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Prayasi Nayak
GBPUAT, Pantnagar, Uttarakhand, India

Sumit Chaturvedi
GBPUAT, Pantnagar, Uttarakhand, India

VC Dhyani
Associate Professor, Dept. of Agronomy, GBPUAT, Pantnagar, Uttarakhand, India

Subhash Chandra
Chief Scientist, Dept. of Agronomy, GBPUAT, Pantnagar, India

Kamalkant Yadav
GBPUAT, Pantnagar, Uttarakhand, India

Aishwariya Mangraj
GBPUAT, Pantnagar, Uttarakhand, India

Corresponding Author:
Prayasi Nayak
GBPUAT, Pantnagar, Uttarakhand, India

Effect of crop residue management and inorganic fertilizer on rice growth, yield and nitrogen use efficiency

Prayasi Nayak, Sumit Chaturvedi, VC Dhyani, Subhash Chandra, Kamal Kant Yadav and Aishwariya Mangraj

Abstract
Around the world, Asia produces and consumes 90% of the world's rice. The sustainability of the rice-wheat cropping system has been questioned in light of the issues that have occurred in recent years in those areas. Low nitrogen use efficiency and ineffective crop residue management are two of the main issues limiting the productivity of the rice-wheat cropping system. The majority of agricultural production systems have relied on large inputs of nitrogen (N) fertiliser, which has led to a rapid increase in the use of mineral (synthetic) fertiliser over time. However, N use efficiency has decreased in most regions. This straw must be applied on an annual basis to maintain adequate soil fertility, but applications can be made in a more sustainable manner to improve soil and crop quality and should be cost-effective. The use of biochar in agriculture, as well as its impact on overall climate change, the soil environment, and plant growth, has sparked increased interest in agricultural science fields. Overuse of inorganic fertilisers gradually reduces microbial biomass, whereas organic sources such as biochar and straw can increase soil microbial biomass carbon and enzyme activity, thereby improving soil health and supporting better plant growth and productivity.

Keywords: Residue management, bio char, nutrient use efficiency, sustainability, carbon sequestration

1. Introduction

Rice (*Oryza sativa* L.) is an important staple food crop for more than70% of the world’s population and a principal source of energy and income for more than 50% of the world's population [1]. Rice-wheat is the major cropping system of South Asia [2] and plays a crucial role in global food security. The Indo-Gangetic plains (IGP) covers about 13.5 Mha area under rice-wheat cropping system, which is more than 85% of this system [1]. However, the existing cropping system is facing several sustainability issues, such as deteriorating soil health, water and labour scarcity, nutrient imbalances and low soil organic matter contents, herbicide resistance, and burning of crop residues [2].

India produces 97.2 Mt of rice straw annually, and 23% of this is burnt in field by farmers especially in the North-Western belt of Rice–Wheat cropping system including the states of Punjab, Haryana, Uttar Pradesh and Uttarakhand [3]. Such residue burning leads to loss of nutrients retained in straw to a greater extent along with causing environmental pollutions with carbon dioxide (CO_2), sulphur dioxide (SO_2), nitric oxide (NO_2) and particulate matter [4]. By burning of the rice straw, 35 kg N, 3 kg P (7 kg P_2O_5) and 2.7 kg S is lost from one hectare of field as rice straw contains 0.6–0.9% N, 0.07–0.2% P and 1.8–3.7% K and 0.07–0.1% S [3]. The residue burning problem can be tackled through managing the rice straw in multiples way: using the rice residue for manure, energy production, biochar, and mushroom cultivation, residue incorporation in to soil, and zero-till seeding and mulching [4]. The comparative performance of residue incorporation and bio char addition methods with respect to nutrient management will be examined through this study.

