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Soil quality assessment of lowland rice soil of eastern India: Implications of rice husk biochar application

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ABSTRACT

The role of biochar in improving the soil properties of problem soils is well known, but its long term impact on lowland rice soil is not well recognized. The soil quality indicators of biochar applied lowland rice soil are not widely reported. We developed soil quality index (SQI) of a biochar applied lowland rice soil based on 17 soil properties (indicators). Field experimentation consisted of six treatments such as 0.5, 1, 2, 4, 8 and 10 t ha^{-1} of rice husk derived biochar (RHB) along with control. An overall SQI was calculated encompassing the indicators using multivariate statistics (principal component analysis) and non-linear scoring functions after generation of minimum data set (MDS). Sequential application of RHB improved the SQI by 4.85% and 16.02% with application of 0.5 t ha^{-1} and 10 t ha^{-1} RHB, respectively, over the recommended dose of fertilizer (control). PCA-screening revealed that total organic carbon (C_{tot}), zinc (Zn), pH and bulk density (BD) were the main soil quality indicators for MDS with 27.79%, 26.61%, 23.67% and 14.47% contributions, respectively. Apart from C_{tot}, Zn is one of the major contributors to SQI and RHB application can potentially be an effective agronomic practice to improve Zn status in lowland rice soil. The overall SQI was significantly influenced by RHB application even at 0.5 t ha^{-1}. The present study highlights that application of RHB improves the soil quality even in fertile, well managed, lowland rice soil.

1. Introduction

Rice husk is an underutilized agro-waste and its open burning is a major source of atmospheric fine particle emissions, causing air pollution. The biochar (derived from agro-wastes as pyrogenic carbonaceous material) application to the soil is considered to be an alternative to open field burning of rice husk. It is also considered to be a highly potential option for long-term carbon sequestration. However, its role as a sustainable agriculture practice is yet to be considered fully by policy makers and farmers. Uncertainties surrounding the long term use and behavior of biochar have made the policy makers reluctant about its inclusion in agricultural policies in India.

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In the long run, there could be some potential negative outcomes of biochar application in soil [1,2] but most of the studies suggest a positive impact of biochar application [3]. The potential positive outcomes of biochar addition include an increase in the proportion of the non-labile C fraction in soil, increase in crop growth and yield, reduction in emission of greenhouse gases, increase of pH in acid soils and stimulation of soil microbial activity particularly in problem soils [4]. However, these outcomes may not be equally applicable to all cultivated soils. The properties and potentials of problem soils are very different from that of fertile agricultural soils (viz., Indian subcontinent) where the studied response to biochar application will be more relevant. Further, some aspects of biochar application have been ignored. For example, micronutrient deficiency is widespread in Indian soils and yet, it is not established whether micronutrients have a significant role in improving the soil quality of a biochar treated lowland rice soil.

To facilitate sound recommendations (for various inputs) to the farmers, robust information on the soil quality indicators is required. There exists a possibility that some of the soil properties are more positively influenced by biochar application than others, contributing to the soil quality index. Therefore, studying the interaction of these properties (using integrative tools), may help in decoding the contribution of any indicator other than the conventionally known soil parameters towards the maintenance of soil quality. Earlier soil quality assessment for biochar applied agricultural soil was carried out by Ref. [5] for the Midwestern agricultural soil of United States of America. They did not follow multivariate analysis to identify the indicators of soil quality. Our study, however, uses the weighted averages to establish the indicators that have the greatest impact on soil quality with grain yield and sustainable yield index as goal function through multivariate analysis. To develop the soil quality index (SQI), we followed the systematic three-step approach 'Identification-Interpretation-Integration' for measuring and interpreting the soil properties (ideally representing the soil quality indicators). The aim of the study was to understand the extent of the contribution made by physical, chemical and biological indicators through SQI towards attaining sustainable yield in biochar applied lowland rice soil.

2. Materials and Methods

2.1. *Experimental site and treatment details*

The experiment was undertaken at ICAR-National Rice Research Institute, Odisha, India (sub-humid tropical climate). The geographical coordinates of the experimental site are 20°27′00.02″ N and 85° 56′00.7″ E. During the years of experiment (2013–2017), the annual precipitation ranged from about 1000 to 1600 mm, of which 75–80% is received during the wet season (June to September). The mean temperatures of wet season were 28.24 °C and that of dry season was 22.26 °C. The wet season receives poor solar radiation due to cloudy conditions leading to poor photosynthetic efficiency and high occurrences of pest and disease infestations. Whereas, the dry season receives more solar radiation leading to higher photosynthetic efficiency in plants. Under irrigated conditions, dry season is more suitable for rice cultivation in this region. The soil is sandy clay loam texture (30% clay, 18% silt and 52% sand), classified under Inceptisols (Aeric Endoaquept) based on Soil Survey Staff, 2014 [6]. At the beginning of experiment, the soil had bulk density 1.40 Mg m^{-3} and optimal pH 6.8. The soil had C/N ratio 12.6 with a total C content of 0.9%.

