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Tillage and residue management for sustaining rice-wheat cropping system in Indo-Gangetic Plains- A review

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Abstract
The rice-wheat cropping system occupying 13.5 million ha is important to meet the challenge of food security in the Indo-Gangetic Plains. The consequences of current production practices viz., degraded soil health, high cost of cultivation, inefficient use of resources and environment raises the danger to its sustainability. In the Indo-Gangetic Plains (IGP) of South Asia, the most widely adopted resource conserving technology has been zero-tillage (ZT) in wheat after rice, particularly in India. The severity of system constraints can be reduced by ZT wheat via earlier/timely planting (5-10% yield gains), control of *Phalaris minor,* reduced cultivation costs (fuel saving of 36-43 litres ha^{-1} and higher returns of Rs 4300-5700 ha^{-1}) and water saving. Soil organic carbon, porosity, aggregate size and infiltration rate also increased significantly with long term zero tillage. The yield increase alongwith a cost saving led to pretty robust adoption rate but still knowledge gaps exist. Therefore, more research is needed to understand the interactions between ZT and soil type, seasonal factors and cumulative effects that cause farmers to adhere to conventional tillage (CT) or reduced tillage (RT) in some plots or seasons. Therefore for further wider adoption, ZT should be considered as a system and be looked more precisely to suit varying farm situation.

Keywords: Cost saving, Indo-Gangetic Plains, rice-wheat, zero-tillage, soil health, long-term effects

Introduction
The rice-wheat system covers an area of about 13.5 million hectare (M ha) in South-East Asia. It extends across Indo-Gangetic Plains (IGP) covering 2.2, 10.5, 0.8 and 0.5 M ha in Pakistan, India, Bangladesh and Nepal and plays an important role in providing livelihood to millions of people [1]. In India, it is the most important cropping system as it contributes to 85% of the total cereal production thus adds substantially to national food bowl [2]. Although yields of this system were boosted in IGP during green revolution, however, recent studies indicate a decline in growth of productivity. Yield stagnation and its decline were also reported in long term studies [3, 4, 5]. The rice and wheat crops require very different soil physical and hydrological properties, which are mainly controlled by the tillage practices, which lead to degradation of soil and water resources and threaten the sustainability of rice-wheat system in IGP [6]. Moreover, efforts for diversification and alternative cropping systems were not successful due to guaranteed profitability and lower risks with this system. Therefore the technologies that can improve resource base, sustain production levels of crop and soils, reduce production cost while conserving the environment, are becoming important [7]. Keeping in view the importance of rice–wheat system, resource conservation technology (RCT) in the form of zero-tillage (ZT) was introduced in the region during 1996–97 and till date it has been regarded as the most successful RCT in this system of Indian IGP [8].

ZT is defined as a system of seeding/planting crops into untilled soil by opening only a narrow slot, trench or band of sufficient width and depth to obtain proper seed coverage [9]. In true sense, it is a system in which the soil should remain permanently covered with cover crops or crop residues from previous crops without soil disturbance. Cover crops and crop rotation need to be included in the no-till system. Thus successful ZT system involves proper sowing and residue management component and is based upon the principles of conservation agriculture [10]. But the ZT as applied to this system, has three distinctive features that make it different from related systems elsewhere [11, 12, 13]. First, ZT is only applied to the wheat crop in this system, although, the succeeding rice crop is tilled intensively. Second, ZT wheat after rice does not necessarily need an increased dependence on herbicide, indicating lesser weed population at harvest time. Third, ZT wheat may not always use crop residues as mulch. In the IGP, the prevailing ZT technology uses a tractor drawn ZT seed drill having inverted-T openers for dropping seed and fertilizers simultaneously and directly into untilled fields [14]. The full benefits of ZT can be achieved by continuously covering the soil surface and practicing it. In order to meet the principles of conservation agriculture (CA) a new machine has been developed by the continuous efforts of Punjab Agricultural University, Ludhiana, India in collaboration with Australian Centre for International Agricultural Research. This second generation ZT drill is known as Happy Seeder, which is capable of drilling the wheat seeds directly into heavy rice residue loads and thus, avoids burning.

This paper reviews and synthesizes the reward of ZT wheat in the rice-wheat system of the Indian IGP. The present paper includes (i) a brief historic overview, current scenario and adoption levels of ZT and (ii) the reported ZT effects on: crop productivity, cost savings and profitability, energy saving, water productivity, weeds, soil properties and environment.

