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Rice (*Oryza sativa* L.) residue management: Key to sustainable wheat (*Triticum aestivum* L.) production in the rice-wheat cropping system

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ABSTRACT

Rice straw poses a significant challenge for rice-wheat cropping systems owing to its high silica content, often leading farmers to burn or remove it for seedbed preparation. However, these practices harm the environment. A study spanning the Rabi seasons of 2019–20 and 2020–21 aimed to address this issue, evaluating diverse rice straw management techniques. The investigation featured seven treatments, including the removal and incorporation of rice straw, to assess their impact on wheat yield and their economics. The experiment followed a randomized block design, ensuring each treatment appeared in every block, maintaining block uniformity. The treatments encompassed variations in recommended Nitrogen doses, straw incorporation, top dressing with nitrogen, and decomposer application. The wheat variety PBW-373 was utilized as the test crop, and various growth and yield attributes were analyzed. Treatment T6 consistently outperformed other approaches over both years. It entailed incorporating 5 t ha-1 of rice straw alongside 125% of recommended nitrogen, 60 kg ha-1 of phosphorus, and 40 kg ha-1 of potassium, with the application of additional top dressing nitrogen. T6 exhibited substantial improvements in wheat yield attributes, including plant height, dry matter accumulation, leaf characteristics, tiller count, spike length, grains per spike, and grain weights, and generated superior economic outcomes compared to alternative methods. Incorporating rice straw into the soil emerged as a promising strategy to enhance soil quality and productivity while addressing environmental concerns. This research underscores the potential of sustainable rice straw management, with maximum benefits demonstrated through the integrated application of Crop residues with a decomposer consortium and additional nitrogen fortification (at 125%). This approach provided a proof of concept to bolster the rice-wheat cropping system's viability and promote both agricultural and ecological benefits. This work offers a valuable roadmap for farmers to adopt ecologically sound practices while optimizing wheat production within the context of the intricate rice-wheat cropping system.

Keywords: *Paddy straw, rice residue management, Rice-wheat cropping system, Wheat production and Growth attributes*

Introduction

India has the second-highest production of rice and wheat in the world. Rice–wheat is an important cropping system for food security, employment, income generation, and livelihoods for millions of people in Asia. This system is practiced on 13.5 Mha of South Asia and is recognized as an important crop for food security in South Asia. Rice-wheat cropping system is followed in the Indo-Gangetic Plains (IGP) of Bangladesh, India, Nepal and Pakistan of South Asia and this plain has fertile alluvial soils is also known as the Indian Green Revolution region, "food bowl" or "food basket" and registered Punjab, Uttar Pradesh, Haryana, Bihar and West Bengal about 15% of the total geographical area of India. This plan is suitable for taking double or triple crops in a year to provide food security to the IGP population, with the production of about 50% of the total food grains in the country to feed 40% of the population[1].

Rice straw is the most suited for this purpose [2], because, on average, it contains about 0.9% N, 0.2% P, 0.2% S, 2.5% K, 0.6% Ca, 7.0% Si, and 40% C. Other factors that favor the use of rice straw as an organic supplement are its on-the-spot availability in amounts varying from 2 to 5 t dry matter ha^{-1} per season and the elimination of straw disposal problems. Depending upon the soil-plant-environment, the methods of straw management vary a great deal from location to location. It can be removed from the field, burnt in situ, piled up or spread in the field, incorporated in the soil, or used as a mulch for the succeeding dry land crop. A voluminous work has been done on straw

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management practices in tropical areas[3]. Worldwide, the removal of crop residue from the field after crop harvest is the norm or cultural heritage to conserve the plantation "clean" [4,5]. The removed residues are generally used for food and fiber (animal feed and bedding, biofuel production, building materials, household fuel, paper making, and mushroom cultivation), negatively affecting soil fertility, agronomic productivity, and environmental quality[6]. In addition, in many developing countries, conventional agricultural methods such as intensive tillage and the burning of crop residue exacerbate these impacts[7]. Therefore, proper management of crop residue is necessary for improving soil fertility and quality. Some researchers suggested that 30 to 50% of crop residue could be removed from the farm without causing any adverse impacts on the soil[8].

