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Research Paper

Growth, nutrient accumulation and crop yields as influenced by crop residues recycling and *Trichoderma* inoculation in rice (*Oryza sativa*)–wheat (*Triticum aestivum*) and sugarcane–ratoon–wheat cropping systems in subtropical India

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ABSTRACT

A field experiment was conducted during 2013-15 at the ICAR-Indian Institute of Sugarcane Research, Lucknow, Uttar Pradesh study the effect of crop-residues recycling and *Trichoderma* inoculation on growth, nutrient accumulation and crop yields in 2 cropping systems, viz. rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.)–rice–wheat and sugarcane–ratoon–wheat. The experiment was laid out in a split-plot design, with cropping systems in main plots and residues management practices in subplots. Among the different crop residue treatments, the highest available N (222.8 kg N/ha and 164.8 kg/ha at 0–15 and 15–30 cm depth, respectively) was recorded in the treatment where full residue was recycled along with *Trichoderma*. The leaf-area index was higher in wheat (3.97) than rice crop (3.07) at the maximum growth stage. Wheat crop grown in sugarcane-based system accumulated higher dry matter (8.02 t/ha) than wheat grown in rice–wheat system (7.71 t /ha). A significant increase in cane-equivalent yield was obtained in sugarcane-based system as compared to rice–wheat system. Cane-equivalent yield ranged from 103.3 to 138.3 t/ha in sugarcane–ratoon–wheat system, considering yields of ratoon-cane and wheat crops. Residue recycling + *Trichoderma* resulted in higher cane-equivalent yields in both the cropping systems. The residue burning/ removal caused significantly low yields in succeeding crop and cane-equivalent yields in both the cropping systems. The benefit: cost ratio (2.96) was the highest with sugarcane–ratoon–wheat cropping system under residue recycling + *Trichoderma*. Thus, residue recycling along with application of *Trichoderma* proved effective in both the cropping systems, but higher benefits could be achieved under sugarcane–ratoon–wheat cropping system.

Key words: Available N, Cane equivalent yield, Dry-matter accumulation; Leaf area: N uptake

The rice–wheat rotation is the principal cropping system in south Asian countries, occupies about 13.5 million ha area in the Indo-Gangetic Plains (IGP) of which 10.5 million ha is in India (Gangwar, 2010), 2.2 million ha in Pakistan, 0.8 million ha in Bangladesh and 0.5 m ha in Nepal. This system covers about 33% of the total rice area and 42% of the total wheat acreage in 4 countries as stated above. Sugarcane is an important commercial crop of India and occupies around 5.042 million ha of land with an annual cane production of around 411 million tonnes (Pathak, 2019).

Residue recycling provides ample scope to sustain soil fertility and improve crop productivity in irrigated agro-ecosystem. Since simple incorporation of rice residue causes nutrient immobilization and yield reduction in wheat. Residue/ stubble decomposition can be enhanced by inoculation of some cellulolytic fungi such as *Trichoderma* (Yadav *et al*., 2009). *Trichoderma* sp. increased the uptake and concentration of a variety of nutrients (copper, phosphorus, iron, manganese and sodium) in roots in hydroponic culture, even under anoxic conditions (Yedidia *et al.,* 2001). *Trichoderma* has shown to have significant decomposing activity of combined harvested paddy straw when incorporated with silica- solubilizing bacteria and *Pleurotus* and showed higher yield in succeeding rice (Hemalatha *et al.,* 2007).

Developing and implementing management strategies that maintain the quality of soil are essential to enhance the performance and sustainability of an agro-ecosystem. Carbon is the key attribute of soil quality because it influences

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nutrient cycling, soil structure, water availability, and other important soil properties (Tirol-Padre *et al*., 2007). The benefits of using organic manure and straw in maintaining soil quality have been increasingly recognized (Shukla *et al*., 2011). Soil microorganisms and the processes that they control are essential for the long-term sustainability of agricultural systems and are important factors in soil formation and nutrient cycling. Rhizosphere is the region of soil where roots influenced the microbial activity. The physico-chemical properties of the region create different growing conditions for microorganisms in comparison to root-free soil. Land-used activities particularly related to residue-management practices can have considerable impact on the size and activity of soil-microbial community and biological health of soil. Some researchers have shown that incorporation of organic amendments increased soil-microbial activity and densities of bacteria (Van Bruggen and Semenov, 2000). The majority of research has shown increased microbial diversity in soils from organic farming systems compared to conventional farming systems (Shannon *et al.,* 2002). Organic matter decomposition serves 2 functions-providing energy for growth and supplying carbon for the formation of new cells.