Scenario of ZT in World and India: In 1973-74 ZT was applied only on 2.8 M ha worldwide but within 10 years i. e. 1983-84 the area under this technology grew to 6.2 M ha. However, the area under no-till had reached to 38 M ha by 1996-97 [20]. Worldwide ZT is now practiced on 155 M ha (Fig 1).

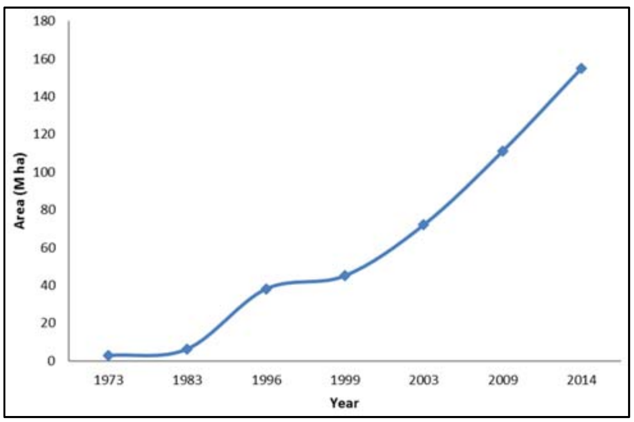


Fig 1: The worldwide growth and expansion of area under ZT
Source: [20, 21]

Presently the area under ZT in different countries of the world is given in Fig: 2 with USA and Brazil being the leading countries.

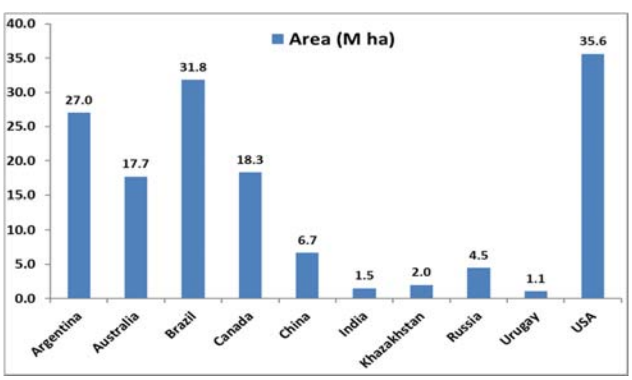


Fig 2: Area under ZT in different countries of world
Source: [21]

In rice-wheat system, ZT is adopted primarily in wheat crop and is concentrated in the north-west IGP. Estimates of area under ZT are often based on the sale of ZT drills and average area coverage per drill [22]. However, from these estimates, it is difficult to separate ZT from RT so that these two technologies are typically lumped together (ZT + RT). In India, during mid-late 1990s, the ZT technology was in its testing phase and farmers were facing the problem of late planting, labour scarcity and herbicide resistance. The total estimated area under ZT + RT wheat was 820 thousand hectares in the Indian IGP during 2003–2004 [23. 24]. This technology was adopted mostly in Haryana (46%), Punjab (26%) and western UP (21%). In India, presently it occupies 1.5 m ha area mainly in IGP [21].

But limited adoption of this technology compels to make modifications after analyzing the experiences of adopters. The data revealed that some farmers use the ZT drill, but maintain a limited degree of tillage (i.e., RT). Some farmers continue to use both ZT and CT side by side on the same farm [25-27]. In Haryana, ten percent of 400 randomly surveyed farm households had dis-continued ZT temporarily in rice-wheat belt [27]. Due to certain problems viz., formation of hardpan, weeds, etc, forced some farmers to discontinue ZT [24]. Therefore, research should be focused on understanding the interactions between ZT and soil type, seasonal factors and cumulative effects that force farmers not to leave CT or RT in some fields or seasons (e.g., as preferred option to control perennial weeds; to remove traffic lines caused by machinery; incorporate excess residues [28]. Besides these emerging issues, the salient advantages of ZT technology are highlighted below.