The scarcity of labor for manual harvesting, the use of combined harvesters with the growth of farm mechanization, timeliness in operation and cleaning of fields, etc. are some major reasons behind in-situ burning of paddy straw [9]. This incineration of crop residue has become an essential source of atmospheric pollution in NW India during paddy harvesting seasons[10].This also leads to health hazards to humans and animals[11]. Besides these, this in-situ burning of rice residue also results in deterioration in soil health and fertility through loss of soil nutrients like 89% N, 5.5% P, 20% K, and more than 50% S.[12,13] Such beneficial nutrients can be conserved and recycled in soil by incorporating crop residues in it.[14] Nitrogen immobilized into crop residue rematerializes later in the season. In southeast Australia, where temperatures are relatively low and there are long fallow periods, it has been recommended to incorporate stubble six months prior to seeding the next crop to avoid early N deficiencies associated with immobilization.[15] However, the soil of Punjab was amended with rice straw and incubated under aerobic moist conditions at 28 ∘C, there was rapid immobilization of soil and fertilizer-N during the first 9 days, followed by N mineralization.[16] Nitrogen is an essential nutrient for plant growth and development being involved in vital plant functions such as photosynthesis, DNA synthesis, protein formation, and respiration.[17,18]

Materials and Methods

A field investigation was conducted at the student instructional farm of Acharya Narendra Deva University of Agriculture and Technology, Narendra Nagar (Kumarganj), Ayodhya during the winter (Rabi) seasons of 2019-20 and 2020-21 to evaluate different rice straw management practices in the rice-wheat cropping system by incorporating varying levels of Nitrogen doses in the form of urea, along with recommended doses of P and K. The experimental site falls under the subtropical zone in the Indo-Gangetic plains having alluvial soil and lies between 24.4°- 26.5° North and 82.12° and 83.98° East longitude with an elevation of about 113 meters above mean sea level. The experiment involved seven treatments in total with the control treatment (T_1) comprising of N:P:K levels of 120:60:40 Kg ha^{-1} respectively; Treatment T_2 was amended only with paddy straw@ 5 t ha^{-1}; T_3 comprised of amendments including paddy straw@ 5 t ha^{-1} with additional Nitrogen top dressing@ 20 Kg ha^{-1}. The other four treatments were amended by adding recommended dose of NPK along with paddy straw @ 5 t ha^{-1} with other additional amendments. Among these four treatments, T_4 comprised of additional amendment through bioaugmentation in the form of Hyperlignocellulolytic fungal consortium; T_5 was supplemented with additional Nitrogen as basal dose at different stages (CRI stage, knot formation and Milking stages) to make total Nitrogen dose upto 125%; Treatment T_6 was amended additionally with 20 Kg/ha nitrogen through foliar spray of Urea; and Treatment T_7 comprised of all additional amendments including basal N-appplication, foliar spray of Nitrogen (@ 20Kg/ha) and decomposer consortium application. All treatments were setup in replicates of four in Randomized Block Design (RBD). The experimental field was levelled and had good irrigation and drainage facilities. After the harvesting of kharif crop, the crop residues were cut into pieces of 10-20 cm and incorporated in the experimental plots followed by manual sowing of wheat seeds for the following crop. The wheat variety PBW-373, used for the study, was sown in first week of December during both years of study, with row to row spacing of 25 cm in continuous seeding and plot size, 4 × 3 m^2 giving a net plot area of 12 m^2. Urea, single super phosphate and murate of potash were the source of fertilizers used for supplying nitrogen, phosphorus, and potassium respectively. The full dose of phosphorus, and potassium fertilizers were applied at the time of land preparation. The recommended dose of 60 kg P_2O_5/ha, 40 kg K_2O/ha were applied as basal in all plots at the time of seed sowing. Half a dose of N was used at the time of seed sowing as a basal dose. The remaining half dose of N was side-dressed at 60 DAS and 90 DAS. The data on plant height and tillers were recorded from the area already marked by tag. Sample for dry matter accumulation was recorded by cutting of plants from 25 cm row length. The fresh samples were first sun-dried and then kept in an electric oven at 65-70^{0}C till the constant dry weight was attained. Yield attributes were recorded from 10 spikes selected randomly from each plot. The evaluated traits were effective tiller (m^{-2}), spike length (cm), grains /spikes, weight of spike (g), grain weight/spike. The leaf of plants was separated and the area was measured with the help of an automatic leaf area meter. In the samples collected for dry matter estimation, 5 leaves from each plot's selected plant were plucked at 30 DAS, 60 DAS, and 90 DAS for the leaf area measurement with the help of leaf area meter (LA-3100). The leaf area for each sample was recorded and averaged to give leaf area of plants/ hill.