A field experiment in micro-plots (1.0 m^2) was conducted in lowland with rice cultivated in wet as well as dry seasons (rice (*Oryza sativa* L.)- rice system), for four years using 'var. Naveen'. The seedlings (25 days old) were transplanted in micro-plots in January (first fortnight) in dry season and in July in wet season every year. Treatments comprised of recommended dose of fertilizers (RDF) and six graded dose of rice husk derived biochar (RHB) ranging from 0.5 to 10.0 t ha^{-1}. The experiment was tried under randomised block design with three replications. The RHB was applied in both the seasons seven days before transplanting of rice. So, the effect of sequential biochar application was studied at the end of fourth year of experiment i.e. after eight crop cycles. The RDF was 120:60:60 kg ha^{-1} NPK applied in the form of urea, single super phosphate and muriate of potash. Half of urea (13 g micro-$plot^{-1}$), single super phosphate (37.5 g micro-$plot^{-1}$) and muriate of potash (10.2 g micro-$plot^{-1}$) were applied at the time of transplanting. Rest half of urea was split into two equal parts and applied at maximum tillering stage and panicle initiation stage. The standing water was drained out ten days before harvesting and the soil had adequate moisture at the time of harvesting. Every year, the crops were harvested in the second fortnight of April and October, in the dry season and wet season, respectively. The grain yield was presented after adjusting the grain moisture content to 14%.

2.2. *Biochar preparation and characterization*

A furnace was designed at ICAR-National Rice Research Institute to produce RHB from rice husk, collected from rice mill in Cuttack, India. The target temperature of 350 °C was reached in about 2 h and it was maintained throughout the residence time of 2 h. The temperature was monitored using Data Logger Thermometer (OMEGA ETTE). The conversion rate of straw to RHB was 40%. The moisture content was determined using standard method described in NREL/TP-510-42,621. The ash content of RHB was determined using method described in NREL/TP-510-42,622. The moisture and ash content of the RHB were about 1% and 20%, respectively. The pH (8.9) and EC (0.7 dSm^{-1}) of RHB was determined using deionised water (1:10 W/V). Total carbon and nitrogen contents were measured by organic elemental analyzer (Thermo Scientific, Flash 2000). The total C content was 50%, while total N content was 0.3% in the RHB. To understand the pore structure of the RHB, samples were examined using scanning electron microscopy –energy dispersive spectroscopy (SEM-EDS). Zeiss EVOMA10 SEM was operated at 20 kV to carry out the SEM-EDS analysis (Supplementary Fig. 1).

2.3. Soil sampling and analysis

The soil samples from 0 to 15 cm depth were collected at the end of 4 years of the crop cycle from four different places and composited. The samples were separately analyzed for physical, physico-chemical, chemical and biological properties. A part of the soil samples was stored in refrigerator at 4 °C for microbiological and biochemical analysis. The other half was air dried, ground and sieved, passed through a 2.0 mm sieve for estimation of physical and chemical properties. BD was measured by core sampler. 1:2.5 soil-water suspension was used to measure soil pH and EC. Readings were taken using glass electrode and conductivity bridge for soil pH and EC, respectively. Total organic C (C_{tot}) was determined using Elemental Analyzer (NC Soil Analyzer, Flash 2000, Thermo Scientific, USA). Particulate organic carbon (POC) in soil was determined with modification to the method described by Ref. [7]. Permanganate oxidizable carbon ($P_{ox}C$) in soil was determined using method suggested by Ref. [8]. Available N was determined using alkaline potassium permanganate distillation method, available-P using Bray and Kurtz method, and available-K using ammonium acetate extraction method. For determination of available Fe, Mn, Zn and Cu, 0.005 M DTPA extraction method was used [9]. Microbial biomass carbon (MBC) was determined using the chloroform fumigation extraction method [10]. Dehydrogenase hydrolase activity (DHA) and fluorescein di-acetate activity (FDA) was estimated using method suggested Casida et al., 1964 [11] and Adam and Duncan, 2001 [12], respectively. β-Glucosidase activity (BGLU) was determined following the method of [13].

