In-situ paddy straw management practices for higher resource use efficiency and crop productivity in Indo-Gangetic Plains (IGP) of India

Ankur Chaudhary¹, Rajender Singh Chhokar²*, Dharam Bir Yadav¹, Vinay Kumar Sindhu³, Hari Ram³, Sandeep Rawal⁴, Rajbir Singh Khedwal³, Ramesh Kumar Sharma³ and Subhash Chander Gill²
¹CCS Haryana Agricultural University (HAU), Regional Research Station, Uchani (Karnal) -132 001
²ICAR-Indian Institute of Wheat and Barley Research, Karnal -132 001
³Punjab Agricultural University, Ludhiana -141 004
⁴CCS Haryana Agricultural University (HAU), Krishi Vigyan Kendra, Yamunanagar - 135 001

Article history
Received: 01 Dec., 2019
Revised: 15 Dec., 2019
Accepted: 31 Dec., 2019

Abstract
The large scale adoption of long duration coarse grain rice varieties and combine harvesting have increased the incidences of in-situ rice residue burning in Indo-Gangetic Plains (IGP). Crop residue burning in addition to causing environmental pollution, is also responsible for loss of precious nutrients (complete nitrogen, about one fourth of phosphorus & potash and about three fourth of sulphur) and efficacy of soil active herbicides. The alternatives to rice residue burning are its removal, incorporation or retention. The in-situ management options are better and further, retention is more advantageous than incorporation in term of energy, time and cost effectiveness. In addition, the surface retention has a series of positive effects, such as, moisture conservation, weed suppression, temperature moderation, and improved soil health. Residue management practices (surface retention or incorporation) also influence the nutrient availability, crop water requirement, weed dynamics, herbicide efficacy, insect-pest infestation and mitigation of climate change effect on long term basis. Hence, the agronomic practices need to be adjusted to prevent temporal nitrogen immobilization, hindrance in precise seeding, weed flora shift, and new insect-pest incidents. Suitable machineries for seeding and harvesting are of paramount importance for proper crop establishment under in-situ residue management practices. Combines fitted with straw management system for uniform spread of straw help in efficient running of conservation agriculture (CA) seeding machines like Turbo Happy Seeder and Rotary Disc Drill. Moreover, for smooth running of CA machinery, the height of anchored straw should be kept as much as possible, so that lesser loose straw is present. The adoption of CA practices (no-tillage and residue retention) in wheat under rice-wheat system can help in improving wheat yield by advanced sowing and reduced problem of Phalaris minor Retz. Moreover, fertilizer application method and timing needs to be fine tuned under in-situ residue management options. The nitrogen top dressing should be done just before irrigation to avoid interception by surface retained residue which can enhance volatilization and immobilization losses of nitrogen. Higher efficacy of pre-emergence herbicides in surface retained residue scenario could also be realized by increasing the spray volume along with modifying the application time and placement of herbicides. Therefore, a paradigm shift in agronomic practices, with respect to paddy straw management, is required for enhancing system productivity and resource use efficiency.

Keywords: Conservation agriculture, herbicide efficacy, nitrogen top dressing, pest dynamics, residue burning, residue retention, rotary disc drill, turbo happy seeder
1. Introduction

The rice-wheat rotation is the most prevalent cropping system of Indo-Gangetic Plains (IGP) covering an area of 13.5 million hectares (m ha) of which about 10 m ha lies in India (Gupta et al., 2004; Gupta and Sayre, 2007). In this cropping system, farmers in north-western IGP (Punjab, Haryana and western Uttar Pradesh) are facing critical emerging issues of recurring nature such as declining factor productivity, evolution of herbicide resistance in wheat associated weeds, shifting of weed flora, and accelerated resource base degradation such as depletion of quality ground water and inherent nutrient soil pool (Ladha et al., 2003; Gupta and Sayre, 2007; Humphreys et al., 2010; Chauhan et al., 2012; Chhokar et al., 2018a). The situation becomes more severe due to burgeoning population, demographic transition and unabated land degradation that are halting sustainable crop productivity and food security at national scale. Also, the system productivity and sustainability is likely to suffer due to stress associated with spatial/temporal drought and heat incidence under climate change scenario. However, this cereal-cereal mono-cropping rice-wheat system is extensively practiced due to numerous benefits associated with it. The benefits are in the form of irrigation facilities at nominal electricity charges, assured procurement at minimum support price, availability of short statured fertilizers and irrigation responsive high yielding varieties along with crop tailored mechanization involving efficient seeders/seed drill/transplanter and combine harvester. That’s why farmers do not opt for other diversification components such as maize and/or pigeon pea. They even hesitate to shift to labour saving technology of direct seeded rice due to timely managed resource driven higher yields associated with puddle transplanted rice (Yadav et al., 2009; Kumar and Ladha, 2011). In paddy based cropping systems, management of paddy straw (6-8 t ha$^{-1}$) in fields is a serious problem (Yadvinder-Singh et al., 2010; Chauhan et al., 2012) and farmers generally follow the legally banned practice of burning paddy straw in their fields after combine harvesting. In quantitative terms, about 80% of rice straw produced is being burnt annually in just 3 to 4 weeks during October-November in between the rice harvest and wheat sowing. The problem is more severe in irrigated agriculture, particularly in mechanized rice-wheat system of north-western India, where combine harvesters are used for the coarse type of rice varieties. This detrimental process has gained momentum in recent years due to scarcity and costly labour availability to remove straw. Also, collection, transportation, handling and storage are the main problems associated with the removal of paddy straw from the field (Sehgal et al., 1999). Moreover, paddy straw in its natural form is also not a popular animal feed, due to its low digestibility, poor palatability, low protein (2-7%) and high silica content that makes it nutritionally inert in nature with abrasiveness in gastrointestinal tract of the cattle (Arora and Sehgal, 1999). The high silica (12-16%) and lignin content (6-7%) of rice residue with wide C:N ratio (80:1), slows down the in-situ decomposition process and leads to nitrogen immobilization under incorporation situations (Bacon, 1990; Janssen, 1996; Yadvinder-Singh et al., 2005).

According to farmers’ perspective, burning provides easy solution due to the unavailability of cheaper suitable machinery to handle huge amount of loose straw, which hinders sowing operation, consequently poor crop stand. Furthermore, incorporation/retention of paddy straw also leads to transitory or temporal yellowing in wheat due to higher immobilization of applied and available nitrogen. Thus farmers are applying higher dose of nitrogen (urea) in residue retained situations to obtain desirable wheat canopy cover comparable to that in conventional field where straw is either removed or burnt. Surface retained straw also ensures undisturbed habitat for rodent breeding and their subsequent damage to crop, while, burning followed by field preparation destroys their habitat and restricts further proliferation besides killing the insect-pest and diseases causing organisms. Burning of straw impart pseudo benefits in the form of timely sowing of succeeding crop, unrestricted wheat emergence with lower rodents and termite infestation, besides, reducing labour and cost associated with the collection and transportation of paddy straw for removal.

1. Crop residue burning status and impact

India produces about 686 mt crop residues annually out of which cereals contribute 368 mt residues. About 234 mt (34% of gross) of crop residues are estimated as surplus that is available in India for variable management options (Hiloidhari et al., 2014). Across different states, residues of rice, wheat, maize, millet, cotton, sugarcane, jute, groundnut and rapeseed-mustard are normally burnt on-farm. Among different crops, major contribution to burnt residue is from rice (40%), wheat (21%) and sugarcane (19%). Regarding states, maximum amount of crop residues were burnt in Uttar Pradesh (22.25 mt), Punjab (21.32), Haryana (9.18 mt) and Maharashtra (6.82 mt) while, the highest amount of cereal crop residues (Fig. 1) are burnt in Punjab followed by Uttar Pradesh and Haryana (Jain et al., 2014). Sahai et al. (2011) estimated that the total dry crop residue generated in India during 1994, 2005 and 2010 was about 217, 239 and 253 Teragram (Tg), respectively, of which 45, 60 and 63 Tg dry crop biomass was burnt during the respective years. Rice and wheat together constituted about 76% of this open field burning. In terms of greenhouse gases (GHGs),
the burning of this dry biomass emitted about 22.4, 24.4 and 26.1 Tg of carbon; 0.30, 0.33 and 0.35 Tg of nitrogen; 4.18, 4.59 and 4.86 Tg carbon dioxide, 2951, 3,240 and 3,431 Gigagram (Gg) of CO; and 120.8, 132.9 and 140.6 Gg NOx during 1994, 2005 and 2010, respectively (Sahai et al., 2011). Ravindra et al., (2018) estimated that about 116 mt crop residue was burnt in India during 2017, which emitted PM\textsubscript{10} (812 Gg), PM\textsubscript{2.5} (824 Gg), elemental carbon (58 Gg), OC (239 Gg) and GHGs (211Tg). The emissions of SO\textsubscript{2}, CO, NO\textsubscript{x}, and NH\textsubscript{4} were estimated to be 25, 6617, 209 and 218 Gg, respectively during 2003-04, which increased to 32, 8511, 268 and 281 Gg, respectively during 2016-17. 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 beneficial microorganisms bio-activity for cycling of nutrient and other vital ecosystem processes, adversely affected the soil physical, chemical and biological properties besides leading to serious environmental issues (Dobermann and Fairhurst, 2002; Yadvinder-Singh et al., 2005; Bijay-Singh et al., 2008; Chauhan et al., 2012; Jain et al., 2014). Burning has led to significant reduction in microbial population of bacteria, fungi, actinomycetes along with phosphate/potassium solubilizing microbes and cellulose degraders. Microbial population and enzymatic activities involved in recycling of biomass failed to recover even after two months which would have reduced the potential productivity of microbial driven processes over a period of continuous burning of both in rice and wheat (Kumar et al., 2019a).