Residue incorporation in the soil is considered to be an effective in-situ residue management option to improve the soil health in long-term [5]. However, this is higher labour and energy requiring process and leads to temporary immobilization of nitrogen, which requires additional N application of 25–30 kg ha^{-1}. Hence, it increases the cost of cultivation and also affects field preparation and crop establishment of rice. Converting the surplus rice straw into biochar is a suitable alternative. Biochar is a high-carbon fine grained residue, which is usually produced through pyrolysis (thermal decomposition at 400–500 °C) of biomass in the absence of oxygen (preventing combustion) [6]. Because of its stability and resilience, bio char is resistant to microbial degradation and can persists in the soil for a longer period of time can. Hence, it be utilised as a soil amendment for carbon sequestration and mitigating climate change [7]. The inherent chemical and physical qualities of bio char, such as porosity, increased surface area, a strong aromatic structure, an alkaline nature and higher cation exchange capacity (CEC) have a direct impact on soil properties such as pH, water holding capacity, and bulk density [8]. Hence, application of bio char alters the nutrient dynamic in soil and increased the availability which further leads to greater crop productivity [9]. Under conventional rice cultivation system, N management in rice poses several challenges, as almost 60% of urea is volatilized as NH_3 and lost to the environment [10]. The bio char application is reported to increase the NH_4^+, and NO_3^- retention in soil and improving N use efficiency [11]. However, bio char production is high energy requiring technology and its effectiveness in residue and nutrient management isn't studied in details in IGP area of India. Hence, present experiment was conducted to study the interactive effect of residue and nitrogen management on growth, yield and nitrogen use efficiency of rice.

2. Material and Methods

A field experiment on effect of residue and nitrogen management on growth, yield and nitrogen use efficiency of rice was conducted at the Norman E. Borlaug crop research centre of GBPUAT, Uttarakhand, India, for two successive years (*kharif* seasons of 2019 and 2020). The centre is located at 29° N latitude and 79.3° E longitude with an elevation of 243.8 m above mean sea level. The research centre falls under the foothills of "Shivalik" ranges of "Himalaya" a narrow belt called "Tarai" of Uttarakhand state. The climate is of sub-tropical and sub-humid type with hot and dry summer and cold winter. The mean annual rainfall and pan evaporation are 1400 mm and 1200 mm**,** respectively. The total amount of rainfall received was 1119.4 mm and 933.7 mm during the first (2019) and second (2020) years, respectively. The experimental soil was clay loam in texture comprising of 47.6% sand 28.7% silt, and 23.7% clay and pH of the soil was 6.8 (1:2.5 soil: water ratio). The soil of the experimental field had 246.3 kg ha^{-1} alkaline permanganate oxidizable nitrogen (N), 22.7 kg ha^{-1} available phosphorus (P), 180.3 kg ha^{-1}1 N ammonium acetate exchangeable potassium (K) and 0.80% organic carbon [12].

The experiment was laid out in randomized block design with four treatments replicated five times. The treatments of the experiment were control, No residue + 100% RDF, Residue + 100% RDF and Bio char + 100% RDF and allotted randomly in plots. Residue management through residue incorporation, Bio char application prepared at 450˚C from rice straw and no residue were taken along with nitrogen management through urea (100% RDF) application. Rice residue and Bio char applied @ 5 t ha^{-1} at the time of field preparation. The recommended dose of nitrogen (RDN) was 150 kg ha^{-1}. Bio char for field scale utilization was derived from a horizontal rotatory drum-type pyrolyzing unit at a pyrolysis temperature. The rice straw biomass was sun dried and chopped in to small pieces of 2-3 cm before pyrolysis. Dried biomass was loaded in to rotator drum after the partial ignition, lid was closed and air was blown with air blower to proceed the pyrolysis process. The rice variety taken under trial HKR-47.The plot size was 6.5 m × 4.2 m. During both the years of the experiment, the field was ploughed twice and then puddled and levelled to prepare the field for transplanting. Before transplanting 60 kg ha^{-1} P_2O_5 through single superphosphate and 40 kg ha^{-1} K_2O through muriate of potash fertilizer were uniformly broadcasted over puddled soil. Nitrogen at 150 kg ha^{-1} was applied through urea in three splits: one-third at basal and the remaining two-thirds at 25 DAT and 50 DAT. In plots, the twenty-five-days-old seedlings of different rice varieties were transplanted at 20 cm × 10 cm spacing in the first fortnight of July in both years. All the other standard recommended cultural practices were followed for the cultivation of rice, and harvesting was done in between the last weeks of October to the first week of November during both years.

At harvesting stage plant height of rice was measured from the base of the plant at ground surface to the tip of the tallest leaf panicle using a standard meter scale. Tillers number was counted from the labelled hill at 60 DAT. Five hills of rice were sampled at 60, 90 days and at harvesting stage of the crop and air-dried followed by hot-air oven drying at 70±2°C till a constant weight. Then the total dry-matter accumulation by rice was estimated and expressed in g m^{-2}. Different indices of Nitrogen use efficiency *viz*., Partial factor productivity, Agronomic efficiency and apparent recovery efficiency were calculated.