2.4. Development of soil quality index (SQI)

For determination of SQI, the methodical steps based on 'Soil Management Assessment Framework' (SMAF) were followed [14] with modifications [15]. The first step was creation of minimum data set (MDS) of soil indicators which involved selection of soil properties based on significant differences among the treatments and then, using the principal component analysis (PCA) to arrive at the most potential indicators that represent soil functions. Further, the redundant indicators were eliminated based on Pearson's correlation coefficients of each principal component. Only one among the highly correlated indicators was referred in the MDS.

In the second step of SQI calculation, the MDS indicators were scored based on their importance and scientific relevance (Supplementary Table 1). Before scoring the MDS indicators, highly weighted indicators were run through multiple regression analysis to learn how best the MDS indicators represented RHB application practice in terms of crop yield and sustainable yield index (SYI). The results were transformed into non-linear score (S) for each MDS indicator and calculated using the following equation [16]:

$$S = a \Big/ \left(1 + (x/x_0)^b\right.$$

where x is the soil parameter value, a is the maximum score (1.00) of the soil property, x_0 is the baseline or value of each variable where the score equals 0.5 and equals the mid-point between threshold soil property values and b is the value of the slope of the equation [15].

In the third step for calculation of SQI, all the indicator scores were integrated to derive at the dimensionless SQI. The scores were weighed using PCA outcomes and transformed using the method described by Ref. [16]. The weighted variable scores of MDS were added for each observation to calculate the SQI using the following equation:

$$SQI = \sum_{i=1}^{n} W_i \times S_i$$

where W_i is the weighing factor derived from the PCA (absolute value) and S_i is the score for the subscripted variable. It was assumed that higher scores represented better soil quality. The resultant SQI values were tested for their significance at $P \leq 0.05$.

Sustainable yield index (SYI) was worked out as goal function. The SYI was calculated for wet season rice and dry season rice separately, because in eastern India, the weather conditions are fairly different in these seasons and have significant influence on crop growth and yield. The SYI was used in the second step for calculation of SQI wherein multiple regressions were performed using the indicators as independent variables while SYI and average yield over four years as dependent variables. The SYI was calculated using the following formula:

$$SYI = (Y - \sigma_{n-1}) / Y_m$$

where Y is average yield, σ_{n-1} the standard deviation and Y_m the maximum yield obtained during the experiment (SAS Version 9.3).

2.5. Statistical analyses

The estimated parameters were tested for significant differences of the mean among the treatments by one way ANOVA (at $P \leq 0.05$). The MDS indicators were deduced using the PCA, Pearson's correlation coefficient and the multiple regression equations using the SAS software package (SAS Version 9.3) to select the indicators for calculation of the SQI.

Table 1

Descriptive statistics of all soil parameters. The difference between the means of treatment is separated by least significant difference (LSD) at 5% level of significance.

Treatment	Physical indicator	Physico-chemical indicator		Chemical indicator									Biological indicator			
	BD	pH	EC	C_{tot}	POC	$P_{ox}C$	Avail N	Bray's P	Avail K	DTPA-Zn	DTPA-Cu	DTPA-Fe	DTPA-Mn	FDA	DHA	BGLU	MBC
RDF	1.52^{A}	6.78^{B}	0.51^{D}	11.92^{C}	0.81^{E}	0.52^{B}	221.0^{E}	11.97^{C}	110.0^{C}	1.08^{B}	0.18	58.77^{BC}	56.72	5.57	15.21^{C}	10.47^{B}	121.0^{B}
RDF + 0.5 t ha^{-1} RHB	1.51^{A}	6.81^{B}	0.58^{CD}	17.21^{B}	0.93^{D}	0.66^{B}	227.3^{DE}	12.30^{C}	112.7^{C}	1.15^{AB}	0.18	56.41^{C}	60.83	6.02	16.02^{BC}	10.47^{B}	164.7^{A}
RDF + 1.0 t ha^{-1} RHB	1.49^{B}	6.87^{B}	0.64^{C}	27.85^{A}	0.99^{D}	1.27^{A}	233.3^{CDE}	12.73^{C}	114.3^{C}	1.18^{A}	0.20	61.67^{AB}	60.70	6.10	16.31^{BC}	13.66^{B}	173.6^{A}
RDF + 2.0 t ha^{-1} RHB	1.47^{B}	7.01^{A}	0.93^{B}	28.24^{A}	1.18^{C}	1.23^{A}	237.7^{BCD}	13.37^{BC}	115.0^{BC}	1.20^{A}	0.18	61.06^{AB}	61.03	6.14	17.13^{AB}	20.08^{A}	117.1^{B}
RDF + 4.0 t ha^{-1} RHB	1.47^{B}	7.04^{A}	1.06^{AB}	28.72^{A}	1.25^{BC}	1.26^{A}	241.7^{ABC}	13.50^{BC}	127.7^{AB}	1.22^{A}	0.20	62.32^{A}	60.43	6.20	17.24^{AB}	20.56^{A}	165.3^{A}
RDF + 8.0 t ha^{-1} RHB	1.46^{B}	7.09^{A}	1.17^{A}	30.04^{A}	1.33^{B}	1.19^{A}	248.3^{AB}	14.93^{AB}	132.3^{A}	1.23^{A}	0.18	62.33^{A}	58.31	6.18	17.54^{AB}	20.64^{A}	196.1^{A}
RDF + 10.0 t ha^{-1} RHB	1.46^{B}	7.11^{A}	1.27^{A}	30.83^{A}	1.49^{A}	1.18^{A}	251.7^{A}	15.23^{A}	133.7^{A}	1.23^{A}	0.19	62.31^{A}	58.45	6.63	23.25^{A}	20.66^{A}	203.9^{A}
SE(d)	0.011	0.034	0.10	1.682	0.038	0.016	5.968	0.748	4.156	0.042	0.017	1.071	1.563	0.42	0.731	1.591	18.06
LSD ($P \leq 0.05$)	0.024	0.074	0.18	3.662	0.827	0.035	13.004	1.6301	9.055	0.086	NS	2.333	NS	NS	01.512	3.465	39.34