Rice vegetative parts at maturity contain about 40, 30-35, 80-85 and 40-50% of nitrogen, phosphorous, potassium and sulphur, respectively (Dobermann and Fairhurst, 2002). Each ton of paddy straw contains approximately 5.5 kg N, 2.3 kg P\textsubscript{2}O\textsubscript{5}, 15-20 kg K\textsubscript{2}O, 1.2 kg S, 3-4 kg Ca, 1-3 kg Mg and 40-70 kg Si. Paddy straw also contains micronutrients such as Zn (96 g ha\textsuperscript{-1}), Fe (777 g ha\textsuperscript{-1}), Mn (745 g ha\textsuperscript{-1}), Cu (42 g ha\textsuperscript{-1}), B (55 g ha\textsuperscript{-1}) and Mo (4 g ha\textsuperscript{-1}) as well as 400 kg of carbon, which are lost due to burning leading to huge amount of plant nutrient losses (Dobermann and Witt, 2000; Verma and Bhagat, 1992; Throat et al., 2015). Straw/residue burning responsible for loss of precious nutrients almost all nitrogen, about one fourth of phosphorus and potash, and about 60-80% of sulphur (Dobermann and Fairhurst, 2002; Sharma and Mishra, 2001). Burning of rice and wheat stubbles resulted in the emission of 11.0 \times 10\textsuperscript{6} kg methane, 23.1 \times 10\textsuperscript{9} kg carbon monoxide, 2 \times 10\textsuperscript{9} kg nitrous oxide and 84 \times 10\textsuperscript{6} kg nitric oxide in India (Gupta et al., 2004). Burning leads to emission of greenhouse gases and is responsible both for global warming and global dimming. As upon burning, about 70, 7 and 0.66 percent of carbon present in rice straw is emitted as carbon dioxide, carbon monoxide and methane, respectively, while 2.09% of nitrogen as nitrous oxide (Samara et al., 2003). While, the same amount of straw on burning releases 60 kg CO, 1460 kg CO\textsubscript{2}, 2 kg SO\textsubscript{2}, 199 kg ash and about 3 kg particulate matter (Jenkins and Bhatnagar, 1991). In a similar way, theremoval of crop straw from fields resulted in negative nutrient balance or nutrient (potassium) mining as about 80-85% of potassium absorbed by rice and wheat remains in their straw (Bijay-Singh et al., 2008). Besides other light hydrocarbons, volatile and semi-volatile organic compounds including polycyclic aromatic hydrocarbons and polychlorinated biphenyls are also emitted. These gases are of major concern for their global impact and may lead to increase in the levels of aerosols, acid deposition and elevated in tropospheric ozone. Emissions from the crop residues alter radiation balance, impacts cloud microphysics and atmospheric chemistry near to earth atmosphere, which may potentially affect biochemical cycles (McNeill et al., 2017). Extensive burning leads to serious environmental implications due to deterioration of air quality associated with levels of aerosols with suspected carcinogens, release of smoke and resulting in aggravation of chronic eye, skin, heart and lung diseases (Jain et al., 2014). In a study, average concentrations of fine particulate matter (PM\textsubscript{2.5}) measured in New Delhi, India, were 127.15 μg m\textsuperscript{-3} ± 95.23 μg m\textsuperscript{-3} that exceeded national standard of 60 μg m\textsuperscript{-3} approximately by 75%. The rise was suspected to be associated with the burning of paddy straw in the IGP but actually may be mainly due to exponential growth of vehicular traffic, small scale industries without environmental safety practices and unabated construction activities in the national capital. However, emissions of reactive nitrogen from wheat residue burning were lower than from paddy straw burning due to more favorable meteorological conditions for smoke dispersal and less quantity of wheat biomass (Bray et al., 2019).

2. Options for paddy straw management and their impact evaluation

Basmati (fine rice) varieties have higher competitive uses especially for feeding to milch animals and therefore fetch good price, but the coarse paddy varieties which are generally harvested with combines are not preferred for animal feeding due to higher silica content. Consequently, paddy straw is usually burnt on-farm for preparing fine seed bed for succeeding crops (wheat and potato). Farmers also burn the remaining wheat stubbles even after running reaper/chopper for Bhassa (hay) making in wheat. As an alternative to paddy straw burning in north-western India, incorporation of straw 15-20 days before wheat sowing has been advocated (Yadwinder-Singh et al.,
have described optimization of crop residues management of paddy straw, clogging of tyne and accumulation of loose straw in drill furrow synchronism of partial burning of paddy straw, clogging frequent lifting of drill under heavy straw load. The and depth of seed placement was non-uniform due to which seed metering drive wheel traction was restricted was a challenge as the loose straw accumulated and was dragged along with the seed drill furrow openers due to which seed metering drive wheel traction was restricted. The and depth of seed placement was non-uniform due to frequent lifting of drill under heavy straw load. The synchronism of partial burning of paddy straw, clogging of tyne and accumulation of loose straw in drill furrow

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

2005, Bijay-Singh et al., 2008). For straw incorporation and seed bed preparation for wheat sowing, multiple tillage operations (2-3 times harrow/power tiller, or rotavator and planker) are required resulting in higher cost of cultivation and delay the wheat sowing.

Area under zero till wheat after partial burning of paddy straw, hiked at significant level during late 1990s due to huge cost savings from reductions in fuel and labour usage along with yield improvement associated with timely sowing (Gupta and Sayre, 2007). Earlier, reports advocated several benefits of zero till sowing with or without residue such as savings on account to labour, time, drudgery and energy requirement (Sharma et al., 2005; Gupta and Sayre, 2007) leading to decreased production cost by excluding preparatory tillage (Malik et al., 2005). The other benefits of zero tillage (ZT) could be enhanced soil quality and carbon sequestration by preventing soil erosion, leaching and runoff of nutrients and boosted soil microbial associated enzymatic activity, restricted infestation of weeds by accelerating weed seed predation and seed bank loss associated with more germination from upper soil layers, reduced termite incidence, increased water and nutrient-use efficiencies by preventing unnecessary soil water evaporation, nutrient losses and advance sowing time (Kumar et al., 2013; Sharma et al., 2004; Sharma et al., 2005; Gupta and Sayre, 2007; Hobbs et al., 2008; Balwinder-Singh et al., 2011a,b). However, due to presence of loose paddy straw in narrow swath in combine harvested field, direct seeding of wheat was a challenge as the loose straw accumulated and dragged along with the seed drill furrow openers due to which seed metering drive wheel traction was restricted and depth of seed placement was non-uniform due to frequent lifting of drill under heavy straw load. The synchronism of partial burning of paddy straw, clogging of tyne and accumulation of loose straw in drill furrow opener has been considerably overcome by the recent developments of machinery like Turbo Happy Seeder (THS) (Sidhu et al., 2007) and Rotary Disc Drill (RDD). These machines facilitate simultaneously surface mulching of rice residue and direct no till sowing of wheat in a single operational pass. The results from 154 on-farm research trials have shown that THS based sowing under rice residue increased weighted average wheat yield by about 3.24% than conventional till sowing during 2007-10 (Sidhu et al., 2011). Use of ZT in combination with crop residues retention in soil increased productivity of rice-wheat system with positive nutrient balance and improved soil quality in terms of decreased bulk density, soil pH, enhanced available P, O (5.8%), exchangeable K, O (7.8%), and soil OM (1.5%) under intensive rice-wheat cropping system (Sah et al., 2014). Similarly, incorporation of crop residues resulted in improved soil quality in terms of enhanced soil organic carbon, hydraulic conductivity, infiltration rate, water holding and cation exchange capacity, enzymatic activities along with improved aggregate stability. However, there was huge difference in crop yields under conservation agriculture (CA) based systems, which were most likely due to variation in regional climate and crops. One meta-analysis has showed that adoption of CA based practices increased crop yield by 6.4 and 5.5% in Northwest and South China, respectively as compared to conventional tillage scenario, while no such effect was observed in North and Northeast China. In relation to specific crop, CA based practices positively influenced maize (7.5%) and rice productivity (4.1%) but lowered that in case of wheat (2.9%) (Zheng et al., 2014). Ranaivoson et al. (2017) have described optimization of crop residues management under CA for sustainable agro-ecological functions in a meta-analysis study, it was found that about 8 t ha of crop residues were needed to reduce soil evaporation by 30% as compared to no-till bare soil where as to attain maximum soil water infiltration with negligible water runoff and soil loss, at least 2 t ha of crop residues were required. At least 4 to 5 t ha of crop residues were required to enhance soil organic carbon with an annual gain rate of 0.38 t C ha year. While, to reduce weed emergence and biomass by 50% compared to a no-till bare soil, residue amounts of 2 t ha or more were required. So there is a need to optimize the crop residue under CA system considering the nature of crop to be grown, regional climatic variation, soil factors and presence of weeds. Numerous reports have shown greater system productivity and sustainability of zero-till sown wheat with in-situ management of paddy straw as compared to conventional practices (Table 3). However, higher cost of THS (Rs 1.25 lakh), paddy straw chopper (Rs 2.80 lakh), paddy mulcher (Rs 1.70 lakh), hydraulic
reversible M.B. plough (Rs 1.8 lakh), baler (up to Rs 10 lakh) and other machinery for straw management limits their extensive use. In addition to it, tractor cost (for 50 HP Rs. 6-7 lakh) on or hiring basis costing of Rs. 1200-1500/acre for single operation, further limits the large scale adoption of these technologies.

To help farmers of Haryana, Punjab, Uttar Pradesh and Delhi, government of India (GOI) took initiatives through implementing a central sector special scheme of providing subsidized agricultural machinery for in-situ management of paddy straw and to address the problem of air pollution associated with intensive crop residue burning. Under this scheme, budget of Rs. 1151.80 crore (Rs. 591.65 crore in 2018-19 and Rs. 560.15 crore in 2019-20) has been allocated to address the issue of stubble burning and resulting air pollution. This monetarily support is being provided to form farm machinery banks or custom hiring centres for promotion of in-situ crop residue management and to overcome the constraints like higher cost of machinery and its availability even to small landholding farmers. Besides, this scheme also deals with creating awareness among stakeholders through demonstration, capacity building activities, information dissemination, education and communication strategies for effective utilization and management of crop residues. The scheme provides subsidy on crop residue management machinery to individual farmers (50%) and to cooperative societies (80%). The preliminary results have revealed astonishing success in elevating the gravity of on farm paddy straw burning. According to the latest report based on satellite data, events of in-situ paddy straw burning have reduced remarkably in Haryana, Punjab and Uttar Pradesh by 29.5, 24.5 and 11.0%, respectively as compared to burning events in Haryana, Punjab and Uttar Pradesh by 29.5, 24.5 and 11.0%, respectively as compared to burning events in the year 2017 (Press Information Bureau, GOI dated 02/01/2019).