The following formula were used to compute LAI and LAR at each stage:

LAI = Leaf area (cm^2) per plant / Ground area covered by plant

LAR = Leaf area per plant (cm^2) / Plant dry weight (g)

Results and Discussion

Growth Attributes

Vegetative growth is the manifestation of organic matter accumulation, expressed in terms of dry matter, which is in turn, the function of plant population, tillers, height, and other morphological characters. Each growth attribute is taken here and presented in tables.

Plant height

The data on progressive plant height at successive stages (30 DAS, 60 DAS, 90 DAS and at the harvesting stage) of crop growth as influenced by various rice straw management practices is presented in Table 1. It clearly indicates that rice straw management treatments have influenced the plant height significantly. The maximum plant height at all growth stages (30 DAS, 60 DAS, 90 DAS, and at harvesting stage) were recorded under treatment T_6 ranging from 25.3 cm at 30 DAS to 103.6 cm at harvest stage. were recorded at respective plant growth stages of, wherein the agriinputs included, 125% of RDN, P:K @

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60:40 (kg ha^{-1}) , Paddy straw @ 5 t ha^{-1} and Top dressing of Nitrogen @ 20Kg ha^{-1}. This treatment comprised of inorganic NPK inputs @ N150: P60: K40 Kg/ha along with Paddy straw @ 5 t ha^{-1} and Top dressing of Nitrogen (@ 20 Kg ha^{-1}) for balancing C:N ratio to aid in faster soil assimilation of incorporated mulch.

It is evident from the data that the effect of treatment was not visible at 30 DAS, after which it affected a significant increase in plant height. These increases have been found in treatments where crop residues were retained on the soil surface or incorporated by conservation tillage. It is also observed that wheat growth was lower during the rice straw incorporation 30 days prior to wheat planting because of the immobilization of soil N in the presence of crop residues with a wide C/N ratio, but in later growth stages, after 60 days, straw incorporation did not affect the growth of plants. In contrast, rice straw incorporation gave significantly higher growth compared to treatments where straw was not applied as mulch. A study conducted by Rice-Wheat Consortium for the Indo-Gangetic Plains (RWC-CIMMYT) has reported similar observations based on rice-wheat cropping system data. [19]

Dry matter accumulations

The incorporation of rice straw at a rate of 5 t ha^{-1}, along with 125% of the recommended dose of nitrogen, 60 kg ha^{-1} of phosphorus (P), and 40 kg ha^{-1} of potassium (K), along with a top dressing of nitrogen at 20 kg ha^{-1} (referred to as T_6), resulted in the highest accumulation of dry matter. This was followed by treatment T_7, which involved 125% of recommended dose of nitroegen, 60 kg ha^{-1} P, 40 kg ha^{-1} K, incorporation of paddy straw at 5 t ha^{-1}, and a subsequent top dressing of nitrogen at 20 kg/ha after the incorporation of paddy straw with the application of a decomposer. Additionally, treatment T_3 which comprised the recommended NPK levels at 120:60:40 kg ha^{-1} along with paddy straw incorporation at the 30 DAS stage of crop growth, also showed significant dry matter accumulation (as shown in Table 1).