Cost savings and profitability: Available studies clearly highlighted the profitability of wheat production under ZT over CT (Table 1). The parameters that contributed to its profitability includes: (i) the increase in yield i. e. yield effect and (ii) the saving in cost of production i.e. cost saving effect. The ZT yield effect and cost saving effect averages Rs 2030 ha^{-1} (US$ 45) and Rs 2320 ha^{-1} (US$ 52) across IGP studies, respectively. In line with the above reported yields, the increase in yield is higher in the E IGP than in the NW IGP and cost saving effect somewhat higher in NW IGP (Table 1). The cost savings are mainly due to the savings in land preparation and crop establishment costs (approx 2/3rd of the total cost saving), amounts to Rs 1690 ha^{-1} across IGP studies. Savings in costs of irrigation and other inputs add to this. [29] In another study it was concluded that farmers in Haryana can save approximately 79 US$ ha^{-1} in terms of total cost of production and net revenue can be increased by about 97.5 US$ ha^{-1} under ZT over CT [29]. In Haryana the cost saving effect amounted to 6-7% [27, 30], and in Uttaranchal 16% of the total cost of CT [31]. The contribution of cost saving effect (53%) was higher than the yield effect (47%) to the net profit of ZT averages Rs 4350 ha^{-1} over CT across IGP studies (Table 1). The average net benefit of ZT in the E IGP is higher (Rs 4760 ha^{-1}), due to more contribution from the yield effect (54%). However, in the NW IGP, cost saving effect contributes 58% to the average net benefit of ZT (Rs 4120 ha^{-1}). Cost savings of 2000-2500 Rs ha^{-1} and net benefit of 4400–5000 Rs ha^{-1} with ZT is reported in Punjab and Haryana [24]. Likewise, highest net returns were also obtained from double zero-till plots of rice-wheat system [32] and maize-wheat system [33]. Saving of 34 US $ ha^{-1} in double ZT has been reported as compared to conventional rice-wheat system in IGP [34].

Table 1: Comparative economic indicators (Rs ha^{-1}) of wheat under ZT and CT in different regions of the Indian IGP and Madhya Pradesh (MP)

Location	Tillage cost saving	Total cost saving	Revenue gain	Net benefit gain
Haryana	-	-1390	2990	4380
	-	-1794	2278	4072
	-	-1868	417	2285
	-1844	-1844	1522	3366
Uttaranchal	-1737	-1961	1159	3120
	-1234	-3863	490	4352
	-	-3904	1302	5206
W UP	-2543	-2811	1706	4517
	-	-2179	3593	5772
E UP	-1927	-3048	1845	4893
	-1683	-2496	720	3216
Bihar	-	-1400	2950	4350
	-	-1835	4865	6700
	-885	-2120	2542	4662
MP [non-IGP]	-1263	-2075	1560	3635
IGP	-1690	-2320	2030	4350
NW IGP	-1840	-2400	1720	4120
E IGP	-1500	-2180	2580	4760

Source: **[35]**

Fuel and energy savings: In rice-wheat system, due to requirement of different soil conditions by rice and wheat crops, wheat need very intensive tillage as rice being grown under anaerobic conditions and wheat under aerobic conditions **[27, 36]**. These tillage operations are energy and input intensive and time consuming [32, 37] which involve 25–30% of total cost of wheat production in RW system of South leading to lower benefit cost ratio [34]. The adoption of ZT decreased the number of field operations for wheat crop establishment to one which otherwise need on an average of 7-8 [27, 36]. Some studies reported 81% saving in tractor operational time under ZT or in the range of 6-12 hr ha^{-1}, with an average of 8.9 hr ha^{-1} across IGP studies (Table 2). ZT was reported to reduce turn-around time which advanced the wheat planting by 7-10 days in Haryana and by 8- 25 days in Bihar [28, 30, 38, 39].

A few studies of ZT wheat in Haryana reported labor savings of 4.3% [36] and 5 person-days ha^{-1} [40]. Operational field capacity, specific energy and energy usage efficiency was enhanced by 81%, 17% and 13%, respectively under ZT as compared to the conventional tillage in the IGP of India [41]. A seasonal saving of 15-60 litre ha^{-1} (average of 36 litre ha^{-1} diesel for land preparation with ZT, or an average 81% saving have been reported across IGP studies. Similar results have been reported in other IGP studies [31, 42, 43]. A considerable reduction in greenhouse gas emissions of 93 kg CO_2 ha^{-1} was achieved alone by the fossil fuel savings **[24]**. Such potential savings have been observed in IGP and central India (Table 2).