Various options promoted for in-situ crop residue management (Table 4) would invariably influence the growth of succeeding crop along with nutrient, water and weed dynamics. These management practices differ in the intensity of tillage operations, amount of straw and methodsof managements such as incorporation of residues with reversible plough and/or rotavator, retention of full residue with chopper or mulcher, standing anchored stubbles with loose straw or in the case of SMS based combine harvesting system followed by sowing with THS or standing stubbles without loose straw as with zero till drill based sowing. These practices over the years may affect nitrogen mineralization, seed germination, insect-pest dynamics and subsequently, the growth and productivity of the succeeding crop. The crops under CA scenario are likely to suffer from system generated problems like aggravated herbicides resistance in weeds due to heavy reliance on post-emergence herbicides, nutrient imbalance, increased acidification in the upper soil surface (Obour et al., 2017), organic matter stratification (Deubel et al., 2011) and increase in soil surface bulk density. There is a big knowledge gap regarding effect of various in-situ paddy straw management options on succeeding crops due to shift in cultivation practice from multiple and frequent tillage to reduced and/or ZT with addition of paddy straw. Addition of 6-7 t ha$^{-1}$ of paddy straw whether retained on soil surface (SMS+HS; Chopper; Mulcher) or incorporated (reversible plough and/or rotavator) is likely to influence the agronomic requirements of the succeeding crops such as sowing time, tillage, amount and time of nutrient application and irrigation scheduling.

Seeding machineries (THS, spatial drill and rotary disc drill) are available for the direct seeding of wheat under full paddy straw load but for the potato and other vegetable growers, an economical feasible option is still lacking for effective planting and desirable establishment of vegetable succeeding the paddy. For in-situ management of huge amount of paddy straw, farmers have no options but to perform multiple tillage operations starting from straw chopping using mulcher, followed by soil inversion using MB plough, preparatory tillage using rotavator and finally seed bed preparation using bed planter. These extra operations not only increase the cost of cultivation but also delay the sowing of next crop. Many a times, additional irrigations are required to facilitate these tillage operations. Moreover, due to the problem of incorporated straw dragging along with tynes, farmers instead of drilling go for broadcast seeding, which has lower yield and input use efficiency.

3. Agronomic practices in relation to straw management

In recent time, developments in machinery like THS, ZT drill and RDD for sowing of wheat under residue load especially in rice-wheat system has become more frequent. Residue of previous crop used as mulch on soil surface influences thermal, nutrient water and weed dynamics. So, there is a need to evaluate the sowing time, irrigation scheduling (Balwinder-Singh et al., 2016), nutrient requirement (Yadvinder-Singh et al., 2010), weed infestation and herbicides efficacy (Sindhu et al., 2017; Chhokar et al., 2018a) of a mulched crop.

3.1. Time of sowing and flowering

Sowing time is a non-monetary input having major dividends and to get the potential yield of any crop timely planting is most critical. Sowing of wheat generally gets delayed in north-western India, when following long duration fine/basmati rice or combine harvested coarse paddy. As combine harvesting is generally followed by cutting/chopping and spreading...
of paddy straw using stubble shavers, In-situ straw burning or incorporation and heavy pre-sowing irrigation. The heavy pre-sowing irrigation, particularly in tilled field delays sowing depending on soil types and prevailing weather conditions. The delayed transplanting of basmati (scented) type rice cultivars is preferred for better quality and thus market price, which eventually delays wheat sowing. Under such circumstances, farmers have to utilize the residual soil moisture by direct drilling the wheat using with no-till machines either in the presence or absence of rice residues.

Delay in wheat sowing beyond mid-late November decreased grain yield by 15.5, 32.0, 27.6, 32.9 and 26.8 kg ha⁻¹ day⁻¹ under Northern Hill Zone, North Western Plains Zone, North Eastern Plains Zone, Central Zone and Peninsular Zone, respectively with corresponding yield losses of 7.6, 18.5, 17.7, 17.0 and 15.5% for timely sown conditions (Tripathi et al., 2005). However, with development of CA machineries (THS, RDD, SMS based combine harvester) and short duration paddy varieties, it has become feasible to avoid the straw burning, sow wheat under heavy residue load much earlier than the conventional practice. Wheat sown in late October with full paddy straw as mulch exhibited more vegetative biomass at anthesis due to longer vegetative phase (Fig. 2) as well as longer grain filling period (Balwinder-Singh et al., 2011b; Balwinder-Singh et al., 2016). When wheat sowing was done mid-November onwards, reduction in grain weight was more under mulch conditions as compared to without mulch. It was associated with exposure to higher temperature (1.1 ºC higher in mulched than non-mulched crops) during the grain filling duration that accelerated grain filling rate and curtail grain filling duration as well as promoted senescence due to decline in leaf photosynthetic activities (Al-Khatib and Paulsen, 1984). Contrary, Balwinder-Singh et al. (2016) based on Agricultural Production Systems Simulator (APSIM) model simulation study have reported that reduction in wheat yield under full paddy straw retention was comparatively lower (20% of years) for 31st October sowing than 30th November (90% of years) sowing. Optimum sowing window for wheat under mulch scenario was the first week of November for sandy loam soils while it was second week of November for clay loam with irrigation scheduling at 50% soil water deficit (SWD). As the sowing was delayed from 15 October, the heat stress days (no. of days with maximum temperature >34ºC) increased under mulch conditions and proportionately the probability of exposure as compared to without mulch (Fig. 3). Zero tillage with retention of rice residue as mulch mitigated the effect of terminal heat stress owing to lowering of canopy temperature and the same was reflected in wheat yield as about 10% higher yield was recorded under mulch as compared to conventional tillage without residue as mulch (Gathala et al., 2011b). The residue retention in ZT keeps canopy temperatures lower by 1-1.5 ºC during grain filling stage (canopy cooling due to transpiration) owing to sustained soil moisture availability to the plants (Gupta et al., 2010). Jat et al. (2009) have also reported that ZT helped in timely sowing and reduced terminal heat stress associated yield loss as compared to CT even under late planting (after 21 November till 20 December) from 77 to 65 kg ha⁻¹day⁻¹. Conversely, Balwinder-Singh et al. (2016) reported that probability of heat stress in wheat increased with delay in sowing and more under mulch conditions. Chen et al. (2007) reported the reduction in maximum soil temperature and increase in minimum soil temperature due to straw retention in wheat. The spring wheat development also delayed by 7 days and consequently the grain yield was reduced by 7% compared to without straw retention scenario. However, it leads to reduction in soil evaporation by 21% under 3 t ha⁻¹ mulch and 40% under 6 t ha⁻¹ compared with no mulch. Lowering of soil temperatures due to straw mulch froze the winter wheat seedlings and roots in the cool winter months and negatively influenced the germination, emergence and tiller formation (Gao et al., 2009; Xue et al., 2017). Retention of paddy straw as surface mulch in wheat reduced mean daily temperature by about 1.6 ºC during first 15 days after sowing and that may provide opportunity for its sowing earlier without yield reduction as it generally happened in early sown wheat under conventional conditions (Timsina et al., 2008). However, initial yellowing of upper leaves in wheat was observed in mulch as compared to non-mulch associated with dropping of soil temperature (minimum) during the frosty period in the late January due to insulating effect of mulch (Balwinder-Singh et al., 2011b; Vidal and Bauman, 1996). The reduced temperature during frost duration under mulch may diminish availability and/or uptake of soil nitrogen. In temperate regions or seasons with low temperature, straw retention may also leads to poor crop germination and delayed emergence by reducing soil temperature or increasing soil moisture, resulting in reduction in winter yield (Boomsma et al., 2010; Drury et al., 1999). Liu et al. (2017) have reported that under mulching, number of spikes and the 1000-grain weight of wheat reduced by 22.9 and 3.8%, respectively, compared to no mulching leading to 6.7% reduction in grain yield. This was due to comparatively lower temperature at jointing and milking stages under mulch condition and allelopathy associated with mulch residue which affected the wheat yield. Fortunately, these conditions are not prevalent in north-western Indo-Gangetic plains. However, further investigations are required to optimize sowing time.
In-situ paddy straw management practices

3.2. Irrigation scheduling

Based on APSIM model simulation study, Balwinder-Singh et al., 2016 reported that in wheat sown on November 7 under mulch condition with irrigation at 50% SWD, one irrigation of about 50 mm in sandy loam and 60 mm on clay loam soils could be omitted in nearly 50% of years due to reduction in soil evaporation, while it was negligible in case of October sown wheat. In mulch conditions, an irrigation (approximately 55 mm) could be skipped for 7, 15, 23 and 30 November sown wheat in 25, 40, 45 and 60% of the years, respectively. While in October sown wheat, reduction in number of irrigation under mulch was estimated in less than 20% of years due to longer duration of crop maturity, rather it may require an additional irrigation. Balwinder-Singh et al. (2011a) found 35 and 40 mm lower total soil evaporation in relatively high and low rainfall years, respectively during the crop growth season (Fig. 4). Several studies have reported higher biomass production and grain yield under mulched conditions (Table 3). Ram et al. (2013) reported that under limited irrigation condition, rice straw mulching (6 t ha⁻¹) increased water use efficiency by 34% as compared to without mulch scenario in wheat besides increasing the grain yield. Sidhu et al. (2019) reported that combination of sub-surface drip irrigation and CA practices in rice-wheat system saved irrigation water, increased water productivity and N use efficiency. Irrigation water savings in rice and wheat were 48-53 and 42-53%, respectively under this combination as compared to conventional flood irrigation system. In a similar study, sub-surface drip saved irrigation water of about 58% as compared to conventional rice-wheat cultivation practices (Jat et al., 2019). Hence, there is need to adopt proactive (nutrient efficient and irrigation tailored) CA system in whole rice-wheat crop rotation.

Moreover, transplanting of paddy should be scheduled in such a manner that after SMS based combine harvesting, sowing of wheat can be performed under residual moisture with ZT drill/THS.