During various growth stages, such as 60, 90, and 120 DAS, as well as at the harvest stage, treatment T_6 consistently exhibited comparable or significantly higher dry matter accumulation compared to treatments T_7 and T_3. The incorporation of rice straw into the soil after harvesting the crop led to a slowdown in decomposition and the immobilization of soil nitrate, as documented by previous studies.[15] Notably, the notable advantage of using 125% along with a top dressing of nitrogen at 20 kg ha^{-1} after the incorporation of paddy straw was its enhanced effectiveness in immobilizing inorganic nitrogen and mitigating the adverse effects associated with nitrogen deficiency. [15,20]

Leaf area (cm^2), leaf area index (cm^2), and Leaf area ratio (cm)

The data concerning leaf area (cm^2) and leaf area index (LAI) of wheat at different growth stages (30, 60, and 90 DAS) under various residue management treatment combinations are presented in table 2. With the augmentation of rice residue quantity and distinct nitrogen doses applied to the wheat crop, the rate of leaf area accumulation displayed an increase. This augmentation in leaf area was discernible at 30 and 60 DAS, culminating in the highest leaf area recorded at 90 DAS. Notably, treatment T_6 (125% of recommended dose of nitrogen + 60 kg ha^{-1} P + 40 kg ha^{-1} K + paddy straw @ 5 t ha^{-1} incorporation + top dressing of nitrogen @ 20 $kgha^{-1}$ after incorporation of paddy straw) exhibited the most substantial leaf area (168.75, 603, and 618.75 cm^2 at 30, 60, and 90 DAS, respectively), outperforming T_7, T_3, T_5, T_4, and T_2. Conversely, the lowest leaf area was observed in treatment T_1 (Recommended NPK @ 120:60:40 kg ha^{-1}) at all growth stages throughout the crop cycle.

The LAI exhibited significant variation due to rice straw management and nitrogen levels, particularly evident at 90 DAS (Table 2). At 30, 60, and 90 DAS, the LAI recorded under the treatment involving rice straw incorporation at 5 t ha^{-1}, 125% of recommended dose of nitrogen , 60 kg ha^{-1} P, 40 kg ha^{-1} K, and top dressing of nitrogen at 20 kg ha^{-1} (T_6) demonstrated comparability and superiority over the treatment with 125% of recommended dose of nitrogen , 60 kg ha^{-1} P, 40 kg ha^{-1} K, paddy straw incorporation at 5 t ha^{-1}, and top dressing of nitrogen at 20 kg ha^{-1} after incorporation of paddy straw with decomposer application (T_7). Additionally, T_6 outperformed the treatment involving recommended NPK @ 120:60:40 kg ha^{-1} with Paddy straw incorporation at 5 t ha^{-1} and top dressing of nitrogen at 20 kg ha^{-1} after incorporation of paddy straw (T_3) in terms of LAI at these growth stages. Previous research indicated that burned rice straw significantly decreased parameters such as flag leaf area, spikes number per square meter, 1000-grain weight, and grain and total yields per field area. [19,20,21]

Yield attributes

The yield attributes character was influenced significantly due to rice residue incorporation. The data of effective tillers, Spike length (cm), Number of grains /spikes, Weight of spike (g) and Grain weight/spike presented in Table 3 revealed the effect of varying treatment on yield attributes of wheat. The tiller was influenced significantly due to rice residue incorporation. There was a significant improvement in the number of tillers and effective tillers the maximum number of effective tillers m^{-2} (343) was recorded by the application of treatment T_6 (125% of RDN +60 P + 40 K, $Kgha^{-1}$ + Paddy straw @ 5 t/ha incorporation+ Top dressing of Nitrogen @ 20$Kgha^{-1}$ after incorporation of Paddy straw) followed by T_7> T_5> T_3> T_4> T_2.The highest spike length (11.4cm) was also recorded under T_6 followed by T_7> T_5> T_3> T_4> T_2 while lowest spike length (9.8 cm) was recorded under T_1 (Recommended NPK @ 120:60:40 $Kgha^{-1}$ + No Paddy straw incorporation.). Similarly, the highest grains per spike (41.5) was also recorded under T_6 (followed by T_7 (41.4), T_5 (41.2), T_3 (41), T_4 (40.8), T_2 (40.6). The lowest grain per spike (40) was recorded under T_1 (Recommended NPK @ 120:60:40 $Kgha^{-1}$ + No Paddy straw incorporation.). A close perusal of data revealed that application of the graded does of RDF along with 20 % excess dose of Nitrogen, foliar application of 20 kg nitrogen, Decomposer and crop residue significantly influenced the spike weight highest by treatment T_6 followed by T_3> T_7> T_4> T_5> T_2. The lowest spike weight (1.6 g) was recorded with the treatment T_1 (Recommended NPK @ 120:60:40 $Kgha^{-1}$ + No Paddy straw incorporation.) during crop period of the crop. The data on progressive Grain weight/ spike at the successive stages of crop growth as influenced by various treatment combinations have been summarized in Table 3. Application of 125% of RDN + 60 P + 40 K, $Kgha^{-1}$ + Paddy straw @ 5 t ha^{-1} incorporation+ Top dressing of Nitrogen @ 20 $Kgha^{-1}$ after incorporation of Paddy straw (T_6) significantly higher grain weight/ spike (1.539 g) was recorded from the above define treatment while lowest value of grain weight/ spike (1.472g) found from the treatment T_1 (Recommended NPK @ 120:60:40 $Kgha^{-1}$ + No Paddy straw incorporation.) of the year of experimentation. The Grain weight/ spike data varied from (1.472 - 1.539 g) was recorded from the various treatments' combinations. The higher values of