Table 2: Tractor time and diesel use in ZT and CT in different regions of the Indian IGP and Madhya Pradesh (MP)

Location	Tractor time (hr ha^{-1})			Fuel use (litre /ha^{-1})		
	ZT	CT	Saving (%)	ZT	CT	Saving (%)
Punjab	2.3	11.2	80.0	12.5	33.0	62.0
Haryana	1.9	8.8	78.0	8.4	44.7	77.7
Uttaranchal	1.6	13.7	88.0	7.1	67.8	89.5
Western UP	2.0	9.5	79.0	7.1	48.8	86.0
Eastern UP	2.5	13.0	81.0	7.5	39.0	81.0
Bihar	2.3	11.5	80.0	7.3	36.5	80.5
M P	3.1	17.4	78.8	10.2	59.3	78.0
IGP	2.1	10.9	81.0	8.2	44.0	81.0
NW IGP	1.9	10.4	81.0	8.6	47.3	82.0
E IGP	2.4	12.3	80.0	7.3	37.3	80.0

Source: **[35]**

Green House gas emissions and environment pollution: Emission of GHGs such as CO_2, N_2O, CH_4 by agriculture sector contributes significantly to climate change. Of the total anthropogenic emissions of GHGs, about 12% are directly generated in agriculture, however, emissions from fertilizer industry, deforestation and land conversion to agriculture amounts to 35% to GHGs [44]. Agriculture's contribution in the total N_2O, CH_4, and CO_2 emissions are 60%, 39%, and 1%, respectively [45] with rice-based cropping systems playing a major role. Rice flooding and transplanting is considered one of the major sources of CH_4 emissions because of prolonged flooding resulting in an anaerobic soil condition. It accounts for 10–20% (50–100 Tg year-^{1}) of total global annual emission of CH_4 [46, 47]. Studies at different parts of the South-East Asia reported 24-79% reduction in CH_4 emission in ZT dry seeded rice than puddled transplanted rice (Table 3).

Table 3: Effects of various tillage and rice establishment methods on methane emissions in Asia

Location	Establishment Method	Seasonal Total emission (kg CH_4 /ha)	% change from TPR
Milyang, Korea	CT-TPR	402	-
	ZT-dry seeding	258	-36
Akasaka, Japan	CT-TPR	159	-
	ZT-dry seeding	34	-79
Suimon, Japan	CT-TPR	271	-
	ZT-dry seeding	129	-52
Sanyoh, Japan	CT-TPR	330	-
	ZT-dry seeding	252	-24
Pantnagar	CT-TPR	315	-
	CT-dry-DSR	220	-30

Source: [48]

Tillage is assumed to have a major influence on soil CO_2 emissions and there are many reports showing that soil tillage enhances oxidation of organic carbon thus releasing high amounts of CO_2 to the atmosphere within a few weeks [49, 50, 51]. In an on-farm study the ZT based wheat production helped to reduce CO_2 emissions by 1.5 Mg ha^{-1} season-^{1}[29]. So, adoption of ZT in Haryana to about 1 M ha under wheat production will reduce GHG emission of about 1.5 M tonnes of CO_2 equivalent. These results corroborates with another finding who also reported lower global warming with ZT system than CT system in a long experiment of 9 years [52].

Burning is the easiest method of crop residue management and farmers burnt most of the (more than 80%) rice straw produced within 3-4 weeks during October-November. Burning of rice straw emit gases contained 70% CO_2, 7% CO, 0.66% CH_4, and 2.09% N_2O [53]. Zero-till seed drill is capable of sowing into bare, non-tilled soil and into anchored rice residue. However, direct sowing of wheat into combine harvested rice fields is difficult due to the problem of loose straw. A new machine, known as the 'Happy Seeder' (HS) reduces the need to burn and/or remove the previous crop's stubble with the attendant environment costs, and contributes to the development of conservation agriculture systems.

Control of Phalaris minor: Weeds in wheat crop were reduced with the adoption of ZT in RW systems in the IGP [54-61]. It has been also reported in Haryana and Bihar that weed infestation decreased due to the adoption of ZT in wheat [40]. The major weed of wheat in the Indian IGP i.e. *Phalaris minor* Retz. (Little seed canary grass), showed emerging resistance to isoproturon herbicide during mid-1990s [55, 62-65]. ZT serves as an effective control measure of *P. minor* by reducing soil movement [14, 55, 66]. So, the ability of ZT to control herbicide-resistant *P. minor* became a major factor for its adoption in NW IGP, and its combined use with new herbicides eventually managed to solve the problem of *P. minor*. Surveyed farmers concur that ZT reduces *P. minor* infestation [28, 31]. With ZT in wheat, weed competition is greatly reduced due to less and late emergence of weeds especially *P. minor.*

