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Review

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

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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 NO_x 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_{10} (812 Gg), $PM_{2.5}$ (824 Gg), elemental carbon (58 Gg), OC (239 Gg) and GHGs (211Tg). The emissions of SO_2, CO, NOx, and NH_3 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 suggests 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, phosphorus, potassium and sulphur, respectively (Dobermann and Fairhurst, 2002). Each ton of paddy straw contains approximately 5.5 kg N, 2.3 kg P_2O_5, 15-20 kg K_2O, 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^{-1}), Fe (777 g ha^{-1}), Mn (745 g ha^{-1}), Cu (42 g ha^{-1}), B (55 g ha^{-1}) and Mo (4 g ha^{-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 x 10^7 kg methane, 23.1 x 10^8 kg carbon monoxide, 2 x 10^6 kg nitrous oxide and 84 x 10^6 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_2, 2 kg SO_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 e*t 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 ($PM_{2.5}$) measured in New Delhi, India, were 127.15 µg m^{-3} ± 95.23 µg m^{-3} that exceeded national standard of 60 µg m^{-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 *Bhussa* (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.*,

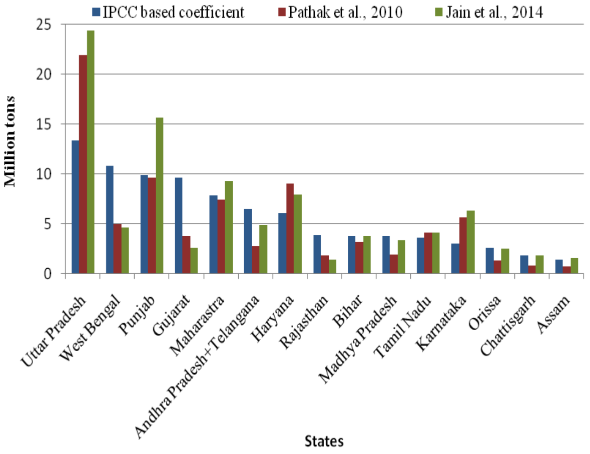


Fig. 1: State wise (top ten) scenario for annual burning of crop residues (mt/year) in India (Devi *et al.,* 2017).

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 likeTurbo 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_2O_5 (5.8%), exchangeable K_2O (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^{-1} 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^{-1} of crop residues were required. At least 4 to 5 t ha^{-1} of crop residues were required to enhance the soil organic carbon with an annual gain rate of 0.38 t C ha^{-1} $year^{-1}$. While, to reduce weed emergence and biomass by 50% compared to a no-till bare soil, residue amounts of 2 t ha^{-1} 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) or on 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 co-operative 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 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 ormulcher, standing anchored stubbles with loose straw as 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 bycutting/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 (Balwiner-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 °C 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 >34°C) 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 °C 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^{-1}day^{-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 °C 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 prevalentin north-western Indo-Gangetic plains. However, further investigations are required to optimize sowing time

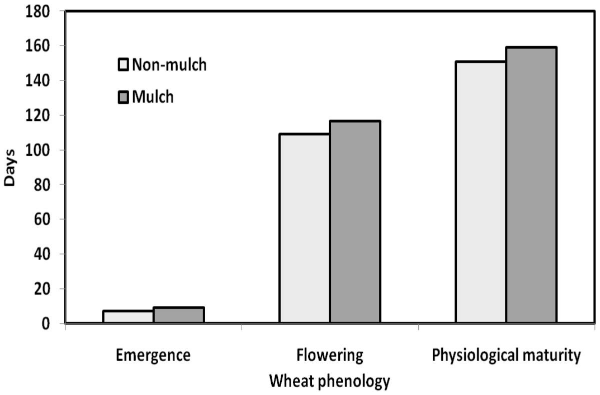


Fig. 2: Effect of surface retained paddy straw on wheat phenological growth stage (Balwinder-Singh *et al.*, 2011b)

under full and partial residue retention scenarios for higher wheat productivity under future vulnerable climatic conditions.

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 itmay 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.