3.3. Optimizing nutrient dose and scheduling

Under no-till conditions, fertilizers are left on the soil surface rather than mixed into the sub-surface soil at the time of sowing. As a result, most of the applied fertilizer is directly exposed to air and sunlight, which may result in an increased loss of nutrients (Rahman et al., 2005). Straw retention may impair crop growth due to nutrient immobilization by soil microbes and may increase incidences of residue-borne diseases (Kaschuk et al., 2010; Duan et al., 2010). Soil surface retained rice straw increases the possibilities of immobilization of surface applied nitrogen (Janssen, 1996; Beri et al., 1995). The surface mulch also promotes ammonia volatilization losses upon broadcasting of granular fertilizers (Bacon et al., 1986). However, fertilizer nitrogen was found more effective in no-tillage when the straw is retained rather than removed (Bhagat and Verma, 1991; Rahman et al., 2005). Straw mulching may reduce nutrient loss.
especially volatilization of N fertilizer and thereby increase nitrogen use efficiency. Nitrogen use efficiency depends on the methods of nitrogen fertilization, soil types and management practices (Yadwinder-Singh et al., 2005; Bijay-Singh et al., 2008). The N in the straw is also available to the microbial population, and after an initial equilibration period that may last up to 3 years following rice straw incorporation (Bacon, 1990), plant available N supply in the soil tends to increase. Rice straw is mainly composed of hemicellulose, cellulose and lignin. Decomposition rate was found the lowest for lignin, highest for hemicellulose, while, whole straw decomposition dynamics followed “first fast and then slow” trend (Ferreira et al., 2016; Yan et al., 2019). The incorporation of paddy straw in soil increased microorganisms multiplication rate and caused temporal insufficiency of nitrogen source, fixation of inorganic nitrogen and consequently significantly decreased the nitrogen content in soil solution (Yan et al., 2018). The decomposition of crop residue in field is influenced by various factors, such as temperature, moisture, presence of soil microbes, nutrient availability along with chemical composition and moisture of the residue (Singh and Sidhu, 2014; Nakajima et al., 2016; Yan et al., 2019). Low temperature during winters (6 months) severely inhibited the straw decomposition, whereas high temperature and sufficient rainfall during the summers (May-October) promoted straw decomposition and the decomposition rates differed significantly in different climatic regions (Yan et al., 2019). The rise in temperature associated with straw retention may stimulate decomposition of straw with more nutrient release and alleviate nutrient immobilization due to microbes (Devevre and Horwath, 2000). The effect of straw retention on crop yield varied from region to region and the straw retention in South China increased crop yield compared to conventional tillage, while no significant differences were found in Northeast and North China regions. In a nylon mesh bagging study, the dynamics of rice straw decomposition and nutrient release during five years showed that paddy straw decomposition occurred largely during the first three years of straw return (Yan et al., 2019). The cumulative amount of decomposition reached 77.0% after the first year, thereafter it decreased linearly with time at the rate of 7.8% per year. The major share of phosphorus and potassium was released during the first month, while, nitrogen during the first two months. Yadwinder-Singh et al. (2010) revealed that buried residue losses about 80% of its initial biomass as compared to the surface placed residues with 2.5 times faster decomposition rate at the end of decomposition cycle. The faster decomposition in case of buried residue was associated to its intimate contact with soil matrix along with optimal moisture level, which in turn provided congenial environmental conditions for decomposition. Yadwinder-Singh et al. (2015) recorded optimum N rate of 120 kg N ha$^{-1}$ for ZT wheat drilled into rice residues in sandy loam soil in residue retention conditions. Further, band placement of 20% of the N fertilizer as diammonium phosphate at seeding, and top dressing of the remaining 80% as urea in two equal splits before first and second irrigation resulted in higher nitrogen use efficiency and grain yield. Narang et al. (1999) reported positive balance in soil nitrogen with incorporation of moderate level of rice residue along with application of nitrogen [120 kg ha$^{-1}$] besides improved wheat yield, organic matter content and available phosphorus. Verma and Pandey (2013) advocated applying additional 30% of fertilizer for adopting paddy straw incorporation practice under rice-wheat cropping system. Incorporation of rice-wheat residue enhanced level of soil inorganic and organic phosphorus, reduced the sorption, improved phosphorus use efficiency and substituted about 13 kg ha$^{-1}$ yr$^{-1}$ inorganic phosphorus (Gupta et al., 2007). Numerous other reports have shown positive balance for soil organic carbon, nitrogen, phosphorus, soil-exchangeable potassium, its uptake and NO$_3$ accumulation with in-situ management of residue (incorporation or retention) (Yadwinder-Singh et al., 2004; Gangwar et al., 2006; Gupta et al., 2007). Yadwinder-Singh et al. (2010) concluded that farmers should apply additional 20-40 kg N ha$^{-1}$ over recommended dose after residue incorporation during the initial years as compared to that where straw is removed and also provide adequate time for decomposition of paddy straw before wheat sowing to avoid adverse effects of nitrogen immobilization. Rahman et al. (2005) also reported positive effects of rice straw as mulch in wheat such as soil moisture conservation, reduced weed infestation, improved root weight, root length, higher nitrogen uptake and apparent N recovery. Three year comparative studies on tillage methods (zero, reduced and conventional), paddy straw management systems (burning, removal and incorporation) and nitrogen levels (120 and 150 kg N ha$^{-1}$) have revealed that reduced tillage with in-situ residue incorporation (5 t ha$^{-1}$) and 150 kg N ha$^{-1}$ provided maximum grain yield of wheat in sandy loam soil (Gangwar et al., 2006). Among the paddy straw management systems, lowest soil bulk density was recorded with residue incorporation. Infiltration rate under residue incorporation was found double (1.50 cm h$^{-1}$) than that under zero tillage (0.75 cm h$^{-1}$). Starter dose of 20 kg N ha$^{-1}$ in addition to recommended dose improved grain yield and nutrient uptake in straw amended plots as compared to burning and straw incorporation without an additional N (Misra et al., 1996; Singh and Sharma, 2000). In a similar study, Brar et al. (2000) observed that application of 40
kg N ha\(^{-1}\) during paddy straw incorporation in addition to recommended nitrogen fertilizer dose (120 kg N ha\(^{-1}\)) in two equal splits (at sowing and 3 weeks after sowing) significantly increased grain yield by 7.5\% and nitrogen uptake by 14.8\% as compared to recommended dose. Irrigation at straw incorporation further enhanced straw decomposition and subsequently wheat grain yield as compared to without irrigation. Another study continued for 15 years in rice-wheat cropping system with different rice straw management methods (burning, removal and incorporation) and nitrogen levels (60, 120 and 180 kg N ha\(^{-1}\)) showed contradictory results (Beri et al., 1995). The residue burning and residue removal resulted in 10.7 and 8\% higher grain yield of wheat as compared to residue incorporation (3.72 t ha\(^{-1}\)), while the increase in rice yield was 23.5 and 22\%, respectively, than the residue incorporation (4.51 t ha\(^{-1}\)). Soil and fertilizer nitrogen immobilization and phosphorus adsorption was advocated as the reason for this yield reduction. However, initial nitrogen deficiency may lead to greater nitrogen use efficiency. Tian et al. (2019) showed that postponing the basal nitrogen fertilization period under nitrogen deficiency up to four-leaf stage promoted deeper root growth, effective root distribution and root biomass during the post-jointing period, which might improved the ability of roots to absorb water and nutrients, and consequently increased the nitrogen uptake, grain yield and reduced N loss. The suitable fertilizer management practices can reduce N immobilization associated with incorporation of crop residues into the soil. However, the practices needed to be fine-tuned with regards to suitable method, time and rate of fertilizer-N application. Effective utilization of N can be explored by its placement below surface soil layer which is temporally enriched with carbon after incorporation of crop residue (Doran and Smith, 1987) and/or increased application rate than the recommended along with starter dose. The band placement of urea prills and/or deep placement of large urea granules would lead to significantly lower amounts of fertilizer N immobilization due to restricted contact between fertilizer N and decomposing microbes with residue matrix (Yadwinder-Singh et al., 1994). Conclusively, the adverse effect of N immobilization on crop growth can be avoided by applying additional fertilizer N at the time of straw incorporation to enhance decomposition of residues. Considering the yield variations and higher cost of tillage/cultivation, farmers generally apprehend to opt for incorporation of paddy straw. Under such conditions, surface residue retention is a better alternative and in this practice top dressing/broadcast of fertilizers (N) should be just before irrigation instead of conventional practice of broadcast application after irrigation. Even in CT system, Gill et al. (2019) have observed better wheat yield and NUE with application of urea before irrigation than after irrigation. Moreover, with the development of new fertilizer formulations such ‘Nano’ their benefits should be explored as spray application under in-situ residue management particularly the residue retention. So, there is urgent need to formulate precise and location specific fertilizer recommendations based on nature of tillage and level of in-situ paddy straw management including frequent split applications to moderate microbial driven nitrogen immobilization complex.

4. Nature of weed flora and herbicide efficacy

Presence of crop residues on soil surface creates micro-environments that are either inhibitive or favorable to crop-weed interference. Crop residues can hinder the weed establishment either by physically obstructing their emergence or altering soil conditions (Teasdale and Mohler, 2000) or by exhibiting allelopathic effects which inhibit weed seed germination (Weston, 1996). Increase in soil moisture content in the topsoil layer due to the presence of surface crop residues can stimulate weed germination and consequently the emergence, particularly under a partially covered soil (Buhler et al., 1996). Further, decomposition of residue may promote weed emergence and growth by increasing soil fertility. Murphy et al. (2006) reported that continuous no-tillage system resulted in increase in weed diversity and proliferation of novel weeds following the ecological succession theory. Light exclusion and insulation of soil surface are two main physical changes under residue retention. These changes have implications on soil temperature and soil moisture and thereby affect weed biomass and their infestation level (Teasdale and Mohler, 2000). Teasdale and Mohler (2000) reviewed that influence of crop residue on weed interference depends on amount of residue, type of residue and nature of weed species. Increasing the crop residue load as surface mulch in wheat can increase the suppression of weeds. On the contrary, burning of paddy straw on soil surface enhanced weed seed germination of Phalaris minor, besides hampering the efficacy of soil active herbicides such as pendimethalin and isoproturon (Chhokar et al., 2009). However, the effect of residue burning depends on the quantity of straw, prevailing environmental conditions, weed species, relative vertical distribution of weed seeds in soil and their stage of dormancy/viability in addition to soil texture and moisture conditions.

Zero-tillage (ZT), even without residues, has been found helpful in reducing the weed germination and growth in wheat than the conventional tillage (Chhokar et al., 2007). The surface retention of the rice residues 5 and 7.5 t ha\(^{-1}\) reduced the weed dry weight (Fig. 5) in wheat by 23.4 to 30.3 and 35.5 to 44.1 per cent, respectively.
(Chhokar et al., 2009). The lesser P. minor infestation in ZT as compared to CT was attributed to less soil disturbance, more mechanical impedance along with restricted exposure to light as a result seeds present in lower soil layer failed to germinate. Therefore, ZT+ is a cost effective and sustainable weed management system but continuous use of ZT may shift the weed flora in favour of other weeds such as Rumex dentatus and Malva parviflora (Chhokar et al., 2007; Chhokar et al., 2012). Brar and Walia (2010) found that surface application of chopped rice residues (6-7 t ha⁻¹) significantly reduced the density (17.2-19.1 no. m⁻²) and dry matter accumulation (60-68 g m⁻²) of P. minor and has recorded higher weed control efficiency (45-52%) as compared to density (39 no. m⁻²), dry matter accumulation (117.4 g m⁻²) and weed control efficiency (6%) observed in rice residue incorporation scenario. Sindhu (2017) noted that residue mulch of 8 t ha⁻¹ suppressed most of the weed flora infesting wheat crop; however magnitude of suppression was higher for some weeds (Coronopus didymus, Chenopodium album, Anagalis arvensis, R. dentatus and P. minor) than others (Melilotus alba, Medicago denticulata and Lathyrus aphaca). It was further observed that residue mulch of 4 and 8 t ha⁻¹ reduced total weed biomass in wheat by 19-24% and 53-54%, respectively over no mulch (0 t ha⁻¹) at 60 DAS; and 19-20% and 57-61%, respectively at 120 DAS.