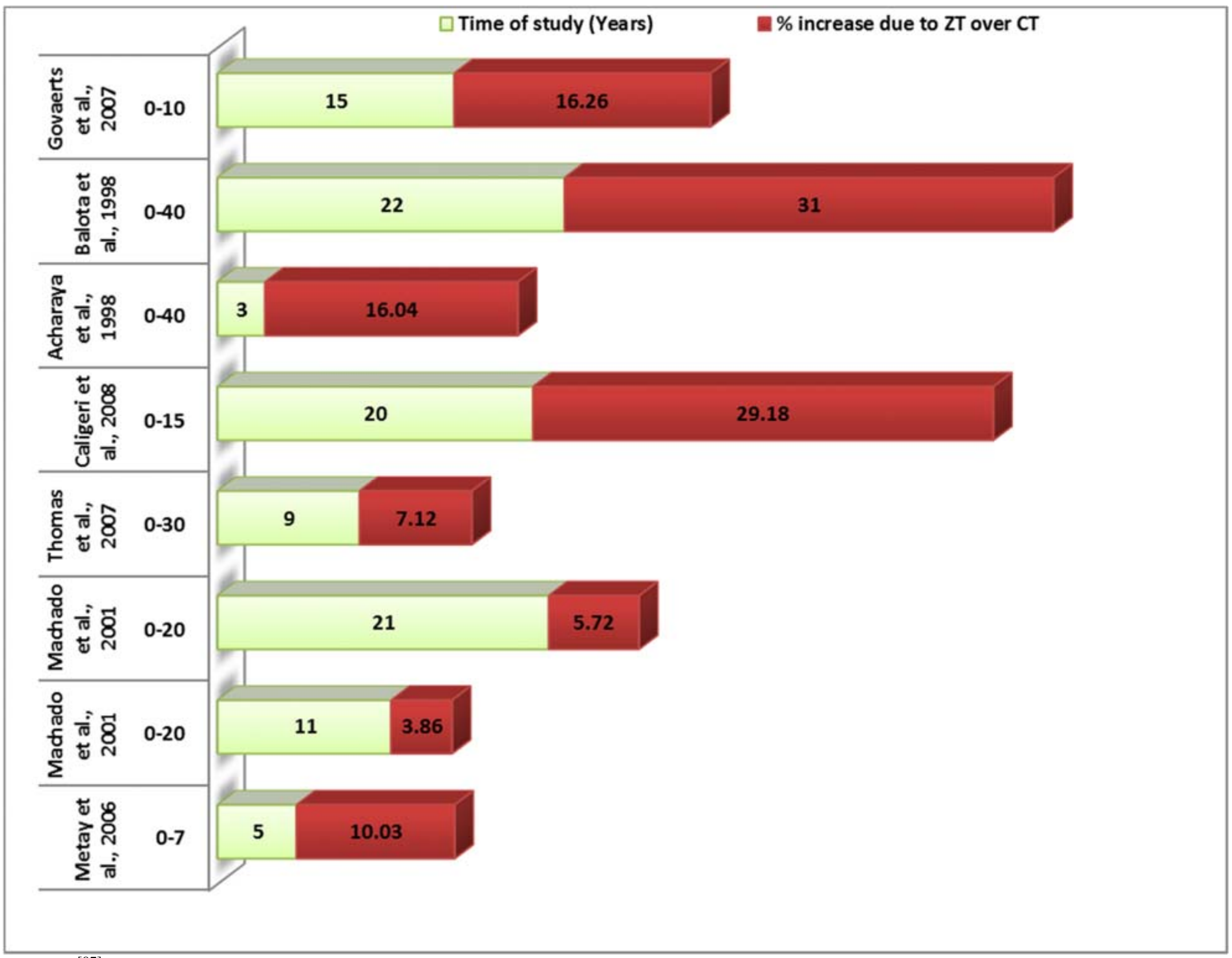
Farmer surveys and long-term experiments reported a change in the weed spectrum in wheat under ZT. In a study, increase in the population of broad-leaved weeds was reported [54] while in a long-term trial conducted in Haryana, 30-40% decrease in intensity of *P. minor* in ZT when compared to CT was recorded, while the population of broad-leaved weeds increased [67]. Less infestation of *P. minor* under ZT was also found in the long-term study in Haryana (1997–98 to 2001–02) [68].

Water savings in ZT: In Punjab and Haryana, about 60–65% of the total irrigation requirement is met through tube wells. Due to over-exploitation of groundwater, water table is depleting at an alarming rate and 75% of blocks have become over exploited in Punjab. Excessive withdrawal of groundwater is aggravated by poor water management which results into decline in water table in some areas and increase in water logging and salinity in other areas [18, 69, 70]. There is increasing agreement that ZT can be successful in improving field-level irrigation efficiency through irrigation savings [7, 71, 72].