RDF, Recommended dose of fertilizers (NPK); BD, Bulk density (Mg m^{-3}); EC, Electrical conductivity (dS m^{-1}); C_{tot}, Total organic carbon (g kg^{-1}); POC, Particulate Organic carbon (g kg^{-1}); $P_{ox}C$, Permanganate oxidizable carbon (g kg^{-1}); Avail N, Available nitrogen (kg ha^{-1}); Bray's P, Available phosphorus (kg ha^{-1}); Avail K, Available potassium (kg ha^{-1}); DTPA-Zn, DTPA extractable zinc (mg kg^{-1}); DTPA-Cu, DTPA extractable copper (mg kg^{-1}); DTPA-Fe, DTPA extractable iron (mg kg^{-1}); DTPA-Mn, DTPA extractable manganese (mg kg^{-1}); FDA, Fluorescein diacetate hydrolase (μg fluroscein g^{-1} h^{-1}); DHA, Dehydrogenase (μg TPF g^{-1}h^{-1}); BGLU, β-glucosidase (μg *p*-nitrophenol g^{-1} soil h^{-1}); MBC, Microbial biomass carbon (mg kg^{-1}).

*Means with same letter are not significantly different at $P \leq 0.05$.

3. Results and Discussion

3.1. Response of soil quality indicators and yield of crop

The results of the soil analysis for all the soil physical, physico-chemical, chemical and biological properties are presented in Table 1. The pH was highest in the soil with RDF +10 t ha^{-1} RHB (7.11), and it was at par with application of 2, 4 and 8 t ha^{-1} RHB along with RDF ($P \leq 0.05$). Addition of RHB may have attributed to increase in cation exchange capacity and base saturation of the soil [17] resulting in higher pH. The EC values showed steep increase with increase in RHB application rates and ranged from 0.51 to 1.27 dS m^{-1}. Rice husk derived biochar contains dissolved salts which increase the EC of the soil [18]. The BD (0–15 cm) values ranged from 1.46 Mg m^{-3} for RDF + 10 t ha^{-1} RHB to 1.52 Mg m^{-3} for RDF. The BD decreased (4.1%) with higher application rates of RHB, which can be attributed to a large surface area due to a wide pore size (Supplementary Fig. 1) distribution. The improvement in BD (10–13%) by adding maize straw derived biochar had been reported by Refs. [19,20], which implied higher soil porosity, improved soil aeration and water holding capacity and better root distribution of crops.

All the three major plant nutrients viz., available N, Bray's P and K (three most commonly used soil chemical quality indicators) recorded significant difference with graded dose of RHB application. Available soil N content ranged from 221 to 251.7 kg ha^{-1}, soil P ranged from 11.97 to 15.23 kg ha^{-1} and soil K ranged from 110 to 133.7 kg ha^{-1}. Higher rates of RHB application recorded higher NPK in soil after the completion of fourth year of micro-plot experiment. Substantial increase in soil P and K on RHB application was reported earlier [21]. In another experiment in China, biochar application was reported to increase the soil exchangeable K by 1.5–5.3 times by increasing the exchangeable K due to higher cation exchange capacity of biochar [22].