2.1 Nitrogen use efficiency

$$\text{Partial Factor Productivity (PFP)} = \frac{\text{Grain yield of treated plot}}{\text{Amount of N applied}}$$

$$\text{Agronomic Efficiency (AE)} = \frac{\text{Grain yield of treated plot} - \text{grain yield of untreated plot}}{\text{Amount of N applied}}$$

$$\text{Apparent Recovery efficiency (ANR)} = \frac{\text{Total N uptake in treated plot} - \text{Total N uptake in untreated plot}}{\text{Amount of N applied}}$$

Harvesting was done followed by threshing, winnowing and cleaning. The grains were dried to 14% moisture content and grain yield of rice was estimated. Similarly, straw yield was recorded by subtracting grain yield from the total biomass yield. Grain and straw yield were expressed in t ha^{-1}. The statistical analysis of all the data obtained from this two year-experiment were done using the F–test, as per the procedure given by Gomez and Gomez [13]. CD values at P=0.05 were used to determine the significance of difference between treatment means and the figures were constructed using the data analysis tool pack of Microsoft Excel (2013).

3. Result and discussion

3.1 Grain yield (t ha^{-1})

The data presented in table-1 revealed that the effect of residue and nitrogen management practices on grain yield (t ha^{-1}) of rice was significant during both the seasons. During 2019, higher grain yield of rice was recorded with application of bio char in combination with 100% RDF (6.37 t ha^{-1}) which was statistically at par with residue incorporation + 100% RDF

(6.28 t ha^{-1}) and it was significantly higher over no residue application (5.50 t ha^{-1}). Likewise, during 2021, maximum grain yield was recorded with application of Bio char + 100% RDF (6.62 t ha^{-1}) which was followed by Residue + RDF (100%), and both the treatments were significantly higher over the yield recorded with residue removal + 100% RDF. Residue management either as bio char or as incorporation along with 100% RDF has increased the grain yield compared to 100% RDF without application of residue. Residue management as bio char and residue incorporation along with 100% RDF increased the grain yield by 15.8% and 14.2% over no residue application + 100% RDF.

3.2 Straw yield (t ha^{-1})

Data presented in table-2 revealed that, integration of residue and nitrogen fertilizer significantly affected the straw yield of rice during both years of experiment. Maximum straw yield was recorded with application of bio char along with 100% RDF (9.32 t ha^{-1}), which was significantly higher over application of 100% RDF without residue and statistically at par with residue incorporation in conjunction with 100% RDF. Minimum straw yield was recorded in control plot (5.26 t ha^{-1}) during both the years of experiment.

3.3 Harvest Index (%)

The effect of residue and nutrient management practices on the harvest index (HI) of rice was non-significant during 2019. It was reported to maximum under bio char + 100% RDF (40.60%) followed by Residue + RDF 100% (40.41%) and no residue + 100% RDF (39.5%). While, in 2020 residue along with nutrient significantly affected the HI of rice and higher HI was recorded under bio char + 100% RDF (40.11%) which was statistically at par with Residue + RDF 100% (39.06%) and significantly higher over No residue + 100% RDF (36.71%).
The increment in biomass and grain yield with application of bio char + 100% RDF and Residue + RDF 100% was 19 to 21% higher than the yield recorded under No residue + 100% RDF. It might be due to the role of bio char in enhancing nutrient retention and availability, soil water holding capacity, soil aggregation, CEC and soil microbial dynamics [14]. Nitrogen, silicon, and carbon are among the essential and beneficial nutrients that rice straw bio char is rich in Wu *et al* [15]. The bio char addition increased the number of filled grains, productive panicles, and seed setting rate, which led to an increase in rice yield [16]. The results were in conformity with Liu *et al.* [17]. The co-application of bio char + 100% RDF resulted in a higher harvest index (40.6%) than residue and no residue application with 100% RDF, which might be attributed to the surface area provided by bio char for nutrient adsorption and retention, slow nutrient release and efficient utilisation enabled better translocation and effective partitioning of photosynthates, as well as their conversion to economic yield [11].