ZT is reported to save 20–35% of irrigation water and reduce water use by about 10 cm ha^{-1} in the wheat crop compared to CT [7, 14, 43]. A study in Haryana reported a 13% saving of tube well irrigation water [27] and 10–27% [73] with ZT in rice-wheat area. The saving of water with ZT might be due to the saving in pre-sowing irrigation as ZT wheat is generally sown in the residual moisture after the rice harvest. This residual moisture is productively used as transpiration by the wheat crop rather than unproductive evaporation. Moreover, irrigation water advances faster in untilled soil as compared to tilled soil and 21% water saving for the first irrigation is reported [27]. So, the problem of yellowing of the wheat plants after the first irrigation is reduced [7, 28, 74]. Moreover, ZT can facilitates buildup of soil carbon and improve soil structure which results in better infiltration, increased water retention, and reduced water use elsewhere [12, 13]. In addition, advancement in planting and harvesting of ZT wheat can reduce the need for one or more late-season irrigations in some areas. ZT can thus save one irrigation in wheat [14, 40, 42, 75, 76]. The irrigation savings leads to cost savings, particularly in the case of diesel-operated pumps. On system basis, 12–15% less water application in double no-till rice–wheat system was reported as compared to conventional system in NW IGP [34]. Likewise, the advantage of double ZT rice-wheat system with 12–20% less water consumption with almost equal system productivity was reported and higher water productivity demonstrated as compared with CT systems [32]. Thus ZT wheat reduces irrigation requirements, save irrigation water and thus enhances water use efficiency. To address the problem of water shortage and declining water table in the rice–wheat growing areas of NW IGP, ZT can be given a due importance [42, 77].

Soil properties: Monoculture of rice-wheat system has been deteriorating the soil and water resources in IGP [6]. For attaining long term sustainability, the residue management and tillage system needed precise thought. The increased losses of soil organic carbon with conventional tillage has been well documented [78]. A 10% loss of initial soil organic matter content was reported during the first 4 years of tillage [79]. In 3 years of continuous rice-wheat system study, 29.6%

increase in the soil organic content on sandy loam and 11.6% on silt loam with straw retention was reported as compared to straw burning [80]. The carbon sequestration was 25% in ZT with rice straw retained as compared to 17% in straw incorporation with CT as straw decomposition rates are generally faster for incorporated residues as compared with surface placed residues, hence proved more efficient in C sequestration. Likewise, it was reported that carbon content in surface 0.4 m soil depth increased by 19.0% in sandy loam, 34.7% in loam and 38.8% in clay loam soil in the long-term (15 years) ZT wheat under RW system of IGP over CT [81] and the carbon sequestration rates were reported as 0.24, 0.46 and 0.62 Mg ha-^{1} year-^{1} in sandy loam, loam and clay loam soil, respectively. Similarly 65, 17 and 7% higher soil organic content was reported with ZT over plough-tillage in the 0-5, 5-10, 10-20 cm soil depths [82]. The comparative analysis of soil organic content under ZT and CT from medium to long term studies conducted by different researchers revealed that ZT recorded higher soil organic carbon content ranging from 3.86-31.0% as compared to CT (Fig: 3) Analysis also revealed that ZT recorded higher organic carbon content over CT over longer period of time [83, 84] and even showed the increase in soil organic carbon content even up to 40 cm soil depth as compared to CT [83, 85]. The results of 9 years experiment with ZT in China resulted in significantly higher soil organic carbon in the top 4 cm of soil, which was reported to be 57.8% higher than that in the top 4 cm of the plough-till. In the next 4 cm depth, organic carbon concentration was 15.1% higher over plough-till. Further it was reported that the organic C concentration from 8-30 cm depths was not affected by tillage systems [86].



Source: [87]

Fig 3: Differences in soil organic carbon content (%) due to adoption of zero tillage over conventional tillage

Soil organic matter build up with long-term straw application while substantial amount of plant nutrients (especially N and S) and organic carbon lost during burning of crop residues, which has also important implications for soil health. In Punjab alone, about 1.5 lakh tonnes of N and S in the rice residue is estimated to be lost during burning, which costs more than Rs. 200 crores at the present prices [53]. In a long-term study of ZT over an 11-year period (1998-2009) in North Plain of China, it was reported 16.1%, 31.0% and 29.6% increase in soil organic matter, available N and P, respectively in the top 10 cm soil layer as compared to CT treatment [88]. The effect of continuous ZT and CT in wheat on soil physico-chemical properties at 6 different locations in Haryana revealed that after 4 years of the multi-site study, organic carbon (%) and available K in the 0-15 cm soil depth were higher in ZT (OC 0.09-0.24% higher, and available K 8-36 kg ha^{-1} higher) as compared to conventional tillage [56]. In a field experiment conducted) at the experimental farm of the Punjab Agricultural University, Ludhiana an increase in the Olsen P in soil after 4 years of rice straw incorporation was reported as compared with its removal from the field [89]. The magnitude of increase in K availability is, however, small because straw burning is known to cause little loss of K from rice straw [90].