Since information on above issues in rice–wheat–rice–wheat and sugarcane–ratoon–wheat cropping systems is very scanty, the present experiment was undertaken to study the growth, nutrient accumulation and crop yields as influenced by crop-residue recycling and *Trichoderma* inoculation in rice–wheat and sugarcane–ratoon–wheat cropping systems in subtropical India.

MATERIALS AND METHODS

The experiment was conducted during 2013–15 at ICAR-Indian Institute of Sugarcane Research, Lucknow, (26º56'N, and 80º52' E with an average altitude of 111 m meter above the mean sea–level), Uttar Pradesh. The climate of Lucknow is typical subtropical with hot summers and dry chill winter. There was a great variation in seasonal temperatures. Summer season prevails during April-June. The temperature during summer month goes up to 47ºC and the climate becomes very hot and scorching. Hot dry winds generally called '*loo*' blow in the summer months. Monsoon sets in July with the arrival of south westerly monsoon winds and lasts till September. Lucknow receives annual rainfall about 101 cm. Winters starts from October and lasts till February. The mean temperature of winter generally revolves around 11ºC. Fog is the common phenomenon of winter season in Lucknow. The minimum temperature during winter season in the month of December and January goes down up to 6ºC. Rainy season starts after onset of monsoon in 3rd week of June and lasts till September. Rainy season is known for high temperature and high humidity (85–95%), conducive for vertical growth (elongation phage) of sugarcane crop.

In sugarcane (plant) –ratoon–wheat system, planting of sugarcane was done on March 2013. However in another cropping system (rice–wheat), rice seedlings were raised in June 2013 and transplanted in July 2013. Before experimental crops (rice and sugarcane), mustard crop was taken in the field as preceding crop. The soil of the experimental plot was sandy loam (sand 60%, silt 30% and clay 10%), slightly alkaline in reaction (*p*H 7.75) with low in available N and medium in available P_2O_5 and K_2O contents, having good drainage facility and moderate water-holding capacity. Initial physico-chemical properties of the experimental field are given in Table 1.

The experiment was laid out in a spilt-plot design with 2 cropping systems (rice–wheat–rice–wheat and sugarcane–ratoon–wheat) in main plots and different crop-residue management practices in subplots. Rice variety 'BPT 5204', wheat cultivar 'PBW 343' and sugarcane variety 'CoSe 92423' were taken in the experiment. In rice–wheat system (CS_1), rice crop was grown as a sole crop and after harvesting of rice crop, after mechanical chopping, the residue, i.e. stalk including dry leaves and stubble were recycled in the soil. In partial-residue recycling, half amount of crop residues produced by rice/ wheat/ sugarcane was recycled in subsequent cropping season. Crop residues included roots, parts of stalk and trash (dry leaves) etc. In rice–wheat system, after harvesting of rice crop, the residue was burnt/ removed/ recycled as per the treatments. However, in sugarcane–ratoon–wheat system (CS_2), sugarcane trash was mulched after harvesting of plant (main) crop and before initiation of ratoon crop. The FYM-based preparation of *Trichoderma viride* was applied in the field @ 20 kg/ha (cfu.10^7 to 10^8 per g culture) and mixed with crop residues applied on soil after harvesting of the preceding crop. In all the treatments, recommended doses of N:P:K were applied for various crops, i.e. sugarcane plant crop (150 : 60 : 60), sugarcane ratoon crop (200 : 60 : 60), rice (120 : 60 : 60) and wheat (120:60:60) kg N, P_2O_5 and K_2O/ha respectively.

Composite soil samples were collected in 2 different layers, i.e. 0–15 cm and 15–30 cm, from the experimental site, analysed for soil pH, available N, P_2O_5 and K_2O and presented in Table 1. After harvesting of the crop, soil samples of 0–15 cm and 15–30 cm depth were also collected and analysed for available N. The Walkly and Black's (1934) rapid titration method was used to determine organic carbon.