3.4 Growth attributes

3.4.1 Plant Height

Plant height increased significantly from 30 DAT to 90 DAT and then remained steady towards harvesting irrespective of treatments and years of cropping. Maximum plant height was recorded at harvesting stage with co-application of bio char and 100% RDF (131 cm and 133.3 cm) which was followed by application of Residue + RDF 100% (128 cm, 131.1 cm), and both were found to be significantly higher than the plant height recorded with 100% RDF + No residue (119.4 cm and 124.3 cm) during both the cropping seasons. Plant height recorded during harvest with combined application of bio char and residue with 100% RDF was 8 to 10% higher than no residue management+100% RDF.

3.4.2 Maximum tiller count

The maximum number of tillers recorded at 60 DAT during both cropping years revealed that co-application of biochar and residue along with 100% RDF has significantly affected the maximum tiller count m^{-2} as compared to only inorganic fertilization (100% RDF). The tiller number recorded with Bio char + 100% RDF during 2019 and 2020 was 407 and 420 and it was followed by application of Residue + 100% RDF (393 and 411). The number of tillers recorded with 100% RDF + No residue was only 366 in 2019 and 373 in 2020 which is approximately 10 to 13% lower than the tiller count obtained with residue + 100% RDF and bio char + RDF.

3.4.3 Dry matter accumulation

The experimental data regarding dry matter accumulation (DMA, g m^{-2}) was recorded at 30, 60, 90 DAT and at harvest. During both the years dry matter accumulation increased constantly up to harvesting stage. At harvest, maximum dry matter production was recorded under Bio char + 100% RDF (1444, 1457 g m^{-2}) which was followed by Residue +100% RDF (1415, 1428 g m^{-2}) but significantly higher than 100% RDF + No residue (690.4 and 627.8 g m^{-2}) during both the years of experiment.
In comparison to 100% RDF, bio char and residue incorporation had an incremental influence on plant height, maximum tiller count and dry matter accumulation. It might be because bio char has a good impact on soil qualities such as cation exchange capacity and oxygen carbon ratio, which has increased nutrient availability, moisture content and stimulated plant growth and development [18]. At crop maturity around 40% of the nitrogen, 30-35% of the phosphorus, 80-85% of the potassium and 40-50% of the sulphur taken up by rice remains in vegetative plant portions. Straw is also a good source of micronutrients like zinc and has a big impact on the soil nutrient pool [19]. Carbonized bio char and straw incorporation increased primary nutrient concentration as well as plant nutrient uptake while increasing nutrient use efficiency, resulting in faster plant growth and development [14].

3.5 Nitrogen use efficiency

Data referring to various N use efficiencies like partial factor productivity (kg GY/kg N), agronomic efficiency (kg GY/kg N) and recovery efficiency (%) in rice as affected by different combination of residue and nutrient management practices has been presented in table 3.

3.5.1 Partial factor productivity

The data presented in table 3 revealed that, the cumulative effect of residue and nitrogen management practices on PFP was significant during both the years of cropping. The highest PFP was recorded under biochar + 100% RDF (42.44 and 44.14 GY/kg N) which was statistically comparable to Residue + 100% RDF (41.84 and 43.33 GY/kg N), but significantly higher to 100% RDF (36.64 and 36.30 GY/kg N). Bio char application with 100% RDF resulted in 15 to 21% higher PFP than sole application of 100% RDF without residue application.

3.5.2 Agronomic efficiency
The data presented in table 3 revealed that, the integrated effect of residue management and 100% RDF on agronomic efficiency was significant during 2019 and 2020. During both the years, the higher AE was observed under Bio char + 100% RDF (23.02 and GY/kg N) followed by Residue + 100% RDF (22.42 and GY/kg N) which was statistically at par to each other and significantly higher over no residue + 100% RDF (17.22 and GY/kg N). The AE under Bio char + 100% RDF and Residue + 100% RDF was 32 to 35% higher than single application of 100% RDF without residue management.

3.5.3 Apparent nitrogen recovery
The effect of combined application of residue, bio char and 100% RDF was significant during both the cropping seasons. During both the years of experiment the higher recovery efficiency was recorded under Bio char + 100% RDF (0.54 and 0.60%) followed by Residue + 100% RDF (0.51 and 0.58%). Residue management practices can enhance the nitrogen recovery as in this study, Bio char + 100% RDF and Residue + 100% RDF recorded on an around 40 to 46% higher N recovery compared to No residue + 100% RDF.