Maxwell and Mortimer (1994) opined that herbicide resistance in weeds is going to much faster and widespread when genetic diversity for the trait is coupled with severe selection pressure with continuous use of single or similar mode of action herbicides in simple cropping systems. Absence of tillage compels or bound growers to be dependent on herbicides to manage the weed. This can be realized as major disadvantage of no till system due to increased reliance on herbicides (D’Emden and Llewellyn, 2006). The biological activity of soil herbicides largely dependent upon clay content, amount of organic matter, presence of mulch and soil moisture; and these factors determine adsorption, biological degradation and persistency of applied herbicides (Banks and Robinson, 1986; Levanon et al., 1993; Borger et al., 2013).

Besides risk of resistance evolution in weeds associated with increased reliance on herbicides under ZT, efficacy of pre-emergence herbicides is also poor due to more interception with previous crop stubble/residues that prevent herbicide and weed seed/plant contact. Also, higher organic matter content, bind soil-applied herbicides at surface leading to greater herbicide sorption and that resulted in poor weed control under continuous ZT scenario (Levanon et al., 1993). Banks and Robinson (1986) revealed that only 30% of the applied herbicide reached the soil in the presence of 2240 kg ha⁻¹ of straw on the surface, while less than 10% reached when straw amount raised to 4480 kg ha⁻¹ and subsequently, reduced the herbicidal action of alachlor, acetochlor and metolachlor. The amount of interception by the wheat straw was more than 90% of the applied doses. The presence of straw on the soil has reduced weed control by acetochlor in both conventional tillage and no tillage. Besides interception of herbicide by surface retained stubbles and/or straw, herbicide efficacy was also affected by accumulation of high organic matter as well as acceleration of microbial activity that could limit potential efficacy of herbicide (Locke et al., 2002; Ferri et al., 2006; Chauhan and Abuhgo, 2012). Increased microbial activities associated with plant residues may also enhance herbicide metabolism and subsequent detoxification. This cause poor weed control and hence requires higher herbicide dose for satisfactory control of weeds. Mahoney et al. (2014) reported that under no tillage, higher dose of herbicides are required to provide sufficient control, for instance flumioxazin/pyroxasulfone rate required to provide 80% control of pigweed was 273 g a.i. ha⁻¹ under no-till while it was just 3 g a.i. ha⁻¹ under conventional till condition. One of the reasons for this differential response could be weed seedling age differences as in ZT if pre planting herbicides are not applied then weeds are of advanced stage compared to CT conditions. So, higher doses are required for effective control of weeds under ZT especially residues retention conditions. Negligible mechanical incorporation under ZT for pre-emergence herbicides further tends to aggravate losses through volatility and photo-decomposition (Parochetti and Hein, 1973). Straw mulch characteristics (hydrophobicity, aromaticity and polarity) and its decomposition rate strongly influenced herbicide behavior in soil as glyphosate desorption increased, while s-metolachlor decreased with mulch (maize) decomposition (Aslam et al., 2013). Borger et al. (2013) reported that effect of trifluralin (non water-soluble) and pyroxasulfone (water-soluble) on rigid ryegrass improved from 53 to 78% with increasing carrier volume due to greater coverage that ensured more herbicide penetration in the stubbles to reach the soil surface subsequently, resulting in higher weed and chemical contact. However, in Australia, crop residues tend to be at lower levels than in RW system in India (1.6-4.5 t ha⁻¹ vs. 7-10 t ha⁻¹). Besides, the carrier volume for PRE herbicide used in Australia is low (30-100 L ha⁻¹).

Regarding herbicides formulation, use of microencapsulated/granular forms reduced alachlor interception with more penetration under surface corn residue/stubble conditions at the time of application as compared to liquid-applied herbicide. However, increasing amounts of post application rainfall
decreased the difference among two contrasting formulations and resultant weed control (Johnson et al., 1989). However, the foliage active post-emergence herbicide efficacy is not altered by the tillage and residue management options. This was realized during late 90s when isoproturon resistant P. minor L. problem was at its peak in north-western Indian plains and ZT and new potent herbicides (sulfosulfuron, clodinafop and fenoxaprop) were recommended to wheat growers. These two technologies in conjunction drastically reduced the P. minor problem and increased the economic returns. However, now major weeds associated with wheat (P. minor L., Avena ludoviciana, Polypogon monspeliensis, R. dentatus and C. album) have become resistant to wide array of available post-emergence best herbicides (Table 1) chemistry (ACCase and ALS) especially in case of rice-wheat cropping system (Singh, 2016; Chhokar et al., 2018a). Due to limited options of herbicides for post-emergence application, there is need to revise the role of pre-emergence herbicides along with their efficacy in surface retained full/partial rice residues for effective management of these herbicide resistant weeds. But the herbicides efficacy under two contrasting conditions ZT and CT differ enormously due to presence of stubbles/straw, level of organic matter, variable level of microbial driven metabolism, nature of herbicides (solubility), drill slit size, seeding depth and weed flora. The information on weed dynamics and interaction of mulch with other crop management practices is limited in RW system. Therefore, sincere efforts are required to devise effective tactics to integrate pre-emergence herbicides with residue mulch and other non-chemical weed control tools in wheat. Sindhu (2017) reported that the herbicide mixture of pendimethalin 1.5 + metribuzin 0.140 kg ha⁻¹ when applied on the top of mulch as pre-emergence with high carrier volume (1000 L ha⁻¹) reduced the density of P. minor, R. dentatus, M. denticulata, M. indica, L. aphaca and other weeds, respectively by 91-93, 87-90, 66-74, 92-94, 50-55 and 86-90% as compared to weedy check at harvest. In this study, although the efficacy of herbicide mixture was not evaluated with lower carrier volume (say 500 L ha⁻¹, the recommended water volume under conventional conditions) for comparison, but it is evident from the reduction in weed density that higher water volume helped in penetration of herbicides through heavy residue mulch (8-9 t ha⁻¹). In another tactic, application of pendimethalin 1.5 + metribuzin 0.140 kg ha⁻¹ with carrier volume of 500 L ha⁻¹ as early post emergence i.e. one day before first irrigation to wheat was also found effective against most of the weeds (Sindhu et al., 2016). Somireddy (2011) reported that herbicides such as trifluralin and isoxaben when applied under the mulch persisted longer compared to herbicides applied alone. This information had major implications for RW system in India as the resistance to the available POE herbicide becomes more common and reliance on PRE herbicides will be more in future. In a recent herbicide-residue analysis study, dissipation of pendimethalin and metribuzin from soil surface was found slower when applied beneath 8 t ha⁻¹ of rice straw mulch in wheat as compared to their dissipation from bare soil. Synergistic integration of zero tillage + higher seed rate (125 kg ha⁻¹) + pre-emergence herbicide mixture (pendimethalin 1.5 + metribuzin 0.210 kg ha⁻¹, applied beneath the mulch) + residue retention (8 t ha⁻¹) provided weed control and wheat yield parallel to weed free conditions (Sindhu, 2017 and Sindhu et al., 2017a). Hence, there is need to optimize herbicidal dose, formulation, scheduling (pre-planting or before irrigation/early post), spray volume for adequate weed control and for better herbicide efficacy under conservation agriculture system in wheat under paddy straw retention conditions.

5. Crop breeding perspectives under conservation agriculture

Globally, crop production is likely to suffer in near future due to significant increase in abiotic stresses like heat and drought associated with global warming as well as water scarcity. So to reduce or modulate these challenges, agronomic practices are needed to be synchronized with the crop breeding strategies for proposing resilient ideotypes. However, in spite of significant interaction of genotype and management practices, no systemic breeding efforts have been performed to screen and identify specific lines. Conservation agriculture provides variable regimes as compared to conventional tilled soils, so genotypes selected under conventional conditions could respond differentially under CA (Sagar et al., 2014). Innovative breeding strategies should be based on introgression of valuable traits in crops specially designed for no-till conditions. Under no-till residues retained conditions, crops faced considerable reduction in root growth due to higher soil strength and above ground growth due to nutrient immobilization. Sometimes poorly aerated environment produces phyto-toxic compounds and causes patchy growth (Kirkegaard et al., 1994). Moreover, modern cultivars are not considerably suitable as these lines exhibit Rht 1 and Rht 2 gene which cause limited coleoptile length that results in indigent emergence with poor crop establishment (Singh et al., 1998). The presence of dwarfing genes is associated with a significant reduction in coleoptile length (Allan et al., 1962; Feather et al., 1968). In this regard, other Rht genes like Rht8 and Rht 12, which are sensitive to gibberellin and produce longer coleoptile can be explored. The wheat cultivars with long coleoptile produce large early leaves with rapid rate of
seedling emergence, subsequently leading to faster leaf area development (Fick and Qualset, 1976; Richards et al., 1996). The amalgamation of specific traits like faster and extensive root development, quick germination and/or emergence, more nutrient efficient to modulate adverse effects of nitrogen immobilization and resistance to phytotoxicity accrues due to organic acids under poorly aerated no-till heavy residue retention situation can deliver potential crop productivity (Joshi et al., 2007; Trethowan and Reynolds, 2005). These traits help to utilize natural available resources like sunlight, nutrient and available moisture efficiently that provide competitive advantage with more surface area cover to crop seedling against weeds besides, reducing initial evaporative losses (Richards, 1992). Cultivars characters can be further fine-tuned for early sowing, terminal heat tolerance, multi-ovary florets without reducing seed size, optimum phenological duration to enhance capacity of photosynthetic assimilation and partitioning to promote higher sink size and growth rate (Richards, 1996; Chen et al., 1998; Reynolds et al., 2001; Richards and Lukacs, 2001; Joshi et al., 2007). Moreover, breeding for nutrient efficient cultivars holds the key to maintain the yield/sustainability under climate change scenario, where crops bound to suffer due to lower availability of nutrients associated with accelerated losses in near future. Conservation tillage provides congenial environment for crop growth and development, hence there is need to optimize timing and duration of development phase which is more crucial for adaptation under specific environment (Worland, 1996). Stem elongation phase (terminal spikelet initiation to anthesis extension) without altering the anthesis time can further increase wheat yield potential (Slafer et al., 2001). Furthermore, simplest way for breeding crops under no till is to make crosses of well adapted parents under ZT and grow segregating populations from crosses to recognize traits with profuse tillering, better emergence characteristics and resistance to insect-pest/diseases (Joshi et al., 2007) and grow superior segregating populations in ZT as well as conventional management to optimize their behaviour for both systems under different locations and climate regimes. Shuttle breeding another valuable aspect can be used to evaluate superior lines alternatively

### Table 1. Herbicide resistant weeds of wheat in India and their infestation in relation to in-situ straw management practices/zero tillage (Chhokar et al., 2018a).