Conventional system of tillage in rice–wheat cropping system was found to deteriorate soil structure and develop a compaction pan beneath the usually tilled layer of 15 cm in different textured soils in rice cultivation areas. Puddling destroys soil aggregates, breaks capillary pores, reduces permeability in sub-surface layers and forms hard pans [91, 92] that have a negative effect on the succeeding wheat crop [93] but soil physical properties were improved as a consequence of decreased disturbance and crop residue cover on the surface in ZT system. North-Western IGP of India, the effect of three tillage systems (conventional flat (CTF); Zero-till flat (ZTF); permanent raised beds (ZTB) revealed that CTF system had higher bulk density and penetration resistance in 10-15 and 15-20 cm soil layers due to compaction caused by the repeated tillage [33]. The most likely reason for higher values of bulk density and soil resistance in CTF compared to ZTF and ZTB is the excessive use of tillage implements causing compaction in the plough layer. These results are in conformity with those reported earlier by [32, 94-97]. The soil bulk density had declined in ZT plots and in 0-10 and 10-20 cm soil layers, it was 2.1% and 4.7% significantly lower than in CT [88]. A similar trend was observed at the 20–30 cm soil depth, but the difference between ZT and CT was negligible. Likewise, the higher bulk density was observed in the 15-20 cm layer of the soils under CT indicated the development of plough sole beneath the usually tilled layer in both rice and wheat crops for several decades while the lower bulk density of same layer under ZT practice demonstrated that no-till system helped reducing sub-soil compaction in long term field trial [81].

A field experiment on rice-wheat system reported under permanent beds and double ZT higher infiltration rate and soil aggregation (>0.25 mm) as compared to lower in the CT [32]. Similarl findings were also reported for maize-wheat system and a higher mean weight diameter of aggregates was found under ZT Bed and ZT Flat in comparison to CT Flat [33]. This increase in soil aggregation was due to more soil organic carbon (4.46 g kg^{-1}) than in CT Flat (4.09 g kg^{-1}because the soil disturbance was least under this treatment. In North China Plain a study was conducted over an 11-year period (1998–2009), it was reported that the mean percentage of macro-aggregates (>0.25 mm, +8.1%) and macroporosity (>60 µm, +43.3%) was statistically higher in the 0–30 cm soil layer with ZT treatment [88]. Higher water intake rate of soils in ZT as compared to CT in long term study have also been reported, however, significant increase (28%) was observed in clay loam soil only [81]. Water infiltration into the soil is controlled by the number and connectivity of surface vented macropores [98], therefore, the practice of ZT may have promoted macropores networking in clay loam soil resulting in higher infiltration as compared to the CT practice [99, 100]. Similar results have also been reported for loam [101] and sandy clay loam [102] soils.

Different changes induced in tillage and residue management practices results in major shifts in the composition of soil fauna and flora and their number, which includes both pests as well as beneficial organisms. A uniform supply of carbon which serves as an energy source for microorganisms is continuously supplied from crop residues. Increased soil aeration, lower temperature and moisture fluctuations resulting in cooler and wetter conditions and higher carbon content in surface soil due to ZT and residue retention are responsible for the favourable effect on microbial population.. Soil where crop residues retained, it inhabited 5-10 times more aerobic bacteria and 1.5 to 11 times more fungi than in soil where residues were either burned or removed [103]. Results of four years study on conservation tillage and residue management in rice based system in NE India revealed that ZT recorded higher soil microbial biomass carbon, dehydrogenase activity and earthworm population which in turn resulted in good growth and higher yields [104].

Crop productivity: Rice-wheat systems in IGP are often characterized by late planting of wheat [14, 18, 19, 75] and there is reduction in the wheat yield by 1–1.5% day^{-1} if planting is done after mid-November [105, 106]. This delay is as a result of the late harvest of the previous crop, intensive tillage operations, non-optimum soil-moisture i.e. either very wet or too dry, unavailability of suitable mechanical power for ploughing, and an urgent of storing facilities, needed to store the harvested rice crop. As ZT allows greatly reduces the turn-around time, timely sowing of wheat is possible, allowing wheat establishment in a single pass almost immediately after the rice harvest. A ZT induced yield advantage of 15.4% in Haryana, which is result of 9.4% gain due to timeliness and 6.0% due to enhanced use of fertilizers. Enhanced water-use efficiency and reduction in *P. minor* population has also been reported [14]. On-station trials across the Indian IGP generally reported increases in wheat yields with ZT in the range of 1-12%, with an average gain of 240 kg ha^{-1} or 6.4% across IGP studies (Table 4).

