvester, about 80% of the residues are left in the field as loose straw or in other words, we can say that it leaves 6-10 cm of paddy stalk on the field and the removal of the paddy stalk that remains in the field is a labour-intensive process. The rise in labour cost and the subsequent costly availability of mechanical implements lead to about 85-90% of paddy straw burnt *in-situ* in the field.

Other reasons which make farmers burn the paddy straw include clearing of fields, fertility enhancement, and pest and pasture management. Burning traditionally provides a fast way to clear the agricultural fields of residual biomass and facilitates further land preparation and planting. It also provides a fast way of controlling weeds, insects and diseases, both by eliminating them directly or by altering their natural habitat. Burning is also perceived to boost soil fertility, although burning has a differential impact on soil fertility. It increases the short-term availability of some nutrients (*e.g.*, P and K) and reduces soil acidity, but it leads to a loss of other nutrients (*e.g.*, N and S) and organic matter.

The Government of India took several steps towards banning crop residue burning in the fields. Crop residue burning was notified as an offence under the Air Act of 1981, the Code of Criminal Procedure, 1973 and various appropriate Acts. In terms of efforts being made to reduce crop residue burning, various approaches have been used by Central Government and various State Governments and other regulatory bodies.

Negative Consequences of Crop Residue Burning

Loss of Nutrients

In addition to the loss of the entire amount of C, 80% of N, 25% of P, 50% of S and 20% of K present in straw are lost due to burning. It also pollutes the atmosphere (Ponnamperuma, 1984). Maximum loss of nutrients is due to sugarcane trash burning followed by rice and wheat straw. Burning of sugarcane trash led to the loss of 0.84 Mt, rice residues 0.45 Mt and wheat residue 0.14 Mt nutrients yr^{-1} out of which 0.39 Mt was N, 0.014 Mt was K and 0.30 Mt was P. If these crop residues are incorporated or retained, then the soil will be enriched, particularly with SOC and N.

Impact on Soil Properties

The heat from burning residues elevates soil temperature causing the death of bacterial and fungal populations. However, death is temporary as the microbe regenerate after a few days. Repeated burning in the field, however, permanently diminishes the microbial population. Burning immediately increases the exchangeable NH_4^+ - N and bicarbonate extractable P (Olsen-P) content but there is no significant build-up of nutrients in the soil profile. Long-term burning reduces total N and C and potentially mineralizable N in the 0-15 cm soil layer.

Emission of Greenhouse Gases

Burning of residues emits significant amounts of GHGs. For example, 70, 7 and 0.66% of C present in rice straw were emitted as CO_2, CO and CH_4, respectively, while 2.09% of N in straw was emitted as N_2O upon burning (Carlson et al., 1992). According to Yevich and Logan (2003), 91, 4.1, 0.6, 0.1 and 1.2 Tg yr^{-1} of CO_2, CO, CH_4, NOx and total particulate matter was emitted due to burning of crop residues in India. GHG emissions from wheat crop residues in Punjab are relatively low compared to those from paddy fields (Badrinath et al., 2006). As per estimates made by Sahai et al. (2011), burning of 63 Mt of crop residue emitted 4.86 Mt of CO_2 equivalents of GHGs, 3.40 Mt of CO and 0.14 Mt of NOx.

Emission of Other Gases and Aerosols

Residue burning also leads to emission of a large number of particulates that are composed of a wide variety of organic and inorganic species. One tonne straw on burning releases 3 kg particulate matter, 60 kg CO, 1460 kg CO_2, 199 kg ash and 2 kg SO_2. This change in the composition of the atmosphere may have a direct or indirect effect on the radiation balance. Besides these, other light hydrocarbons, volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) and SOx, NOx are also emitted. These gases are important for their global impact and may lead to a regional increase in the levels of aerosols, acid deposition, increase in tropospheric ozone and depletion of the stratospheric ozone layer. These may subsequently undergo trans-boundary migration depending upon the wind speed and direction of the wind.

Residue Recycling

Recycling of crop residues can be handled in two ways. Residues can be directly left to decay on field surfaces after the harvest by using Happy Seeder machine and zero seed drill for direct sowing of ensuing crops without land preparation or use mulcher to chop out the previous crop residue so that these will decay easily or by incorporating them into the soil by mouldboard plough, harrowing/disking, or chiselling. Alternatively, these could be used as mulches and composts or returned to fields via animal wastes as has been done in traditional agriculture. Recycling of residues provides several critical and mostly irreplaceable environmental and soil health benefits as has been demonstrated through diverse soil, plant science, and agronomic researches.