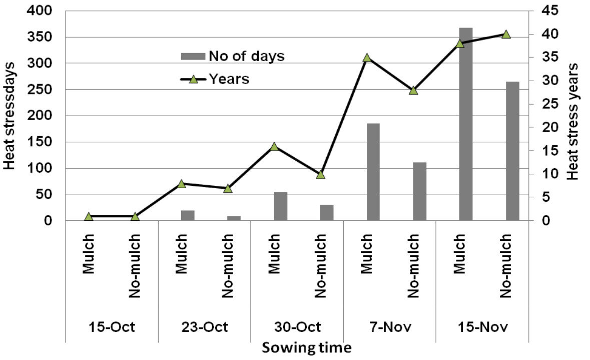
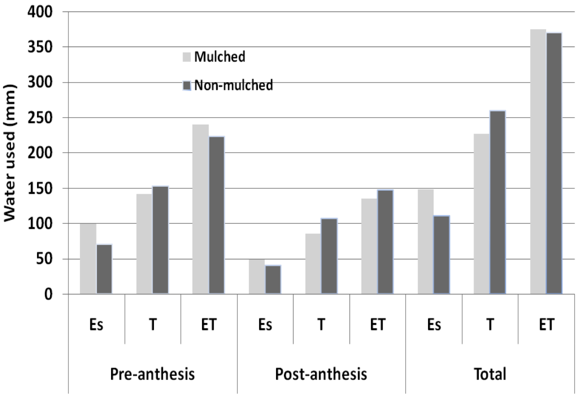


Fig. 3: APSIM model simulation study (40 seasons) for heat stress scenario during grain filling in relation to mulch in wheat (modified and adapted from Balwinder-Singh *et al.*, 2016)

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,



Es- Soil Evaporation, T- Transpiration, ET- Evapo-transpiration

Fig. 4: Effect of mulch on evaporation from soil and transpiration in wheat during pre and post anthesis (Balwinder-Singh *et al.*, 2011a).

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 micro-organisms 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 rice residues lost 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 thatwhere 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 studieson 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 in10.7 and 8% higher grain yield of wheat as compared to residue incorporation (3.72 t ha^{-1}),while the increase in rice yield was 23.5and 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 rice 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*, *Anagallis 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 raisedto 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 Abugho, 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 conjugation 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 is becoming 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 *Rht* 8 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

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).

Weeds	**Resistance against the chemical groups**	**Effect of *in-situ* retention of paddy straw/ no till on weed establishment and growth**
Phalaris minor	Phenyl urea (Isoproturon), Aryloxy phenoxypropionic (Clodinafop), Sulfonylurea (sulfosulfuron, mesosulfuron), and Phenylpyrazole (pinoxaden)	[a]Reduced due to higher upper soil strength and physically inhibition by huge residue load. [b]Emergence of *Phalaris minor* reduced by 45 % with paddy straw as mulch (6 t ha^{-1}) as compared to no mulch.
Polypogon monspeliensis	Sulfonylurea (sulfosulfuron, mesosulfuron), Triazolopyrimidine sulfonamide (pyroxsulam)	[d]Rice residue as mulch (5.0-7.5 t ha^{-1}) reduced foxtail grass weed biomass by 26 to 40%.
Rumex dentatus	Sulfonylurea (metsulfuron, triasulfuron, iodosulfuron), Triazolopyrimidine sulfonamide (pyroxsulam, florasulam)	[b]Seeds are float and accumulate on soil surface after puddling in rice and while remain on soil surface, so likely to be a problem in zero till conditions. [a]Emergence of *Rumex dentatus* reduced by 88% with paddy straw as mulch (6 t ha^{-1}) as compared to no mulch
Chenopodium album	Sulfonylurea (sulfosulfuron, metsulfuron)	[c]Conservation tillage promoted earlier emergence of *C. album*as compared to conventional tillage [a]Emergence of *Chenopodium album* reduced by 83% with straw mulch (6 t ha^{-1}) as compared to no mulch
Avena ludoviciana	Aryloxyphenoxypropionic (Clodinafop), Sulfonylurea (sulfosulfuron, mesosulfuron)	[c]Conservation tillage promoted earlier emergence of *Avena* species.