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growth characters with application of residues were mainly due to rapid growth caused by maintenance of adequate and continuous supply of nutrients to crop resulted in maintaining better establishment of roots and various metabolic processes which contributed to rapid cell division, cell elongation and thus resulted in higher growth of the plant. [22] The higher values of all yield attributing characters with increased supply of nutrients through residues were due to more proliferation of roots build-up higher concentration of nutrients in soil that hasten cell division and elongation. This favors the root branching accompanied by higher tiller development, plant height and dry matter production which contributed to higher yield attributes through increased photosynthetic activity of leaves. Besides translocation of assimilates from source to sink also increased under higher nutrient supply which led to improved yield attributes.[23, 24] The significant response of trace elements released by residues on yield attributes of wheat was due to its favorable influence in various enzymatic reactions, growth processes, hormone production, protein synthesis and also the translocation of photosynthetic to reproductive parts thus leading to better yield attributes.[24]

Economics

Significant variations in gross returns were observed among different treatments, with the split application of nitrogen leading to higher gross income. The incorporation of rice straw with 120 kg ha^{-1} nitrogen, coupled with an additional N dose (25% of recommended dose of nitrogen and 20 kg ha^{-1} top dressing after straw incorporation), resulted in substantial returns, yielding Rs. 95,369 in net profit and a benefit-cost ratio of 2.13. Among the treatments, T_6 demonstrated the highest profitability, followed by T_7 and T_3. Conversely, the lowest benefit-cost ratio was recorded in T_1 (Recommended NPK at 120:60:40 kg/ha + No Paddy straw incorporation), possibly due to increased tiller count, grains per spikelet, and test weight, ultimately contributing to higher total wheat production compared to other treatments. Similar findings were reported regarding diverse paddy straw management practices, highlighting improved productivity, yield attributes, and elevated net returns with favorable benefit-cost ratio.[25,26,27]

Conclusion

Rice cultivation holds a significant share of India's arable land, and the recycling of rice crop residues offers substantial potential for replenishing soil nutrients in rice-based farming systems. The challenge of yield stagnation, attributed to declining soil organic carbon levels, poses a notable threat to this system. This concern is exacerbated by the increased use of mechanical harvesters for grain collection, which results in substantial residue accumulation in the fields. In light of managing these rice residues, the findings of this study lead to the following key conclusions:

Optimal fertilization for wheat crops involves applying 125% recommended dose of nitrogen with 60 kg of phosphorus and 40 kg of potassium per hectare. Incorporating paddy straw at a rate of 5 tons per hectare, followed by a top dressing of 20 kg per hectare of nitrogen after straw incorporation, proves advantageous in a rice-wheat cropping system. This approach not only enhances yields but also offers economic viability for nitrogen application in wheat cultivation.

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Conflict of interest: The authors declare that there is no conflict of interest.