Protecting Soils against Erosion and Improving Water Retention

Excessive soil erosion is a major threat to sustainable farming (Pimentel et al., 1995). Estimating the effect of erosion on agricultural productivity remains controversial (Crosson, 1997), but there is no doubt that soil erosion leads to significant loss of plant nutrients with decline in soil quality (Troeh et al., 1991). Wind and water erosion both are controlled most effectively by residue retention; the degree of erosion control is directly proportional to the field covered by residues. Increase in the mass of wheat residue from 0.56 to 1.12 t ha^{-1} can cut down the wind erosion by more than 95% (Finkel, 1986). When 20% of the soil surface is covered by residues, soil erosion will be 50% less than that from a residue-free field (Shelton et al., 1991), and a 90% cover can reduce water erosion by as much as 93% as compared to the bare soil (Wischmeier and Smith, 1978). Reduced erosion and increased soil water storage, in turn, result in higher crop yields. Residues control erosion primarily by two modes of action: reducing wind speeds below the threshold level for soil particle movement, and intercepting falling raindrops, thereby preventing them from detaching soil particles. Besides, the presence of residues reduces surface water runoff by way of increasing water infiltration rates.

Even long straws are good absorbers of water, averaging 2-3 kg of water absorbed kg^{-1} of straw; shredding further enhances this capacity to 3-3.8 kg kg^{-1} of crop residue. Stubble-mulch tillage, in which implements are used to control weeds and prepare seedbed while most residues remain well anchored on the soil surface because plant roots are cut 7-10 cm below the surface, is a highly effective means of controlling both wind and water erosion (Unger, 1994). Traditional mouldboard ploughing leaves a mere 5-10% of residual phytomass on the surface; undercutting leaves 70-90% of residual phytomass on the surface. Lower yields, and hence lower mass, of residues produced in semi-arid and arid environments, limit their use to control erosion and enhance soil moisture storage in such environments.

Enhancing Soil Organic Matter

Universal consequence of converting grasslands to croplands has been an appreciable decline in concentrations of soil organic matter (SOM). Long-term records show that soil N content decreased by 25-70% over periods ranging from 30 to 90 years; these records also showed decline in soil carbon by up to 50% over similar periods (Aref and Wander, 1998). Decline in SOM is frequently accompanied by structural deterioration of affected soils, resulting in surface crusting; in turn, reduced water infiltration and scarcer phytomass litter have led to the reduced presence of the soil microorganisms and invertebrates whose activity is essential for the sustenance of highly productive soils (Reganold et al., 1990; Madsen, 1995). Earthworms are particularly effective in producing desirable physical and chemical changes in soils; their abundance declines sharply with the removal of crop residues and with the burning of residues in the field (Edwards and Lofty, 1979; Knight et al., 1989). Such changes have significant long-term effects. A century of data from the Morrow Plots (at the University of Illinois at Urbana) shows that plots with higher SOM content have higher yields than those with low SOM content (Aref and Wander, 1998). Data from Russia suggests that reducing SOM by 55% cuts down grain yields by half (Libert, 1995). Recycling roots and stubble might suffice to maintain high levels of SOM in some soils, particularly where crop rotations include "green manure" (*i.e.*, leguminous cover crops grown for short periods and then ploughed under) or leguminous forages. Rate of this increase depends mainly on factors controlling decomposition, and there is an upper limit to the amount of SOC that can be held in mineral soils with only stubble ploughed in. Wheat fields at Sanborn Field Experimental Plots in Missouri had less than 650 g m^{-2} of crop-origin carbon at the end of 12 years, whereas after just 6 years of recycling stubble and all straw, these fields accumulated approximately 2.6 times this amount of SOC (Buyanovsky et al., 1997). Conversely, reducing the rate of residue recycling led to a decline in SOC. Experiments in Minnesota showed that cutting corn stover recycling from 8.0 t ha^{-1} to 5.6 t ha^{-1} reduced the SOC by 274 kg ha^{-1} (Huggins and Fuchs, 1997).