SOC (Mg/ha) = SOC (g per kg soil) × BD × 2.22

where SOC, Soil organic carbon; BD, Bulk density of the soil

Plant samples at random in 1.0 m length were taken

Table 1. Initial physico-chemical characteristics and microbial population along with soil-enzymes status at the experimental site

Soil chemical parameters	Results		Methods adopted
	0–15 cm	15–30 cm	
1. Soil *p*H	7.75	7.82	Beck man's Xeromatic *p*H Meter (Jackson, 1958)
2. EC (dS/m)	0.20	0.12	Electrical Conductivity Meter
3. Organic carbon (Mg/ha)	14.87	11.88	Walkley and Black method (Walkley and Black, 1934)
4. Available nitrogen (kg/ha)	245.2	234.4	Alkaline permanganate methods (Subbiah and Asija, 1956)
5. Available phosphorus (kg P_2O_5/ha)	48.93	41.80	Olsen-P Ascorbic acid Method (Watanabe and Olsen, 1965)
6. Available potassium (K_2O kg/ha)	226.4	212.1	Flame Photometer Method (Toth and Prince, 1949)

from sample rows leaving border lines in each plot. Ten random leaves were measured at maximum leaf-area stage (90 days after transplanting/ sowing/ planting in rice, wheat and sugarcane respectively) by scale (length and width) and leaf area of these leaves was calculated through plotting on graph paper. Later on, leaf-area constant was calculated through multiplying length and breadth. The leaf-area constant (LAC) of rice and wheat was worked out as 0.73 and 0.78 respectively.

LAC = Actual leaf area / length × breadth

Leaf-area index (LAI) was calculated as the ratio of leaf area and ground area.

$$LAI = \frac{LA}{GA}$$

where, LA and GA indicate leaf area and ground area respectively.

The destructive samples were taken at harvesting stage from 1 m row length of second rows of either side of each plot. During the sampling, the plants were uprooted from the ground level. After drying in shed, these samples were kept in the hot-air oven at 60°C to a constant weight and dry weight was recorded and expressed in t/ha. Total content of N (%) in grain, straw, stubble/ roots of rice, wheat and sugarcane were determined by Kjeldahl's method.

The minimum support price of rice, wheat and state advisory price (SAP) of sugarcane were taken in to account for working out economics of various treatments, cost of production and cane-equivalent yield. Cost of rice, wheat and sugarcane-crop residues, particularly in partial-residue recycling and residue-removal treatments have been adjusted in harvesting cost. Cost of various treatments was worked out and deducted from gross return to obtain net return. Benefit: cost was also worked out considering gross return and cost of production of each treatment. The recorded data were analysed statistically through SAS software available online for authenticated users available on website of IASRI (www.iasri.res.in).

RESULTS AND DISCUSSION

Available nitrogen in soil and its uptake

Higher level of available nitrogen (N) in soil was recorded in sugarcane–ratoon–wheat system than the rice–wheat system (Table 2). After harvesting of rice crop in 2013, available N was marginally increased (248.8 kg N/ha) as compared to initial N level (245.2 kg N/ha). However, after harvesting of sugarcane, it increased up to 253.7 kg N/ha. Available N in soil increased significantly in sugarcane–ratoon–wheat cropping system over the rice–wheat–rice–wheat cropping system. After harvesting of ratoon cane, mean available N at 0–15 cm depth was 254.4 kg/ha as compared to 164.1 kg /ha after harvesting of rice in 2014 (Table 2). Similar trend was observed in 15–30 cm depth also with lower values.

The mean available N at 0–15 cm depth after completion of cropping system was 194.74 kg N/ha. Among the different crop-residue treatments, the highest available N (222.8 kg N/ha and 164.8 kg/ha at 0–15 and 15–30 cm depth, respectively) was determined in the treatment where full residue was recycled along with *Trichoderma*. At 0–15 cm depth, residue removal plots (150.7 kg/ha N) and at 15–30 cm depth residue burnt plots (113.9 kg/ha N) recorded the lowest available N. It was followed by partial residue recycling along with *Trichoderma*. While crop-residue recycling was beneficial in recycling nutrients, plowing under required energy and time leads to temporary immobilization of N and the high C: N ratio needs to be corrected by applying extra fertilizer N at the time of residue incorporation (Singh *et al.,* 2005; Singh *et al.,* 2008). Addition of organic manures and residue recycling improved organic carbon aggregation and reduced bulk density of the soil (Halvorson *et al.,* 1999). Trash mulching improved the soil organic carbon and available N, thereby increasing the yield of sugarcane ratoon crop, whereas trash burning reduced the organic carbon content (Yadav *et al.,* 1994, 2009).