<table>
<thead>
<tr>
<th>Weeds</th>
<th>Resistance against the chemical groups</th>
<th>Effect of in-situ retention of paddy straw/ no till on weed establishment and growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phalaris minor</td>
<td>Phenyl urea (Isoproturon), Aryloxyphenoxypropionic (Clodinafop), Sulfonylurea (sulfoxuron, mesosulfuron), and Phenylpyrazole (pinoxaden)</td>
<td>*Reduced due to higher upper soil strength and physically inhibition by huge residue load. *Emergence of Phalaris minor reduced by 45% with paddy straw as mulch (6 t ha⁻¹) as compared to no mulch.</td>
</tr>
<tr>
<td>Polygagon monspeliensis</td>
<td>Sulfonylurea (sulfoxuron, mesosulfuron), Triazolopyrimidine sulfonamide (pyroxsulam)</td>
<td>*Emergence of Rumex dentatus reduced by 88% with paddy straw as mulch (6 t ha⁻¹) as compared to no mulch.</td>
</tr>
<tr>
<td>Rumex dentatus</td>
<td>Sulfonylurea (metsulfuron, triasulfuron, iodosulfuron), Triazolopyrimidine sulfonamide (pyroxsulam, florasulam)</td>
<td>*Conservation tillage promoted earlier emergence of C. album compared to conventional tillage *Emergence of Chenopodium album reduced by 83% with straw mulch (6 t ha⁻¹) as compared to no mulch.</td>
</tr>
<tr>
<td>Chenopodium album</td>
<td>Sulfonylurea (sulfoxuron, metsulfuron)</td>
<td>*Conservation tillage promoted earlier emergence of Avena species.</td>
</tr>
<tr>
<td>Avena ludoviciana</td>
<td>Aryloxyphenoxypropionic (Clodinafop), Sulfonylurea (sulfoxuron, mesosulfuron)</td>
<td></td>
</tr>
</tbody>
</table>

(Kumar et al., 2013; Chhokar et al., 2007; Bullied et al., 2003; Chhokar et al., 2009)
In-situ paddy straw management practices

Table 2. Exploring genetic diversity to tailor wheat for enhancing productivity in conservation agricultural.

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Treatments</th>
<th>Observations/Remarks</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Twelve wheat genotypes (HUW 234, HUW 468, HUW 510, HUW 516, PBW 343, PBW 443, HD 2027, HD 2733, UP 2338, NW 1012, DBW 14, Raj 3763) evaluated under conventional and zero-till conditions</td>
<td>PBW 343, HUW 468 and HUW 234 performed good under no-till and conventional till conditions, while PBW 443 and HD 2627 failed to show any significant yield response. The faster-growing lines, Raj 3765 and HUW 234 recorded 25% less yield in association with weeds as compared to slow-growing line PBW 343 and had yield decline of about 35%</td>
<td>Joshi et al., 2007</td>
</tr>
<tr>
<td>2.</td>
<td>Forty two differentially adapted lines of wheat with permanent bed (zero tillage) with full residue retention (CA), raised bed with no residue (CTFB) and conventionally performed flat-bed (CTFB). Quantification of genotypes and management interaction using additive main effect and multiplicative interaction (AMMI) and genotype main effect (G) plus genotype by environment interaction (GGE) methods.</td>
<td>CA has higher genotypic performance index (GPI) score of 0.80 and 0.74 during 2011-12 and 2012-13, respectively compared to 0.74 and 0.62 under CTFB in 2011-12 and 2012-13, respectively. Indicator score identified HD3117 and HDCSW 18 for CA, validated the use of indicator scoring as a selection tool in plant breeding.</td>
<td>Sagar et al., 2014</td>
</tr>
<tr>
<td>3.</td>
<td>Screening of 42 genotypes under conventional tillage flattened (CTFB) and conservation agriculture (CA) based on indicator scoring system for identification of genotypes</td>
<td>Parents CSW02 and HD3117 are good combiner for grain filling duration (GFD) while, CSW2 and CSW77 are good combiner for grain filling (GFR) while, based on (AMMI) cultivars HD3113, HD3117, CSW2, CSW4, CSW16, CSW18, CSW23, CSW25, and CTFB4565 showed higher adaption to both CA and CTFB. While, CSW33, CTRB1666, CTRB1816, CTRB1817 and CTFB4539 are grouped together for (CTFB) Under heat stress scenario, CA discriminated the genotypes and was more informative due to temperature modulation and moisture conservation under CA as compared to other which were penalized due to terminal heat stress under conventional condition.</td>
<td>Kumar et al., 2017</td>
</tr>
<tr>
<td>4.</td>
<td>Half diallel fashion during the rabi 2013-14 to generate 21 F1s for genetic study. The F1s along with their parents were raised in rabi 2014-15 in RBD with two replications.</td>
<td>Cultivar K 7903 showed better growth, yield attributes and physiological parameters than the other genotypes and gave significantly higher grain yield both under no-till (3.4 t ha(^{-1})) and conventional tillage (3.46 t ha(^{-1}), followed by HD 2967 due to higher leaf chlorophyll retention and photosynthetic rate during grain-filling period.</td>
<td>Sagar et al., 2016</td>
</tr>
<tr>
<td>5.</td>
<td>Cultivars K 9351, K 7903, HD 2967, DBW 14 and HI 1563 of wheat (Triticum aestivum) under no-till and conventional tillage.</td>
<td>Cultivar K 7903 showed better growth, yield attributes and physiological parameters than the other genotypes and gave significantly higher grain yield both under no-till (3.4 t ha(^{-1})) and conventional tillage (3.46 t ha(^{-1})), followed by HD 2967 due to higher leaf chlorophyll retention and photosynthetic rate during grain-filling period.</td>
<td>Kumar et al., 2017</td>
</tr>
<tr>
<td>6.</td>
<td>Thirty two wheat varieties (28 aestivum and 4 durum) were evaluated under timely sown conditions under CA and CT scenario of rice-wheat system. Five wheat varieties were evaluated in CA under delayed sowing in sugarcane-wheat rotation</td>
<td>Seven genotypes HD 2967, HDCSW 18, PBW 723, HI 8498, UAS 428, MPO 1215 and MACS 6222 gave higher yield out of which three (HI 8498, MPO 1215 and UAS 428) were durum genotypes. However, no significant yield differences were recorded under conservation and conventional based practices. For very late sown (20-25(^{th}) January), under trash mulching after sugarcane harvest, five aestivum wheat varieties namely PBW 550, DBW 71, Raj 3765, WR 544 and WB02 yielded 30.24, 33.80, 32.62, 32.46 and 27.54 q ha(^{-1}), respectively.</td>
<td>Chhokar et al., 2018b</td>
</tr>
<tr>
<td>7.</td>
<td>Four rice cultivars, two coarse (HKR-47 and IR-64) and two fine cultivars (Sharbati and PB-1) were evaluated under direct seeding and puddle transplanted conditions</td>
<td>Compared to the puddle transplanted conditions, the DSR treatments exhibited lower yields (15.8%) with coarse varieties (HKR-47 and IR-64), but fine cultivars (Sharbati &amp; PB-1) exhibited similar yields under both systems</td>
<td>Chhokar et al., 2014</td>
</tr>
</tbody>
</table>

at various locations to identify or strengthen the quality selection process. Furthermore, there is need to reevaluate traits like coleoptiles length and its relationship with Rht genes, duration of phenological stages and their relationship with Vrn genes and Ppd genes (Yadav et al., 2014).

Furthermore, traits for faster decomposition (dependent on differences in nitrogen, carbon to nitrogen ratio, lignin and nitrogen ratio) can also be explored to moderate straw decomposition rate (Kumar and Goh, 2000). Moreover, paddy varieties with short duration and short stature without economical yield reduction will provide adequate window for straw decomposition and optimum straw for in-situ management. Specially designed coherent cultivars are required for DSR as well, where conventional cultivars suffer a lot from iron chlorosis, zinc and phosphorus deficiencies (Joshi...
et al., 2007) to achieve full potential of conservation based agricultural practices in rice-wheat cropping system. Besides agronomic aspects like nature of tillage, placement and amount of crop residues and diversity of crop rotational practices, the genotypes suited to CA are also important tools to increase system productivity.

6. Fine tuning of machinery for paddy straw management

More than 70% of rice is harvested by combine harvester in north-western India (Singh et al., 2008). The sowing of wheat into the rice residues was not possible in the past because of clogging of the conventional zero till seed drill with the loose rice straw. Therefore, rice residues in combine harvested fields were normally burnt in situ prior to sowing of wheat. However, with the recent development of the Turbo Happy Seeder (Sidhu et al., 2007, 2015), it is now possible to sow wheat directly into the combine harvested rice residues immediately after rice harvest. The THS cuts and shreds the straw in a narrow strip in front of each inverted T-shape sowing tyne, and at the same time the flails sweep the straw away from the tyne, with the result the sown rows are not covered with residues. The power requirement is high (> 45 HP tractor). The main requirement for the smooth operation of THS is evenly spreaded dew free loose straw. However, recently efficiency of THS has been improved with modification in flail’s design and number. Earlier there were two flails fixed at 180° and now three at 120°. Moreover, for improving the field efficacy of THS, a straw management system (SMS) consisted of two units (straw manager and spreader), has been developed by PAU. It is attached to the rear side of combine harvester just below the straw walkers and behind the chaffer sieves. The straw manager cuts the straw into pieces and while passing through spreader, it is uniformly distributed in the field. Thus it has overcome the problem of clogging of THS associated with presence of huge amount of loose straw in fields. Chhokar et al. (2018b) have reported that THS was more effective for direct seeding of wheat in heavy residues load of rice, while in sugarcane ratoon trash, Rotary Disc Drill (RDD) is more suitable. The new version of RDD having SoilRazor discs effectively cuts the heavy residue load of rice and sugarcane trash. However, for the efficient working of these CA machines, the height of anchored residue should be kept as much as possible. Additionally, nine-row conveyor seeder (pick up conveyor-cum-elevator attached in front of no-till drill) has enabled direct drilling of wheat seeding under loose straw and standing stubbles in combine harvested paddy fields by lifting loose straw in front of furrow openers of drill. The conveyor seeder has reduced cost of operation almost by 31 and 57 % as compared to THS and conventional based sowing of wheat (Mahal et al., 2016). Another option is the tractor mounted straw chopper cum spreader which harvest the straw/anchored stubble left after combine harvesting and chop them into pieces and uniformly spreads in the field in a single operation (Singh et al., 2011). A study has shown that after chopping of loose and anchored stubbles with chopper-cum-spreader in combine harvested paddy, sowing with 3-member frame no-till drill (spatially modified) with more vertical clearance (600 mm) and spacing (600 mm) from tyne to tyne provided effective wheat seeding without clogging and straw accumulation. Moreover, yield and yield attributes (test weight, grain number spike & effective tillers) were at par with conventional no-till drill operated in clean field (Singh et al., 2014).