([a]Kumar *et al.,* 2013; [b]Chhokar *et al.,* 2007; [c]Bullied *et al.,* 2003; [d]Chhokar *et al.,* 2009)

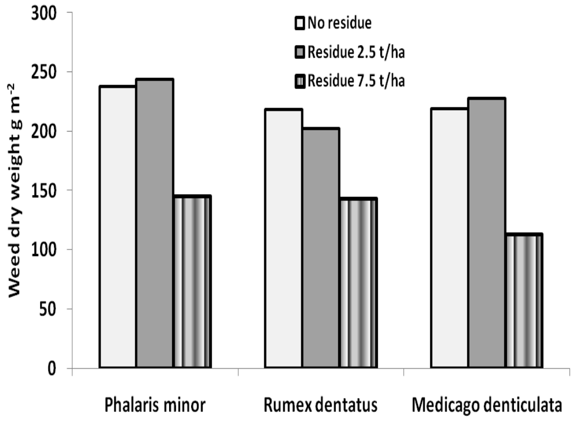


Fig. 5: Effect of rice residues retention on dry matter accumulation of wheat associated weeds at 120 DAS (Chhokar *et al.,* 2009)

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 2. Exploring genetic diversity to tailor wheat for enhancing productivity in conservation agricultural. based rice-wheat cropping system

Sr. no.	Treatments	Observations/Remarks	References
1.	Twelve wheat genotypes (HUW 234, HUW 468, HUW 510, HUW 516, PBW 343, PBW 443, HD 2627, HD 2733, UP 2338, NW 1012, DBW 14, Raj 3765) evaluated under conventional and zero-tillage conditions	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%	Joshi *et al.*, 2007
2.	Forty two differentially adapted lines of wheat with permanent bed (zero tillage) with full residue retention (CA), raised bed with no residue (CTRB) 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.	In GGE bi-plot analysis for yield, cultivars HD3115, CSW2, CSW16, CSW18, CSW23 and CSW25 showed distinct and positive interaction with CA and CTFB. While, based on (AMMI) cultivars HD3115, 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.	Sagar *et al.*, 2014
3.	Screening of 42 genotypes under conventional tillage flatbed (CTFB) and conservation agriculture (CA) based on indicator scoring system for identification of genotypes	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.	Sagar *et al.*, 2016
4.	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.	Parents CSW02 and HD3117 are good combiner for grain filling rate (GFR) while, CSW02 and CSW77 are good combiner for grain filling duration (GFD). CSW02 was in general good combiner for both the traits under study and therefore, can be effectively involved in the crossing program to make further gain.	Kumar *et al.*, 2017
5.	Cultivars K 9351, K 7903, HD 2967, DBW 14 and HI 1563 of wheat (*Triticum aestivum*) under no-till and conventional tillage.	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.	Kumar *et al.*, 2017
6.	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	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 (20-25th 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.	Chhokar *et al.*, 2018b
7.	Four rice cutivars, two coarse (HKR-47 and IR-64) and two fine cultivars (Sharbati and PB-1) were evaluated under direct seeding and puddle transplanted conditions	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 & PB-1) exhibited similar yields under both systems	Chhokar *et al.*, 2014

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^{-1} and 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

Duration / location/ Soil texture	Crop establishment	Results	References
5-years (2009-14)/ Karnal/ Loam	Conventional puddled transplanted rice followed by (*fb*) Conventional wheat (CPTR-CTW); Puddled transplanted rice *fb* zero-till (ZT) wheat *fb* ZT mungbean (CPTR-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)	(CPTR-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 (CPTR-CTW). Integrating opportunistic diversification with reduced tillage under precision resource management (CPTR-ZW-ZMB) reduced irrigation water (24%) and GWP (21%), besides increasing yield (0.9 t ha^{-1}) compared to (CPTR-CTW)	Kumar *et al.,* 2018
3-years (2001-02 to 2003-04)/ Karnal/ loam	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.	Out of the three tillage crop establishment methods, ZT and CT drill provided about 0.3 t ha^{-1} higher wheat grain yield over farmer's practice of CT-broadcast sowing. The reduced expenditure on tillage and higher yield, provided additional profit of about US $ 161.3 ha^{-1} for ZT over farmer's practice	Chhokar *et al.*, 2007
3-years (2009-12) at 3 locations/ Patna/ Clay loam	Tillage practices in rice included zero-till-drill rice (ZTR), un-puddled mechanical transplanted rice (MTR), direct wet sowing (DWS) and puddled transplanting (PTR) whereas, in wheat three methods of sowings viz. zero-till-drill (ZTW), manual line sowing (MSW) and sowing with Turbo Happy Seeder (THS)	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.	Sanjeev and Ujjwal, 2014
2 year (2008-10)/ Meerut/ Sandy loam	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).	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.	Kumar *et al.*, 2019b
4-year (2011-15) / Karnal/ Sandy clay loam	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)	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.	Jat *et al.*, 2019
7 year study/ Uttar Pradesh/ Sandy loam	Six treatments as T1: transplanted rice after conventional puddling and drill-seeded wheat after conventional tillage (CT-TPR/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-DSR/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)	Average rice yields (7.81- 8.10 Mg ha^{-1}) were maximum in T1 andT2 and increased with time (0.26 Mg ha^{-1} yr^{-1}) inT2. Yields of rice lower in T5 (16%) and T3 (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 T1 and 19% lower than other treatments. Maximum net returns in rice CT and crop establishment practices, but higher with ZT in wheat. Hence, highest net returns (~1225US$) were found in T2 and T5 and lowest (747-846 US$) in T3 and T4 in the RWS.	Gathala *et al.*, 2011a