Total N uptake in rice–wheat–rice–wheat and sugarcane–ratoon–wheat cropping system was worked out at the harvesting stage of each crop in the system. Mean N removal from rice and sugarcane (plant crop) was recorded as 101.2 and 143.8 kg/ha, respectively (Table 3). The highest N removal was determined under residue recycling along with *Trichoderma* in both the cropping systems. The total N removal from rice and wheat system in a year was higher than N uptake by sugarcane plant/ ratoon crop in the system. Besides, in 2 years cropping system, mean N removal in rice–wheat–rice–wheat cropping system was obtained as 435.8 kg/ha, being was 15.79% higher than N removal in sugarcane (plant crop)–ratoon–wheat cropping system (376.3 kg/ha). The highest N removal in each crop in the system was observed where residue recycling was done along with *Trichoderma*. It was followed by residue application + 25% additional N and partial residue application + *Trichoderma*. Higher LAI and dry-matter accumulation and crop yields in residue recycled treatments were obtained because of increased availability of nutrients and congenial rhizopheric environment. This higher biomass and crop yields caused the higher removal of N also.

In rice–wheat cropping system, the effect of various treatments was observed in the first cropping season as well. However, the effect was much pronounced in the second cropping season. Mean N uptake recorded in 2014 in rice and wheat crops was 102.3 kg/ha and 97.8 kg/ha, respectively. The inoculation of *Trichoderma* and residue application enhanced the N uptake in all the crops. The highest N removal from rice, wheat and sugarcane ratoon crops was 161.0, 116.5 and 102.6 kg/ha in wheat, rice and again wheat crop, respectively, grown in rice–wheat–rice–wheat cropping system. *Trichoderma* inoculation significantly improved the N uptake in residue-recycled plots. Similar trend was also observed in sugarcane–ratoon–wheat cropping system. Sugarcane ratoon crop removed the highest N (152.5 kg/ha) with residue recycling + *Trichoderma*. However, mean N removed from sugarcane plant and ratoon crops was 143.8 kg/ha and 133.6 kg/ha respectively. Mean N removal from wheat crop after the second crop cycle in rice–wheat system was higher than wheat grown in sugarcane-based system. The mean highest N removal from wheat (128.8 kg/ha) was obtained under residue recycling + *Trichoderma* in sugarcane–ratoon–wheat system.

Leaf-area index and dry-matter accumulation in crops

Leaf-area index in rice–wheat–rice–wheat cropping system and sugarcane–ratoon–wheat cropping systems was determined and presented in Figs. 1 and 2. The leaf area was maximum in all the crops at 90 days after planting/ sowing/transplanting. During 2013–14, in rice–wheat cropping system, mean maximum leaf-area index (LAI) of rice was observed as 3.07. However, in succeeding wheat crop, the various residue-management practices influenced the LAI significantly. During 2013–14, in wheat crop, maximum LAI ranged from 3.23 to 4.65. The lowest leaf-area index was observed in residue-removed plots. The maximum LAI was observed with residue recycling + *Trichoderma*. The higher leaf area of wheat crop was observed in 2014–15 than that in 2013–14. Mean increase in LAI owing to residue recycling was 1.42, 1.31 and 1.60 unit in

Table 2. Effect of residue management and cropping system on available N in soil (kg /ha) after harvesting of rice/sugarcane ratoon and wheat crops

Treatment	After harvesting of wheat crop in Rice–wheat cropping system		After harvesting of rice/ sugarcane ratoon		After completion of crop cycle in both the cropping systems	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Cropping system						
CS_1, (Rice–wheat–rice–wheat)	–	–	164.10	129.26	183.06	129.92
CS_2, (Sugarcane–ratoon wheat)	–	–	254.49	200.44	206.42	141.10
SEm±			5.90	7.22	5.46	3.80
CD(P=0.05)	–	–	17.34	21.56	16.34	11.32
Residue management						
T_1, Residue removal	217.3	180.7	166.4	128.9	150.8	114.0
T_2, Residue burning	200.4	194.8	174.1	138.0	155.4	103.6
T_3, Complete residue recycling	265.2	231.3	236.6	167.0	208.1	142.7
T_4, Complete residue recycling + *Trichoderma*	233.7	212.2	222.2	169.9	222.8	164.9
T_5, Complete residue recycling + 25%N extra N	234.5	231.3	220.7	197.7	199.7	130.2
T_6, Partial residue recycling	253.5	228.7	221.4	172.9	201.9	155.4
T_7, Partial residue recycling + *Trichoderma*	219.6	194.8	223.8	184.6	218.6	125.4
T_8, Partial residue recycling + 25% extra N	241.1	194.8	209.3	159.8	200.7	148.1
SEm±	4.7	4.6	4.3	5.7	4.8	3.7
CD (P=0.05)	14.2	13.6	12.9	16.7	14.1	10.9
After harvesting of first rice crop	248.8	230.4				
After harvest of sugarcane (plant) crop	253.7	202.1				
Initial	245.2	234.4				