Table 1: Plant height (cm) and Dry matter accumulations (m^{-2}) (2 years Pool data)

Treatment	Plant height (cm)				Dry matter accumulations (m^{-2})			
	Days after sowing				Days after sowing			
	30	60	90	At harvest	30	60	90	At harvest
T_1.	24.00	61.30	85.80	87.60	68.50	519.60	866.00	1056.00
T_2	23.60	59.60	83.60	85.20	67.40	499.40	832.30	1015.00
T_3	24.60	69.40	96.00	98.90	70.30	559.80	932.80	1138.30
T_4.	24.20	64.40	89.20	92.00	68.90	540.00	900.00	1098.00
T_5.	24.50	67.30	95.00	96.00	69.90	562.40	939.00	1145.10
T_6.	25.30	72.70	101.90	103.60	72.30	640.00	1064.80	1298.60
T_7	25.00	68.60	96.70	98.20	71.40	588.90	981.50	1197.00
SEm ±	**0.72**	**2.10**	**2.86**	**2.80**	**2.07**	**16.69**	**30.25**	**35.70**
CD(P=0.05)	**2.08**	**6.08**	**8.27**	**8.09**	**5.98**	**48.21**	**87.36**	**103.11**

Table 2: Leaf area (cm), Leaf area index (cm) and Leaf area ratio (cm) (2 years Pool data)

Treatment	Leaf area (cm)			Leaf area index (cm)			Leaf area ratio (cm)	
	30	60	90	30	60	90	30-60	60-90
T_1	159.75	562.50	579.38	1.40	4.60	4.75	1.69	0.84
T_2	157.50	517.50	534.38	1.42	5.00	5.15	1.71	0.88

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T_3	164.25	585.00	596.25	1.46	5.20	5.30	1.69	0.84
T_4	160.88	560.25	571.50	1.43	4.98	5.08	1.69	0.84
T_5	163.13	590.63	599.63	1.45	5.25	5.33	1.69	0.84
T_6	168.75	603.00	618.75	1.50	5.36	5.50	1.64	0.76
T_7	166.50	596.26	609.75	1.48	5.30	5.42	1.67	0.82
SEm ±	**05.13**	**16.24**	17.38	**0.05**	**0.16**	**0.16**	**0.05**	**0.03**
CD(P=0.05)	**14.82**	**46.91**	**50.20**	**0.13**	**0.47**	**0.46**	**0.15**	**0.07**

Table 3: Number of effective tiller (m^{-2}), Spike length (cm), Number of grains /spikes, Weight of spike (g) and Grain weight / spike (2 years Pool data)

Treatments	Effective tiller (m^{-2})	Spike length (cm)	Grains /spikes	Weight of spike (g)	Grain weight / spike
T_1	277.20	9.80	40.00	1.60	1.47
T_2	283.40	10.20	40.60	1.62	1.50
T_3	304.0	10.80	41.00	1.65	1.52
T_4	293.60	10.60	40.80	1.63	1.51
T_5	304.40	11.20	41.20	1.62	1.52
T_6	343.00	11.40	41.50	1.68	1.54
T_7	317.00	11.30	41.40	1.64	1.53
SEm ±	**8.89**	**0.34**	**1.26**	**0.05**	**0.05**
CD(P=0.05)	**25.69**	**0.98**	**3.65**	**0.15**	**0.13**

Table 4: Effect of rice straw management and nitrogen level economics of wheat crop by various treatments and their combination. (2 years Pool data)

Treatments	Common cost (Rs. ha^{-1})	Cost of treatment Nitrogen	Cost of decomposer application	Cost of cultivation (Rs. ha^{-1})	Gross return (Rs. ha^{-1})	Net return (Rs. ha^{-1})	B:C ratio
T_1	43767	-	-	43767	108890	65123	1.48
T_2	43767	-	-	43767	113362	69595	1.59
T_3	43767	664	-	44431	122607	78176	1.75
T_4	43767	-	750	44517	118027	73510	1.65
T_5	43767	590	-	44357	123375	79018	1.80
T_6	43767	854	-	44621	139990	95369	2.13
T_7	43767	854	750	45371	129105	83734	1.84

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