Recycling Nutrients

Recycling of residues and their eventual mineralization would supply approximately 1/3rd of N, between 1/5th and 1/3rd of P, and more than 100% of K applied via inorganic fertilizers. But unlike nutrients from inorganic fertilizers, macronutrients in crop residues are not readily available. The high cellulose and lignin content of crop residues precludes rapid degradation, particularly in colder climates. Also, the high C:N ratios of crop residues which commonly range from 50 to 150, with only those of leguminous residues being below 40, are much higher than those of fresh leafy phytomass (12- 15 for grasses) or animal manure (typically 15-25). Biomass with C:N ratios below 20 will fairly rapidly release net nitrogen for plant growth. However, decomposition of high C:N ratio residues will withdraw N from the soil, temporarily immobilizing the nutrient during the early stages of decay and thereby reducing the short-term productivity of the soil. The pattern of P immobilization is similar to that of N. Of course, the immobilized nutrients become available eventually but these cannot be counted on to enhance short-term growth, yields, or profits. How fast the nutrients will be released depends on the activity of microbial decomposers, which is predominantly temperature and moisture dependent. In colder climates and dry environments, more than one-half of the residue left on the surface may remain undecomposed even after 1 year (Lynch, 1979; Schomberg et al., 1994). By contrast, in warm humid climates, residues decompose rapidly, making nutrients much more readily available but also making the year-round reduction of soil erosion and water runoff much more difficult. In cold or dry environments, decomposition of residues can be speeded up by appropriate agronomic practices. Experiments with wheat and sorghum straw in Texas showed that N in residues left on the surface was immobilized three times longer than nitrogen in the buried phytomass and that decay rates increased linearly with the amount of applied water (Schomberg et al., 1994). The need to make a more comprehensive appraisal of residue recycling is demonstrated by experiments conducted at the IRRI, Philippines (Cassman et al., 1996). Rice straw was found to be a poor N source when used alone but its combination with fertilizer (applied as urea) resulted in agronomic efficiency just 15% lower than for the use of fertilizer-N alone. This slight disadvantage was offset by several compensating factors. Rice straw provided greater residual benefit (*i.e.*, it provided N over a longer period) than other organic sources of N and, with high C:N ratio it was a better source of organic carbon and was able to increase bacterial N fixation. Recycling of rice straw may thus have a greater potential for reducing requirements for applications of inorganic N than the use of green manure. Well managed crops of tropical lowland rice could derive N to the extent of 75 kg ha^{-1} yr^{-1} from straw. Efficient recycling of this N would be promoted by optimized timing of fertilizer N application, by better incorporation of the recycled straw into the soil, and, eventually, by using mechanical harvesters that leave straw in the field (rather than hand-harvesting, which involves the removal of all phytomass). Crop residues should be treated as a valuable renewable resource to be managed carefully to maintain soil quality and promote crop productivity.

Technologies Available for Management of Crop Residues

Crop residues are processed for use in construction applications. For example, rice husk is used as a cement mix. Banana peels and sugarcane wastes are utilized in the paper industry. These alternative measures have been suggested by scientists and agriculturists over the past decade as an alternative to crop residue burning, but due to lack of awareness and social consciousness among the farmers, these measures have not been fully implemented.

In this section information on four such agricultural applications that have either been overlooked or skipped due to various reasons are presented. These include mushroom cultivation, composting, biochar, and *in-situ* management through mechanical intensication. Each is discussed below:

Mushroom Cultivation

Straw of rice and wheat is an excellent substrate for mushroom cultivation. Generally, edible mushrooms are used not only for their nutritional value but are now also in demand for their medicinal properties and therapeutic attributes (Chang, 1996; Ribeiro and Salvadori, 2003; Borchers et al., 2004). Among various mushrooms, *Agaricus bisporus* (button mushroom), *Calocybe indica* (milky mushroom), *Pleurotus ostreatus* (oyster mushroom), *Volvariella* spp. (paddy straw mushroom), *Lentinula edodes* (Shiitake mushroom) and *Auricularia polytricha* (Jew's ear mushroom) are commonly available edible species in India. Button mushroom is grown on composted substrates and a variety of substrates have been used in composting world over. These composted substrates show huge variation in the yield of button mushroom, indicating thereby the role of various physicochemical factors and the compositional changes in the substrate (Sharma, 1991) as these are important factors contributing to the composting process and hence to yields. Consequently, the growing of mushrooms on paddy straw is one such avocation, which if put into practice, cannot only lead in the improvement of dietary and economic standards of the masses but also in combating environmental pollution due to burning of this precious agro-waste. Moreover, paddy straw is cheaper. Therefore, it can be profitably utilized for the mushroom production to combat the day after day increasing cost of mushroom production. Although paddy straw does not provide good physical structure to compost, yet it gives good results when mixed with wheat straw in different ratios (Rana, 1998). Therefore, the growth of mushrooms fully depends upon the compost for their nutrition. Efficiency of the mushrooms to utilize various constituents of compost depends upon the substrate used in composting which further depends on many physiochemical factors responsible during the composting process and mushroom growth.