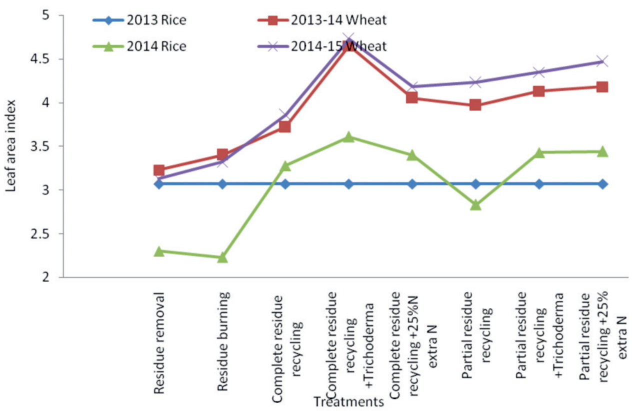

Fig. 1. Maximum leaf-area index in rice–wheat–rice –wheat cropping system as influenced by residue management

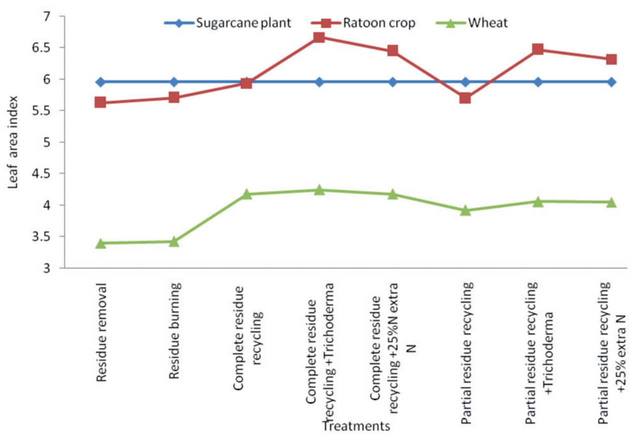

Fig. 2. Maximum leaf-area index in sugarcane–ratoon–wheat cropping system as influenced by different treatments

wheat, rice and subsequent wheat crops taken during 2013–14 and 2014–15, respectively, as compared to residue-removed plots. The higher mean leaf-area index was in wheat (3.97) than in rice crop. In sugarcane–ratoon–wheat cropping system, mean maximum leaf area of sugarcane plant crop during the first year was recorded was 5.96. However, in sugarcane ratoon crop, it ranged from 5.63 to 6.47. An increase in maximum leaf area because of residue recycling and inoculation of *Trichoderma* was observed as 0.66, 1.24 and 0.52 unit in rice, wheat and sugarcane crops, respectively, as compared to residue-removal plots. The residue application along with *Trichoderma* increased the LAI which reached the level of 6.67 in sugarcane ratoon crop. Wheat sown in sugarcane–ratoon–wheat cropping system also showed similar trend. The LAI of wheat crop in sugarcane–ratoon–wheat cropping system ranged from 3.40 to 4.25 in various treatments. Availability of nutrients, favourable soil physical, chemical and biological conditions created in residue-recycled plots favoured LAI in all the crops.

The highest dry-matter accumulation in both the cropping systems was obtained at the harvesting stage (Figs. 3 and 4). During 2013–14, mean maximum dry-matter accumulation in rice and sugarcane crops was recorded as 4.45 and 26.63 t/ha respectively. However, in next cropping season, the response of residue recycling and *Trichoderma* application was observed significantly higher in all the crops. During 2013–14, total dry-matter accumulation in wheat crop ranged from 6.99 to 8.27 t/ha. Residue application increased the dry-matter accumulation over residue-removed plots in wheat, rice and again wheat crops grown in sequence during 2013–14 and 2014–15, respectively. Residue recycling along with *Trichoderma* was found superior to all the treatments. However, residue recycling along with 25% additional was also found comparable to residue recycling + *Trichoderma*. Partial residue recycling was also found superior to residue removed/ burnt plots.