Regarding straw incorporation, due to greater soil complexity coupled with variable straw properties there is also need to fine tune the rotary tillers for optimizing straw incorporation process on energy and working basis. Efficiently designed rotary system can prevent excessive humping/sinking of soil and/or heaping of straw with better incorporation of straw in the soil matrix. A study by Chen et al. (2015) has shown that for mini-power rotor tiller, down-cut rotary resulted in greater incorporation (89%) as compared to up-cut tilling system (83.3%), while reverse to it, heaping-up of straw was higher in later one (33.0%) as compared to earlier one (24.8%). Moreover, moderately humped soil surface was observed in down cut system along with smaller coefficient of variation for the total length of straw and more straw concentration in upper surface (5-10 cm) in over tilled region. While, up-cut system led to sink of surface soil in mid and ridges along two sides of tilled plot coupled with even distribution of soil volume (Chen et al., 2015). In another study, based on mass and cover relationships from three combine harvester with respect to straw distribution and soil surface cover in a rice–wheat cropping system revealed that straw distribution pattern mainly depends on instantaneous material feeding through the combine as higher the feed rate, poorer is uniformity in straw distribution (Belal et al., 2017). The straw return system in soil with rotary tillage failed to provide effective incorporation in soil matrix due to higher amount of straw fragments accumulated in the ploughing layer, besides more or less similar proportion still left over field surface (Yang et al., 2018). In addition to it, this practice also leads to prompt nitrogen immobilization, poor wheat seedling emergence associated with more soil pores causing poor seed and soil contact (Yang et al., 2016) with more vulnerability to frost damage (Xue et al., 2017). So a novel soil tillage system i.e. “Ditch-buried Straw Return” has been suggested to overcome the problems associated with rotary tillage system (Wang et al., 2015; Yang et al., 2018). It is based
### Table 3: Effect of conservation agricultural based practices on productivity of rice-wheat based cropping system

<table>
<thead>
<tr>
<th>Duration / location / Soil texture</th>
<th>Crop establishment</th>
<th>Results</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-years (2009-14)/ Karnal/ Loam</td>
<td>Conventional puddled transplanted rice followed by (fb) Conventional wheat (CTPR-CTW); Puddled transplanted rice fb zero-till (ZT) wheat fb ZT mungbean (CTPR-ZW-ZMB); ZT direct-seeded rice (ZT-DSR) fb ZT wheat fb ZT mungbean (ZTDSR-ZTW-ZTMB); ZT maize fb ZT wheat fb ZT mungbean (ZTM-ZTW-ZTMB)</td>
<td>[CTPR-ZW-ZMB], [ZTDSR-ZTW-ZTMB] and [ZTM-ZTW-ZTMB] enhanced the system productivity (10-17%) and profitability (24-50%), besides reducing water requirement (15-71%), energy (17–47% reduction) and led to lower (15–30%) global warming potential (GWP). (ZTDSR ZTW-ZTMB) and (ZTM-ZTW-ZTMB) resulted in higher wheat productivity (15-17%) compared to (CTPR-CTW). Integrating opportunistic diversification with reduced tillage under precision resource management (CTPR-ZW-ZMB) reduced irrigation water (24%) and GWP (21%), besides increasing yield (0.9 t ha⁻¹) compared to (CTPR-CTW)</td>
<td>Kumar et al., 2018</td>
</tr>
<tr>
<td>3-years (2001-02 to 2003-04)/ Karnal/ loam</td>
<td>Three tillage crop establishment methods (ZT drill, CT drill and CT broadcast sowing) were evaluated for productivity and profitability of wheat in rice-wheat system.</td>
<td>Out of the three tillage crop establishment methods, ZT and CT drill provided about 0.3 ha⁻¹ higher wheat grain yield over farmer’s practice of CT-broadcasting and profitability of wheat in rice-wheat system. The reduced expenditure on tillage and other high cost inputs provided additional profit of about US $ 161.3 ha⁻¹ for ZT over farmer’s practice</td>
<td>Chhokar et al., 2007</td>
</tr>
<tr>
<td>3-years (2009-12) at 3 locations/ Patna/ Clay loam</td>
<td>Tillage practices in rice included zero-till-drill rice (ZTR), un-puddled mechanical transplanted rice (MTR), direct wet sowing (DWS) and puddled transplantsing (PTR) whereas, in wheat three methods of sowings viz. zero-till-drill (ZTW), manual line sowing (MSW) and sowing with Turbo Happy Seeder (THS)</td>
<td>Wheat under rice tillage system as MTR and ZTR exhibited significantly higher yield of 48.2 and 44.6 q ha⁻¹ with an output: input ratio of 2.0 and 2.1 respectively, while, THS performed best and produced significantly higher grain yield (43.8 q ha⁻¹) compared to other methods of sowing due to mulching effect.</td>
<td>Sanjeev and Ujjwal, 2014</td>
</tr>
<tr>
<td>2 year (2008-10)/ Meerut/ Sandy loam</td>
<td>Puddled transplanted rice followed by conventionally tilled wheat (CTPR-CTW); Direct seeded rice on the flat followed by zero till wheat (CTDSR-ZTW); Zero till direct seeded rice with residue followed by zero till wheat with residue (ZTDSR+R ZTW+R); Transplanted rice after rotavator puddling followed by zero till wheat (RTTPR-ZTW); Transplanted rice after rotavator puddling followed by rotary till wheat (RTTPR-RTW) and Farmer practice rice–wheat (FP-RW);</td>
<td>Wheat planted with ZTDSR+R-ZTW+R gave 30% higher grain yield than farmer practice. Overall, among all the tillage and crop establishment treatments the rice-wheat system yields and net returns were maximum under ZTDSR+R-ZTW+R.</td>
<td>Kumar et al., 2019b</td>
</tr>
<tr>
<td>4-year (2011-15)/ Karnal/ Sandy clay loam</td>
<td>Conventional basmati rice-wheat (no residue); Conventional basmati rice-wheat- mungbean (mungbean residue incorporated); Zero till basmati rice-wheat (no residue); Zero-till basmati rice-wheat- mungbean (mungbean residue retained); Zero till basmati rice-wheat with residue (both rice and wheat residues retained); Zero till basmati rice-wheat- mungbean with residue (all residues retained)</td>
<td>Conservation agriculture based management under zero till direct seeded rice-wheat-mungbean recorded 36% higher system yield than conventional till rice-wheat system (14.91 Mg ha⁻¹). CA based rice-wheat system and rice-wheat-mungbean system saved about 35% irrigation water compared to conventional RW system (2168 mm ha⁻¹). Total water productivity improved by 67% with CA based rice-wheat-mungbean system (0.90 kg grain m⁻³) over conventional system.</td>
<td>Jat et al., 2019</td>
</tr>
<tr>
<td>7 year study/ Uttar Pradesh/ Sandy loam</td>
<td>Six treatments as T1: transplanted rice after conventional puddling and drill-seeded wheat after conventional tillage (CTTPR-CT-DSW), T2: transplanted rice after conventional puddling with mid-season alternate wetting and drying and drill-seeded wheat after zero-tillage (CTAWD–TPR-ZT-DSW), T3: direct drill-seeded rice and wheat on permanent raised beds (Bed-TPR-Bed-DSW), T4: transplanted rice and drill-seeded wheat on permanent raised beds (Bed-TPR-Bed-DSW), T5: zero-tillage direct drill-seeded rice and wheat (ZT-DSR/ZT-DSW), T6: ZT transplanted rice and zero-tillage drill-seeded wheat (ZT-TPR/ZT-DSW)</td>
<td>Average rice yields (781- 810 Mg ha⁻¹) were maximum in T1 and T2 and increased with time (0.26 Mg ha⁻¹ yr⁻¹) in T2. Yields of rice lower in T3 (10%) and T4 (43%) as compared to T1. While, wheat gave 18% higher yield after zero compared to CT. T2 had maximum water productivity with 25% lower use of water than CT T1 and 10% lower than other treatments. Maximum net returns in rice CT and crop establishment practices, but higher with ZT in wheat. Hence, highest net returns (~$1295 US$) were found in T2 and T3 and lowest (747-846 US$) in T3 and T4 in the RWS.</td>
<td>Gathala et al., 2011a</td>
</tr>
</tbody>
</table>
on the concept of rotational tillage in the rice-wheat system and the straw or crop residues are concentrated in deep ditches, while the position of straw ditches is alternated after each crop season (Yang et al., 2018). This straw management system has technological feasibility as it simultaneously explores synergism of two tillage system (deep ploughing and minimum tillage), strong capability of straw incorporation, minimum soil disturbances (only 10% of field area for ditching), saving of machinery operation and energy as lower proportion of straw residues remained on soil surface and without fragmentation, enhance soil carbon sequestration. Moreover, the straw ditches reflected as drainage channels and prevent waterlogging stress in wheat associated with sub soil compaction (Yang et al., 2018). Conclusively, wide arrays of machineries are available for the management of paddy straw (Table 4) but defining a complete set of agronomic practices under each operational domain is lacking.