5-year field experiment established in 2011/ PAU Ludhiana/ Sandy loam	(1) PTRWS0, puddled transplanted rice (PTR) with no wheat straw (2) PTRWS25, puddle transplanted rice with 25% anchored wheat stubbles retained (3) PTRWS0 plus green manure (GM), and (4) PTRWS25 plus GM. Three sub-plots treatments in subsequent wheat included (1) CTWRS0, conventional tillage wheat without rice straw (2) ZTWRS0, zero tillage wheat without rice straw and (3) ZTWRS100, ZTW with 100% rice straw retained as surface mulch.	The activities of dehydrogenase, β-glucosidase and concentration of easily extractable glomalin and total carbohydrate carbon under ZTWRS100 were 36.8, 24.6, 25.9 and 23.3% higher than CTWRS0. Application of GM and wheat straw retention in previous rice significantly increased grain yield of subsequent wheat crop by 26.5%. The majority of the increases in biochemical properties were higher at vegetative growth (at 40-45 DAS) and flowering (at 80-85 DAS) stages compared to the initial and at maturity.	Saikia *et al*, 2019
Experiment started in 2010/ Sandy loam/ PAU Ludhiana	Twelve treatment combinations of tillage, crop establishment and crop residue management included four main plot treatments in rice: (1) conventional tillage (CT)-DSR, (2) ZT-DSR, (3) DTR, ZT machine transplanted rice and (4) PTR, conventional puddled transplanted rice. The three subplot treatments were: (i) CTW-R, CT wheat with both rice and wheat residues removed, (ii) ZTW-R, ZT wheat with residues of both the crops removed and (iii) ZTW+R, ZT wheat with rice residue retained as surface mulch in subsequent wheat.	Average wheat grain yield under ZTW+R was 6% and 10% higher than CTW-R and ZTW-R respectively. Soil enzyme activities increased (5-18%) under ZTW+R compared with ZTW-R and CTW-R at different growth stages of wheat. The residual effect of rice establishment methods was significant on soil enzyme activities during wheat cropping, which were highest under ZT-DSR followed by CT-DSR, DTR and PTR. SOC content in the 0-7.5 cm layer was significantly higher (7-9%) under the ZTW+R treatment compared with all the other treatments. Principal component analysis (PCA) identified three enzyme activities (dehydrogenase, fluorescein diacetate and phosphatase), and SOC content as the most sensitive indicators for assessing soil quality for RWS based on conservation agriculture.	Bera *et al.*, 2017

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 decomposable 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 CO_2-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 P_2O_5 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 reesei* resulted in higher alkaline phosphatase, dehydrogenase, humus content and it was superior to the treatments, where both *T. reesei* 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 tripple disc suitable for sowing wheat under surafce 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 clearnace helps in drilling of wheat under loose straw with more anchored stubbles. In this drill the tyne to tyne 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 (Gaind 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 dirhamnolipid (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 CO_2-eq ha^{-1} yr^{-1}) and GHGI (1.20 kg CO_2-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 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.

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