Table 3. Total N uptake (kg/ha) in rice–wheat–rice–wheat and sugarcane–ratoon–wheat cropping systems

Treatment	Rice–wheat–rice–wheat system			Total N uptake in the system	Sugarcane–ratoon–wheat system 2013–15		Total N uptake in the system
	2013–14	2014–15					
	Wheat	Rice	Wheat		Ratoon	Wheat	
T_1, Residue removal	114.4	79.2	86.4	381.2	108.4	76.6	328.8
T_2, Residue burning	117.7	90.6	100.8	410.3	110.3	108.5	362.6
T_3, Complete residue recycling	126.9	101.2	112.7	442.0	140.5	15.8	300.1
T_4, Complete residue recycling + *Trichoderma*	161.0	116.6	102.6	481.4	152.5	128.9	425.2
T_5, Complete residue recycling + 25%N extra N	142.9	112.3	97.0	453.4	146.6	118.0	408.4
T_6, Partial residue recycling	137.9	98.4	99.8	437.3	130.5	105.2	379.5
T_7, Partial residue recycling + *Trichoderma*	148.1	108.5	94.3	452.2	142.9	122.5	409.2
T_8, Partial residue recycling + 25% extra N	126.8	103.4	88.6	420.0	137.1	116.5	397.4
SEm±	3.5	1.8	3.4	8.9	1.9	2.5	4.8
CD(P=0.05)	10.5	5.4	9.8	27.0	5.7	7.3	14.4
Total N uptake in rice (2013)	101.2						
Mean N uptake in sugarcane plant crop (2013)	143.8						

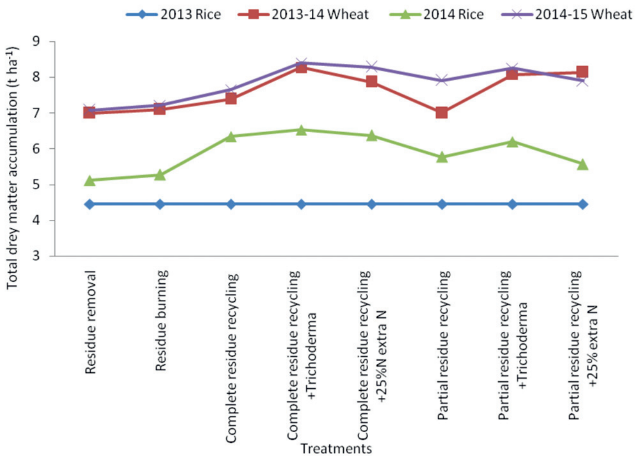

Fig. 3. Total dry-matter accumulation in rice–wheat–rice –wheat cropping system as influenced by residue management

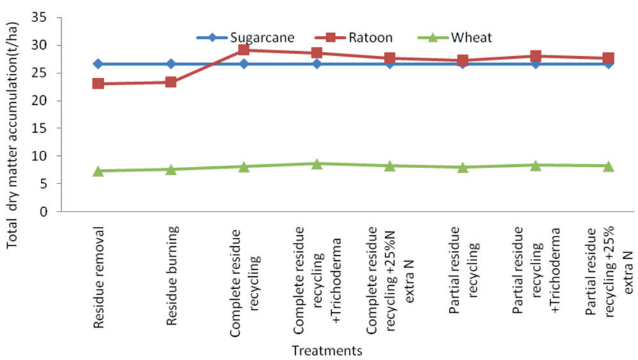

Fig. 4. Total dry-matter accumulation in sugarcane–ratoon–wheat cropping system as influenced by different treatments

The similar response was observed in sugarcane–ratoon–wheat cropping system. Higher mean dry-matter accumulation (8.02 t/ha) was observed in wheat crop grown in sugarcane based system than wheat grown in rice–wheat system (7.71 t/ha). This indicated superiority of sugarcane–ratoon–wheat cropping system to the rice–wheat cropping system owing to higher availability of nutrients in soil.

Residue application favours nutrients availability in soil when applied with *Trichoderma* or additional nitrogen. This caused significant effect on increasing dry-matter production. Sugarcane being annual crop responded well and in rice–wheat cropping system, the positive effect was much pronounced in 2nd cropping season. *Trichoderma* being growth promoters (Yedidia *et al.,* 2001; Shukla *et al.,* 2008; Yadav *et al.,* 2009) improved the root growth and favoured accumulation of nutrients which caused higher dry-matter accumulation in all the crops. Effect of application of *Trichoderma* along with residue recycling could not be compensated by additional 25% N.

Rice, wheat, sugarcane and cane-equivalent yields

Mean rice grain yield (4.350 t/ha) of the experimental plots was obtained (Table 4) during first cropping season. Wheat yield was significantly influenced by residue-management practices adopted after harvesting of rice (Table 4). The maximum wheat yield (5.203 q /ha) was obtained in the treatment where full residue was incorporated (T_3). All the treatments of residue incorporation with and without *Trichoderma* and/or 25% additional N application resulted at par. Residue-applied plots were significantly superior to no residue (burnt/ removal). Mean sugarcane yield in plant (main) crop was 84.75 t/ha. Application of *Trichoderma* enhanced the sugarcane yield in residue-recycled plots. Improvement in soil fertility owing to trash mulching with *Trichoderma* was responsible for such an effect.