Composting

Composting is not a new concept to India. While small scale backyard composting and making compost from organic material in management of solid wastes (MSW) is common. However, there is no information in the literature to prove that it is also the case for the agriculture industry in India. In a publication, Hettiarachchi et al. (2018) discussed the common challenges faced in organic waste composting. This is one of the challenges but the agricultural community does not have to worry about if they make compost *on-site* out of their crop residue as it can be easily fed back to the same agricultural lands. Higher organic carbon content in crop residue makes it an ideal raw material for compost similar to animal manure and food waste. Composting is the natural process of rotting or decomposition of organic matter by micro-organisms under controlled conditions (Misra et al., 2003). As a rich source of organic matter, compost plays an important role in sustaining soil fertility and ultimately achieving sustainable agricultural productivity. Addition of compost to the soil improves physio-chemical and biological properties of the soil and can supplement the application of agricultural chemicals such as fertilizers and reduce the use of pesticides. Higher potential for increased yields and resistance to external factors such as drought, disease and toxicity are the benecial effects of compost amended soil (Shilev et al., 2006; Lei et al, 2010). These techniques also help in higher nutrient uptake, and active nutrient cycling due to enhanced microbial activity in the soil. Composting is mediated by different micro-organisms operating in the aerobic environments. Bacteria, fungi, actinomycetes, algae, and protozoa are naturally present in organic biomass or added artificially to facilitate decomposition (Tuomela et al., 2000). It is the biological maturity under aerobic condition, where the organic matter of animal or plant origin is decomposed to materials with shorter molecular chains and more stable, hygienic, humus-rich compost, beneficial for crops and recycling of soil organic matter is ultimately formed (Sequi, 1996).

During composting, organic matter is acted upon in two phases namely, (i) degradation and (ii) maturation. The first phase of degradation starts with breakdown of easily degradable organics like sugars, amino and organic acids. The aerobic microorganisms consume oxygen and release CO_2 and energy. The first thermophilic phase is dominated by high temperature, high pH and humidity, essential for activating the microorganisms and proceeds for several weeks to months (Aladjadjiyan, 1992). During this phase, it is also ensured that the substrate is properly cooled with sufficient supply of oxygen (Beck-Friis et al., 2000). The second phase continues for a few weeks, with the breakdown of more complex organic molecules followed by a decrease in the microbial population. There is a change from thermophilic to mesophilic phase with a decrease in temperature to 40–45 ^{o}C (Maynard, 2000; Wu et al., 2000). Further at the final stage, temperature declines to an ambient value and the system becomes biologically less active. Finally, a dark brown to black colour soil-like material is produced. This soil-like material also exhibits an increased humus content and decreased C:N ratio with a neutralized pH (Misra et al., 2003). Aerobic composting is affected by many factors, such as the amount of oxygen, moisture content, nutrient supply, temperature, pH and lignin content. The nutrient supply or C:N ratio should be optimum in the range of 20:1 to 40:1 for proper growth of microorganisms. Temperature plays a vital role during composting as higher temperature in the thermophilic range contributes to the destruction of the pathogens and disinfects the organic matter (Sonesson et al., 2000). Eventually, the biomass is transformed into material rich in nutrients, which can improve the structural characteristics of the soil (Sommer and Dahl, 1999). The aerobic process also involves a release of a large quantum of energy (Dumontet et al., 1999; Schaik et al., 2000).

Pratap Singh and Prabha (2017) performed an experimental and observational bio-composting study in Uttar Pradesh. Wheat straw, rice straw, vegetable crops, leaves of garden plants constituted the total weight of the biomass for this study. The final bio-compost contained 45% of total solids, 26.7% organic matter, 15.3% C and 1.36% total N, treating it to be a rich compost of carbon and organic matter. They found a significant increase in the agronomic properties of the rice and wheat crops studied by them. Nutrients like N and P provided to the crops by the bio-compost were significantly important in the crop production strategy (Brady and Weil, 1996).

Addition of compost also increases the microbial population and native microflora and fauna necessary for the soil health (Nielsen and Angelidaki, 2008; Wall et al., 2015). Pratap Singh and Prabha (2017) reported that that a one-inch thick bio-compost layer added approximately 1.0 t of total N and 24 t of organic carbon in the soil besides adding significant quantities of nutrients such as P, K, Ca, Mg, S, Fe, Zn, etc.