This is due to the fact that rice straw bio char's sorption capacity grows with application. Applying bio char increases soil surface area right away, aiding in nutrient retention and adsorption. It increases the soil's capacity to hold NH_4^+ and NO_3^- for uptake by rice plants by enhancing ammonium adsorption and reducing ammonium volatilization loss. Higher nitrogen utilisation efficiency was achieved by synchronising nutrient supply with crop nutrient demand through the gradual release of sorbed nutrients from the Bio char-treated plot [20]. The rhizosphere bacteria populations can be altered by residue management practices which improved microbial nutrient transformation as reported by Gao *et al.* [21]. Bio char can also be used to enhance the root activity and the nitrate reduction ability of the root system, therefore, improving the N absorption and utilization Pereira *et al.* [22] speculated that the synergistic interaction between bio char and N inputs might be led to an increase in NUE and it was driven by a combination of mechanisms: (i) The high carbon input may have induced microbial biomass growth and a steady delivery of N and (ii) C inputs and bio char increased cation exchange capacity and thereby nutrient retention and availability to the plants.

Table 1: Effect of residue management practice along with RDF on plant height (cm), tiller count (m^{-2} at 60 DAT) and Dry matter (g) of rice

Treatment	Plant Height (cm)		Maximum tillers at 60 DAT (m^{-2})		Dry matter (g)	
	2019	2020	2019	2020	2019	2020
Control	87.12	85.48	205	197	690.4	627.8
NR-RDF (100%)	119.4	125.4	366	373	1260	1228
R-RDF (100%)	128	131.1	393	411	1415	1428
B-RDF (100%)	131	133.3	407	420	1444	1457
C.D.	8.74	8.31	39	41	128.6	116.3
SE(m)	2.8	2.82	12	13	41	37.34

NR, No residue addition; R, Residue addition@ 4 t ha^{-1}; B, Bio char addition@ 4 t ha^{-1}; RDF: 150:60:40 N, P_2O_5 and K_2O kg ha^{-1}

Table 2: Effect of residue management practice along with RDF on yield and harvest index of rice

Treatment	Grain yield (t ha^{-1})		Straw Yield (t ha^1)		Harvest Index (%)	
	2019	2020	2019	2020	2019	2020
Control	2.91	2.84	5.26	5.19	35.7	35.40
NR-RDF (100%)	5.50	5.44	8.40	9.38	39.5	36.71
R-RDF (100%)	6.28	6.50	9.26	10.12	40.4	39.06
B-RDF (100%)	6.37	6.62	9.32	9.88	40.6	40.11
C.D.	0.50	0.64	0.43	0.62	2.37	2.21
SE(m)	0.16	0.20	0.14	0.20	0.76	0.71

NR, No residue addition; R, Residue addition@ 4 t ha^{-1}; B, Bio char addition @ 4 t ha^{-1}; RDF: 150:60:40 N, P_2O_5 and K_2O kg ha^{-1}

Table 3: Effect of residue management practice along with RDF on nitrogen use efficiency of rice

Treatment	Partial factor productivity (kg yield kg^{-1} N applied)		Agronomic efficiency (kg yield increase kg^{-1} N applied)		Apparent nutrient recovery efficiency (%)	
	2019	2020	2019	2020	2019	2020
Control	--	--	--	--	--	--
NR-RDF (100%)	36.64	36.30	17.22	17.37	0.36	0.41
R-RDF (100%)	41.84	43.33	22.42	24.40	0.51	0.58
B-RDF (100%)	42.44	44.15	23.02	25.21	0.54	0.60
C.D	3.22	4.26	3.28	4.23	0.06	0.08
SE(m)	1.03	1.36	1.05	1.35	0.02	0.03

4. Conclusion
The cumulative effect of residue and nitrogen management on plant growth, yield, and nitrogen use efficiency under rice-rice rotation is discussed in this study. Residue, either directly incorporated or in the form of biochar, coupled with inorganic fertilizers significantly improved plant growth, yield, and biomass production, as well as the effective utilisation of applied nutrients. Our findings revealed that treatment with bio char + 100% RDF had the highest value of all the studied parameters whereas mineral fertilisation used without residue management recorded minimum plant growth, yield and nitrogen use efficiency. Bio char contributed significantly to soil organic carbon sequestration by increasing the labile organic matter component and soil microbial biomass, both of which are important components of soil organic matter. Inorganic fertilisation gradually reduced microbial biomass;

however, inorganic fertilisation combined with organic sources such as bio char and straw increased soil microbial biomass carbon and enzyme activity while increasing nutrient use efficiency, and it had a significant effect on crop growth and yield.

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