Sugarcane ratoon yield ranged from 86.0 to 118.5 t/ha in different treatments. The highest ratoon cane yield (118.5 t/ha) was obtained with application of *Trichoderma* along with full residue application. However, the residue-re-

Table 4. Rice and wheat yields (t/ha) in different cropping systems

Treatments	Rice–wheat cropping system			Sugarcane– ratoon–wheat system
	2013–14	2014–15		2013–15
	Wheat grain yield (t/ha)	Rice yield (t/ha)	Wheat grain yield (t/ha)	Wheat yield (t/ha)
T_1, Residue removal	4.25	3.57	3.49	3.61
T_2, Residue burning	4.42	3.97	3.81	3.50
T_3, Complete residue recycling	5.20	4.15	4.69	3.78
T_4, Complete residue recycling + *Trichoderma*	5.03	4.59	4.64	4.11
T_5, Complete residue recycling + 25% N extra N	4.91	4.88	4.57	4.67
T_6, Partial residue recycling	4.75	4.31	4.64	4.25
T_7, Partial residue recycling + *Trichoderma*	4.59	4.73	4.47	4.27
T_8, Partial residue recycling + 25% extra N	4.82	4.79	4.31	3.89
SEm±	0.07	0.07	0.16	0.09
CD (P=0.05)	0.21	0.21	0.46	0.28
Rice yield (2013)	4.35	4.37	4.33	4.01

moved plots gave the lowest cane yield. Yadav *et al.* (2009) reported increase in nutrient uptake by *Trichoderma* inoculation and application of trash in sugarcane ratoon crop. They also found significantly greater yields in the plots receiving *Trichoderma* over the control owing to the increase in soil organic carbon, soil-microbial biomass nitrogen and available nutrients and better physical and chemical conditions for both soil microorganisms and crop. Our experimental results also showed similar trend. Stimulation of root-system through *Trichoderma* application and exploiting larger mass of soil by the plant was described as a probable explanation (Shukla *et al.,* 2008). *Trichoderma* is known for releasing growth-promoting substances and enhanced uptake of nutrients and yield (Yadav *et al.,* 2009a). Application of *Trichoderma* enhanced the crop yields in all residue-recycled plots.

Sugarcane-equivalent yield in both the cropping systems was also worked out (Table 5). During 2013–14, sugarcane-equivalent yield in rice–wheat system ranged from 38.89 to 42.50 t /ha. However, during the period sugarcane plant crop yielded as 84.75 t /ha. It was significantly higher than the mean cane-equivalent yield in rice–wheat system. During 2014–15, sugarcane-equivalent yield in rice–wheat system ranged from 33.52 to 44.86 t/ha. However, in sugarcane-based system, the ratoon and wheat crops were taken during second cropping season and the significant increase was observed in cane-equivalent yield obtained in sugarcane based system as compared to rice–wheat system. Sugarcane-equivalent yield during 2013–15 considering ratoon and wheat crops ranged from103.39 t/ha to 138.33 t /ha. In both the systems, residue recycling + *Trichoderma* showed higher cane-equivalent yields. During 2014–15, in rice–wheat system, residue recycling and partial residue application did not show tangible differences. However, the residue burning/ removal significantly lowered the yields and cane-equivalent yields in both the cropping systems. The positive effects of crop-residue recycling along with *Trichoderma* on rice, wheat and sugarcane yields also improved the cane-equivalent yields in both the systems. Competitive higher market price of sugarcane as compared to rice and wheat crops also enhanced the cane-equivalent yield in sugarcane-based system as compared to rice–wheat–rice–wheat system.