7. Optimization in-situ based microbial decomposition

The major components of rice straw are hemicelluloses, cellulose, lignin and water soluble polysaccharides. Puttaso et al. (2011) observed variable decomposition pattern and subsequent accumulation of organic matter in soil with incorporation of residues of different crops (groundnut stover, rice straw, tamarind and dipterocarp) (10 t ha⁻¹) in sandy soil for thirteen years. The rate of decomposition was positively correlated with cellulose, while negatively to amount of lignin and polyphenol content in residues. Lignin physically shields the easily degradable constituents from enzymatic hydrolysis (hemicellulose and cellulose), whereas, polyphenols combines with nitrogen based compounds in residues to form recalcitrant complexes (Handayanto et al., 1995). Moreover, rate of mass loss was fastest in groundnut stover (high in nitrogen), followed by rice straw (high cellulose) and tamarind, while slowest in dipterocarp (high polyphenol and lignin amount). The metabolic quotient (ratio of CO₂-carbon evolution to microbial biomass carbon) was recorded higher during first fifteen days upon residue incorporation of different crops as compared to without incorporation and highest for groundnut followed by rice straw and dipterocarp. Further, C:N was not sole factor that defined decomposition pattern, as despite of high C:N in rice (78), it decomposed more rapidly attributed to amount of cellulose in straw than dipterocarp (80) and tamarind (32). Johnson et al. (2007) reported that not just C:N, but also the N concentration, starch, total lignin, and acid-insoluble ash were the major indicator of active residue decomposition. The incorporation of paddy straw (7.5 t ha⁻¹) with cellulolytic fungal inoculum (Aspergillus spp.) and 50 kg N ha⁻¹ was found promising in alluvial sandy loam soil (Tiwari et al., 1987). Varma and Mathur (1990) also reported that mesophilic cellulolytic fungal inoculum (Trichoderma viride) combined with urea (60 kg N ha⁻¹) and rock phosphate (60 kg P₂O₅ ha⁻¹) produced significant effect on wheat yield. Incorporation of rice straw in conjunction with nitrogen (60 kg ha⁻¹), phosphorus (60 kg ha⁻¹) and Trichoderma reesi resulted in higher alkaline phosphatase, dehydrogenase, humus content and it was superior to the treatments, where both T. reesi and Aspergillus awamori were applied.
**Table 4:** Machineries for crop residue (paddy straw) management and seeding machineries for sowing of wheat

**A). Seeding machineries for crop sowing under paddy straw conditions**

**Rotary Disc Drill** (Sharma *et al.*, 2008; Chhokar *et al.*, 2018b): The rotary disc drill is a new conservation agriculture machine based on rotary mechanism, having tripod disc suitable for sowing wheat under surface retained or incorportaed crop residue. It is a single pass seeding machine with real minimum soil disturbance. This machine is also capable of seeding in full trash retained sugarcane ratoon crop. It can be used at any time during day or night for seeding crop and has no limitation of wet residue condition. It economizes on fuel and time especially when wheat sowing is delayed after rice harvest, particularly of basmati type rice.

**Turbo Happy Seeder** (Sidhu *et al.*, 2007): It consists of a rotor for managing the paddy residues (stubble mulching) and a zero till drill for sowing of wheat. Flails are mounted on the straw management rotor which cuts (hits/shear) the standing stubbles/loose straw coming in front of the sowing tine and clean each tine twice in one rotation of rotor for proper placement of seed in the soil. The main requirement for the operation of THS is evenly spread, dew free loose straw. The power requirement is also high (>45 or above HP tractor).

**Zero Seed Drill** (Malik *et al.*, 2005): Zero seed drill is used for direct drilling of wheat seeds in standing paddy stubbles. It is particularly useful where basmati is cultivated and which is manually harvested leaving short anchored stubbles. It is lighter machine compared to Happy Seeder and can be pulled easily by lower power (<45 HP) tractor.

**Spatial No-till drill** (Singh *et al.*, 2014): Three member frame, no-till drill with more vertical clearance helps in drilling of wheat under loose straw with more anchored stubbles. In this drill the tine to tine spacing of 60 cm on each frame helps in negligible dragging of loose straw along with tynes.

**B). Straw cutter machineries for in-situ incorporation/retention of paddy straw**

**Paddy straw chopper** (Singh *et al.*, 2011): It is used for chopping the paddy stubbles in smaller pieces for easy incorporation of paddy straw into soil to get clear fields for wheat sowing.

**Straw shredder/Shrub master:** For ex-situ management of paddy residues, three machines viz. shrub master, raker and baler are essential.
Super SMS: It is an additional equipment attached with combine machines. It cuts the standing stubbles into smaller pieces and spread evenly on the field. Direct drilling of wheat seeds can be done using happy seeder machine in paddy residues chopped and spread using Super SMS in combine machines.

Mulcher: Mulcher with vertical axis of rotation is a rotation mower. It is used to chop the straw into smaller pieces which are then pressed by a roller attached at the rear side. It will compress the straw creating a mulch layer over the top soil. Afterwards Happy Seeder or reversible MB plough can be used to sow wheat or invert straw into the soil, respectively.

C). Machineries for straw incorporation

Reversible MB plough: It is used in virgin fields, fields that are left unploughed for many years. It is useful for residue management particularly in crops like potato, sugarcane and vegetables where field preparation is necessary for good establishment. Paddy straw can be chopped using mulcher, followed by inversion using MB plough and then other primary tillage machines can be used to prepare seed bed.

Rotary-till-drill (Sharma et al., 2008): The rotary-till-drill is a single pass soil pulverization and seeding machine. The sowing of wheat is completed in a single tractor operation leading to substantial savings on fuel and time required for conventional field preparation. This machine simultaneously incorporates anchored crop residue during seeding. It can also be used for pudding operation in rice cultivation

D). Straw collection and disposal

Raker: Raker is used for making windrows of harvested stubbles. To increase the capacity of straw baler, raker is operated to collect in rows after using shrub master. This reduces the number of pass of baler to collect straw for baling and thus field capacity is increased.

Baler: Straw baler collects the paddy straw and compress into bales for easy transportation to far flung area which then can be used for making packing material, card boards, biogas preparation and electricity generation.
with same fertilizer level (Gaidn and Nain, 2007). Choudhary et al. (2016) identified four lignocellulose degrading fungi viz., Aspergillus flavus, A. terreus, Alternaria alternate and Penicillium pinophilum based on their greater enzymatic activities, which can be employed for quick in-situ decomposition of rice-wheat straw. These autochthonous fungi viz., Aspergillus flavus, A. terreus, A. niger and Panicillium janthinellum showed higher activities for cellobiase, CMCase, FPase, xylanase and laccase enzymes, while earlier ones (Aspergillus spp.) showed greater degradation (30%) of straw within ten days after incubation (Choudhary et al., 2015). A consortium of lignocellulolytic fungi comprising Aspergillus flavus RPW 1/3 and Penicillium pinophilum RPWM 2/2 show partial mutual compatible interaction and may be explored further for accelerated degradation of crop residues (Choudhary et al., 2016). Moreover, the rate of delignification can be enhanced with use of bio-surfactants also. A study based on dirhammolipid (0.007%) as bio-surfactant showed that it hastened the bio-delignification process of paddy straw with Phanerochaete chrysosporium attributed to greater lignin peroxidase activity by 86% without altering manganese peroxidase activity and subsequently, increased the lignin degradation rate by 54% (Liang et al., 2010). Another study (Ma et al., 2019) on wheat straw management reported that application of straw decomposing microbial inoculants with wheat straw and fertilizer reduced net global warming potential (nGWP) by 34.6% and greenhouse gas intensity (GHGI) by 37.7% as compared to nGWP (11.6 t CO₂ eq ha⁻¹ yr⁻¹) and GHGI (1.20 kg CO₂-eq kg⁻¹ grain) for the treatment where only fertilizer was applied without wheat straw and microbial inoculation. While, straw-derived biochar along with fertilizers reduced above mentioned values approximately by about 60 and 66%, respectively (Ma et al., 2019). Potential environmental benefits with in-situ straw management can be further amplified with straw derived biochar and/or by using microbial driven degradation. Rajkhowa and Borah (2008) reported incorporation of paddy straw (5.0 t ha⁻¹) along with cellulose decomposing microbes and earthworms culture enhanced grain yield by 2.46 t ha⁻¹. However, efforts for faster degradation may aggravate nitrogen immobilization more due to exponential growth of microbes as stimulated by ex-situ support. The accelerated degradation of paddy straw may limits their potential advantages to the succeeding crops in terms of heat stress in wheat associated with canopy cooling due to abnormal hike in temperature along with saving of water and nutrient. Further, there is need to quantify the global warming potential of microbial inoculate assisted accelerated in-situ decomposition of straw in rice-wheat system.

8. Conclusions
1. Various options of in-situ paddy straw management are available with the farmers, but a delineation of complete set of practices are lacking for succeeding crops (wheat, potato and/or vegetable growers).
2. There is need to moderate and/or stop the current pattern of removal or burning of paddy straw from farmers’ fields for other purposes such as electricity, ethanol production, bio-gas, etc. as these practices in long terms may lead to severe loss in soil fertility associated with extensive nutrient mining resulting in negative nutrient balance.
3. The innovations are required for technologies/practices to encourage in-situ paddy straw/residues management and their synchronization/compatibility with on-going system and location specific current farmers’ practices for resilient crop production under future climatic aberrations.
4. Various options promoted for in situ crop residue management would invariably effect the growth of succeeding crop along with nutrient, water and weed dynamics. The change in sowing window due to direct drilling of wheat in standing stubbles requires adoption/development of varieties which are of longer maturity with early vigour. Moreover, transplanting of paddy should be scheduled in such a manner that after SMS based combine harvesting, sowing of wheat can be performed with T/THS/ZT Drill/RDD on residual soil moisture without pre-sowing irrigation.
5. Fertilizer application method and its scheduling (dose and timing) owing to standing/chopped/incorporated straw on soil is needed to be revised. In addition to it, there is need to overlook the idea of accelerated in-situ paddy straw decomposition with the help of potential microbial consortia and its global warming potential, because these practices may abolish potential advantages of in-situ retention/incorporation of paddy straw in succeeding crops. Soil inversion practices along with straw with Hydraulic Reversible M.B. Plough need to be logically examined with respect to aggravation of anaerobic conditions and emission of greenhouse gases in puddled transplanted rice-wheat cropping system.
6. Further, there is also need to formulate the conditions for higher efficacy of pre-emergence herbicides in surface retained residue scenario by modifying spray volume, spray nozzles and time of herbicides application.
9. References


23. Chauhan BS and SB Abuhgo. 2012. Interaction of rice residue and PRE herbicides on emergence
and biomass of four weed species. Weed Technology 26: 627-632.


soil properties in a wheat-rice rotation in northern India. Fertilizer Research 33: 97-106.

149. Vidal RA and TT Bauman. 1996. Surface wheat (Triticum aestivum) residues, giant foxtail (Setaria faberii), and soybean (Glycine max) yield. Weed Science 44: 939-943.