Table 4: On-station yield of wheat (t ha^{-1}) under ZT and CT in research centers in different regions of the Indian IGP and Madhya Pradesh (MP)

Location	ZT	CT	Gain (%)
Punjab (Ludhiana)	3.88	4.08	-5.1
Haryana (Kaul)	4.76	4.66	2.0
Uttaranchal (Pant.)	4.50	4.11	9.5
W UP (Meerut)	4.97	5.07	10.3
E UP (Faizabad)	3.91	3.61	8.7
E UP (Varanasi)	3.06	2.26	38.1
Bihar (Patna)	3.62	3.29	9.9
Madhya Pradesh [non-IGP]	4.84	4.60	5.2
IGP	3.98	3.74	6.4
NW IGP	4.49	4.51	-0.3
E IGP	3.54	3.09	14.8

Source: [35]

Table 5: Yield gains of wheat crop under on- farm trials and farmers survey in IGP

Location	% Yield gains	
	On farm trials	Farmer field surveys
Punjab	3.7	-
Haryana	5.4	4.7
W UP	5.2	-
E UP	15.4	-
Utranchal	-	4.5
Bihar	10.0	8.7
IGP	6.6	5.0
NW IGP	4.9	4.6
E IGP	11.0	-

Source: [35]

On-farm trials across the IGP have more consistently highlighted the higher yields with ZT, with an average gain of 290 kg ha^{-1} or 6.6% across IGP studies and reported greater ZT yield gains in the E IGP than the NW IGP. In the NW IGP the gain averages 230 kg ha^{-1} or 5% while in the E IGP the gain averages 400 kg ha^{-1} or 11% (Table 5). These gains are consistent with the reports that reported an average 280 kg ha^{-1} increase in wheat yield in 112 farm trials across five states in the IGP [107]. Their average ZT yield gain also increases proceeding eastwards: 110 kg ha^{-1} in Punjab, 172 kg ha^{-1} in Haryana, 273 kg ha^{-1} in Uttaranchal, 345 kg ha^{-1} in E UP and 490 kg ha^{-1} in Bihar. Marked yield gains with ZT, with the gains increasing from Punjab towards the middle Gangetic plains reflecs the increasing importance of timeliness in sowing. Likewise, significantly higher productivity of maize-wheat system was reported in ZT flat and ZT bed as compared with CT practices in IGP [33]. Additional advantages like less weed growth, water savings, improved soil health and environment qualities besides yield gains of 3.24% were also reported with retention of straw mulch with HS technology from 154 on-farm trials under Punjab conditions [108].

Conclusions

Wheat grown through zero tillage after rice results in significant advantages at the farm level, in terms of higher yield gains (5–10%), fuel saving of 36-43 litres ha^{-1} and subsequently higher returns of Rs 4300-5700 ha^{-1}. ZT also emerged as new tool for integrated management of *P. minor* in wheat besides saving irrigation water. These benefits explain the widespread interest of farmers and the rapidity of the ZT diffusion across the Indian IGP, further aided by the wide applicability of this mechanical innovation. Soil organic carbon, porosity, aggregate size and infiltration rate was also increased significantly with long term zero tillage. The combined effect of a yield increase with a cost saving led to pretty robust adoption rate but, significant knowledge gaps exist. Farmers in certain pockets are using the ZT drill, but they often do a minimum degree of tillage (i.e., RT). In spite of its various advantages farmers even discontinued its adoption temporarily due to problems like formation of hardpan and increased infestation of weeds especially the perennial weed. To overcome these problems the need of for occasional tillage occurs. If we want the farmers to adopt it at a large scale, analysis of the experiences of adopters should be done and necessary modifications in the technology should be done, so as these suit the local needs and enable even wider adoption and adaptation. Therefore, still more analysis and research is required to understand the interactions between ZT and soil type, seasonal factors and the factors that cause farmers to adhere to CT or RT in some area and/or seasons. Hence for further wider adoption of ZT in IGP, the ZT should be considered as a system and be explored more thoroughly to suit varying farm situation.

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