Economics of cropping system

Economics of both the cropping systems was worked out (Table 6). Various components, viz. gross return, net return and benefit: cost ratio were computed considering the minimum support price of the rice, wheat , sugarcane and cost of production during the period. During 2013–15, the maximum gross returns (₹243,000/ha) in rice–

Table 5. Sugarcane and sugarcane equivalent yields in both the cropping systems

Treatment	Rice–wheat–rice–wheat system					Sugarcane–ratoon–wheat system		
	2013–14		2014–15			2013–15		
	Sugarcane equivalent yield of wheat (t/ha)	Sugarcane equivalent yield of rice and wheat	Sugarcane equivalent yield of rice (t/ha)	Sugarcane equivalent yield of wheat (t/ha)	Sugarcane equivalent yield of rice and wheat	Ratoon yield (q/ha)	Sugarcane equivalent yield of wheat (t /ha)	Sugarcane equivalent yield (t/ha)
T_1, Residue removal	19.48	38.89	16.72	16.80	33.52	86.0	17.39	103.39
T_2, Residue burning	20.28	39.69	18.58	18.35	36.93	92.23	16.88	109.11
T_3, Complete residue recycling	23.88	43.29	19.40	22.59	41.99	99.63	18.24	117.87
T_4, Complete residue recycling +*Trichoderma*	23.09	42.50	21.49	22.38	43.86	118.5	19.83	138.33
T_5, Complete residue recycling + 25%N extra N	22.52	41.93	22.83	22.03	44.86	114.0	22.50	136.5
T_6, Partial residue recycling	21.81	41.22	20.14	22.39	42.53	105.4	20.48	125.88
T_7, Partial residue recycling + *Trichoderma*	21.06	40.47	22.11	21.57	43.68	111.5	20.58	132.08
T_8, Partial residue recycling + 25% extra N	22.13	41.54	22.40	20.77	43.16	97.79	18.74	116.53
SEm±	0.42	0.84	0.52	0.42	0.83	3.30	0.42	2.90
CD (P=0.05)	1.20	2.54	1.56	1.12	2.58	9.62	1.23	8.78
Sugarcane equivalent yield of rice (2013)	19.41							
Sugarcane yield (2013–14)						84.75		

Rice price @ ₹1,250/q in 2013–14 and ₹1,310 in 2014–15; wheat price @ ₹1,285/q in 2013–14 and ₹1,350/q in 2014–15; sugarcane price @ ₹280/q in Uttar Pradesh during both the cropping seasons

Table 6. Economics of rice–wheat–rice–wheat and sugarcane–ratoon–wheat cropping systems

Treatment	Gross return (× 10^3 /ha)		Net returns (× 10^3 /ha)		Benefit: cost ratio	
	Rice–wheat–rice–wheat system	Sugarcane–ratoon–wheat system	Rice–wheat–rice–wheat system	Sugarcane–ratoon–wheat system	Rice–wheat–rice–wheat system	Sugarcane–ratoon–wheat system
T_1, Residue removal	201.3	493.6	94.4	208.0	1.88	2.52
T_2, Residue burning	213.2	508.3	106.2	312.7	1.99	2.60
T_3, Complete residue recycling	239.2	531.4	131.1	387.8	2.21	3.70
T_4, Complete residue recycling + *Trichoderma*	242.8	584.8	133.8	387.1	2.23	2.96
T_5, Complete residue recycling + 25% N extra N	243.0	580.9	133.7	382.6	2.22	2.93
T_6, Partial residue recycling	234.9	552.7	127.3	356.4	2.18	2.82
T_7, Partial residue recycling + *Trichoderma*	235.8	569.0	127.4	371.8	2.17	2.89
T_8, Partial residue recycling + 25% extra N	236.3	528.0	127.6	330.4	2.17	2.67
SEm±	3.10	5.45	1.73	11.23	0.051	0.07
CD (P=0.05)	9.13	26.54	5.15	32.45	0.15	0.22

wheat cropping system were obtained with application of residue + 25% additional N. However, in sugarcane-based system, the highest gross returns (584,800/ha) were obtained with complete residue recycling + *Trichoderma*. The highest net returns (133,800/ha in rice–wheat–rice–wheat cropping system and 387,100/ha in sugarcane–ratoon–wheat cropping system) were obtained with complete residue recycling + *Trichoderma.* The B: C ratio (2.96) was the highest in residue recycling + *Trichoderma* treatment under both the cropping systems. In general, benefit: cost ratio was higher under sugarcane–ratoon–wheat cropping system than the rice–wheat cropping system. Thus, residue recycling along with application of *Trichoderma* proved effective in both the cropping systems, but higher benefits was achieved under sugarcane–rratoon–wheat cropping system.

After 2 years of study and considering growth, yield and soil health parameters, it could be concluded that complete residue recycling along with application of *Trichoderma* in sugarcane–ratoon–wheat system increased leaf area, growth and dry-matter accumulation at higher rates than the rice–wheat–rice–wheat system. The practice of residue recycling and application of *Trichoderma* also improved soil fertility status besides increasing benefit: cost ratio.

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