Production of Biochar

As a measure for controlling GHG emissions, agricultural research community has been constantly looking for ways to effectively enhance natural rates of carbon sequestration in the soil. This has increasingly interested the scientists in applying charcoal, black carbon and biochar as a soil amendment to stabilize the SOC content. These techniques are viewed as a viable option to mitigate GHG emissions while considerably reducing the volume of agricultural waste. The process of carbon sequestration essentially requires increased residence time and resistance to chemical oxidation of biomass to CO_2 or reduction to CH_4, which leads to a reduction of CO_2 or CH_4 release to the atmosphere (Srinivasarao et al., 2013). The partially burnt products are pyrogenic carbon/carbon black and become a long-term carbon sink with a very slow chemical transformation, ideal for soil amendment (Izaurralde et al., 2001; McHenry, 2009). Biochar is a fine-grained carbon-rich porous product obtained from the thermochemical conversion called the pyrolysis at low temperatures in an oxygen-free environment (Amonette and Joseph, 2009). It is a mix of C, H, N, O, S and ash in different proportions (Masek, 2009). When added to the soil, the highly porous nature of the biochar helps in improved water retention and increased soil surface area. It mainly interacts with the soil matrix, soil microbes, and plant roots (Lehmann and Joseph, 2009), helps in nutrient retention, and sets off a wide range of biogeochemical processes. Many researchers have reported an increase in pH with its usage (Tryon, 1948; Gaunt and Cowie, 2009).

Specically, biochar is used in various applications such as the water treatment, construction industry, food industry, cosmetic industry, metallurgy, treatment of wastewater and many other chemical applications. In India, currently use of biochar application is limited and mainly seen in villages and small towns. Based on its wide applicability, promotion of biochar production and usage seems to be a better proposition in India

In-situ *Management with Mechanical Intensification*

In-situ application of the crop residue is a natural process adopted by many farmers. This method also imparts certain benefits to the soil. There are two ways of conducting field applications, but both these methods involve leaving crop residue on the farmland after harvesting. How these two methods differ is based on what happens with tillage in the next season. In the first method, planting in the next season is carried out without tillage or with less tillage and in the other method, crop residue is incorporated into the soil by mechanical means during tillage operations (Marjanovic, 2018). While *in-situ* management of crop residues can offer long-term cost savings on equipment and labour, both methods need special (new) equipment, *e.g*., machinery for crop residue incorporation into soils or no-till seeing the equipment. Crop residue retention with no-tillage is mostly practiced in North America and about 40% of the cropland across the United States alone is cultivated with no-till practice (Marjanovic, 2018). This method has many advantages for the soil such as cooling effect, increased moisture, source of carbon, and erosion protection. However, this method also finds some negative implications namely, microbial infestation, the formation of phytotoxins and nutrient immobilization. This results in a reduced yield which may warrant additional use of agricultural chemicals (Marjanovic, 2018; Yadvinder-Singh and Sidhu, 2014). For improving the soil organic matter, crop residue is incorporated into the soil by ploughing. Adding nitrogen fertilizers while ploughing at a depth of 20–30 cm can enrich the soil with humus and prevent nitrogen depression (Marjanovic, 2018). The National Policy for Management of Crop Residue specically mentions *in-situ* management through methods such as direct incorporation into soils and mulching as methods that should be promoted in India not only to control crop residue burning but also to prevent environmental degradation in the croplands. Any specific follow-ups or Government-supported interventions have not yet been reported in the literature since the establishment of this national policy. However, it is worth noting that the National Conference on Agriculture for *kharif* campaign that took place in 2017, re-emphasized on the same facts and listed mechanization practices to avoid crop residue burning among the recommendations made by the focus groups (DACFW, 2018).

Conclusions

In India, huge amounts of crop residues are generated every year but their management is very poor and largely unsustainable. Crop residue as a vital source of plant nutrients can be a boon for sustainable agriculture in the country. Residue burning is a very critical issue where we are deprived of important resource and polluting the environment. The residue burning causes losses of nutrients, emission of harmful greenhouse gases and aerosol, and negatively affects the soil properties. However, the main reasons for crop residue burning are the narrow window availability between the sowing of sequential crop and harvesting of the previous crop. The residue recycling in agroecosystem could be helpful in protecting soils against erosion and improving water retention, enhancing SOM and recycling nutrients. It works on the principle of takeaway whatever you want and give back to the soil the rest for sustainability. Technologies available to manage crop residues are mushroom cultivation, composting, production of biochar, production of non-woven composites, and *in-situ* management with mechanical intensification using conservation agriculture-based crop management practices. Considering large scale residues production in Indo-Gangetic Plains, *in-situ* management is the more sustainable and practical solution for the residue recycling in the agro-ecosystem.

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