Among the micronutrients, Zn and Fe recorded significant response to application of RHB, while Cu and Mn did not record any significant difference among the treatments. It has been reported that concentrations of extractable Zn in soil increased with biochar application, whereas extractable Cu did not change. Significant increase in Zn and Fe may be attributed to their respective content in the RHB (Zn, 2.05 mg kg^{-1}; Fe, 81.5 mg kg^{-1}) [23]. Microbial biomass carbon (MBC) and β-glucosidase (BGLU) activity responded positively and recorded significant difference among the treatments. Treatment receiving 10 t ha^{-1} RHB recorded maximum MBC (203.9 mg kg^{-1}) and BGLU activity (20.66 μg TPF g^{-1} h^{-1}), which was at par with 4 and 8 t ha^{-1} RHB application. The improvement in the soil properties (pH, nutrients) due to RHB application increased the soil microbial population which led to increased enzymatic activity viz., MBC and BGLU. The MBC and BGLU activity have been considered as important indicators of soil quality as these parameters are sensitive to management practices. Bera et al., 2016 [24] and Lopes et al., 2021 [25], suggested that MBC and BGLU activity are two of the most important soil quality indicators in biochar amended soils. Fluorescein di-acetate and DHA also increased with increase in RHB application rates, however the differences were found to be non-significant.

In terms of yield, there was a positive response of RHB application and grain yield of rice increased with an increase in RHB application rates (Table 2). This was consistent across the seasons and years of experimentation. After the fourth year, the dry season yield ranged from 525.4 to 640.4 g m^{-2} and wet season rice yield ranged from 531.0 to 637.4 g m^{-2}. Application of 10 t ha^{-1} RHB recorded 21.9% and 20.0% higher yield over control in dry season and wet season, respectively. Our results reveal that under more congenial conditions, the response to biochar application is higher. So far it has been observed and reported that, a positive impact of biochar application in a degraded and resource-poor soil is highly likely. Our results, partially alleviate this concern expressed by Jones et al., 2012 [4], that, well managed fertile soils may not show considerable response to biochar application. As mentioned earlier, under irrigated conditions, dry season is more suitable for rice cultivation in this part of the world. The overall SYI was higher in dry season (0.82) compared to wet season (0.78). It may also be inferred from the results that the effect of RHB application is evident even in a favourable, well managed soil under favourable climatic conditions. This could be a result of single or multiple benefit(s) from nutrient additions, enhanced availability of nutrient, improved nutrient retention resulting from higher exchange capacity, favourable soil pH, improved soil physical characteristics, and increased soil microbial population. These factors improved the soil quality and established its direct link with crop productivity [26–28].

Table 2

Effect of continuous biochar application on grain yields and sustainable yield index (SYI). The difference between the means of treatment is separated by least significant difference (LSD) at 5% level of significance.

Treatments	Dry season yield	SYI-Dry season	Wet season yield	SYI-Wet season
RDF	525.4^{D}	0.73^{D}	531.0^{E}	0.70^{C}
RDF + 0.5 t ha^{-1} RHB	545.0^{D}	0.79^{CD}	555.1^{DE}	0.73^{BC}
RDF + 1.0 t ha^{-1} RHB	571.0^{C}	0.81^{BCD}	585.1^{CD}	0.79^{AB}
RDF + 2.0 t ha^{-1} RHB	595.6^{B}	0.81^{BC}	592.4^{BC}	0.79^{AB}
RDF + 4.0 t ha^{-1} RHB	598.7^{B}	0.84^{ABC}	617.5^{AB}	0.82^{A}
RDF + 8.0 t ha^{-1} RHB	628.0^{A}	0.88^{AB}	628.9^{A}	0.84^{A}
RDF + 10.0 t ha^{-1} RHB	640.4^{A}	0.90^{A}	637.4^{A}	0.82^{A}
SE(d)	9.68	0.022	14.50	0.020
LSD ($P \leq 0.05$)	21.09	0.077	31.59	0.072

*means with same letter are not significantly different at $P \leq 0.05$.

3.2. Generation of soil quality index (SQI) through minimum data set

For screening of sensitive soil quality indicators, multivariate analysis was undertaken. In the dataset, 78.95% of the variability was explained with four principal components which had Eigen values more than 1 (Table 3). Pearson's correlation coefficient was worked out separately for the highly weighted variables under each principal component (Table 4). Under PC1, there were nine potential indicators that were highly weighted and highly correlated. So, the decisions were made on the basis of experience and opinions of collaborating authors. It is generally suggested that choice among the highly correlated indicators could also be based on the practicability [14].

A total of nine soil parameters qualified for MDS. Among the physico-chemical parameters, pH was highly correlated to most of the PC1 variables and had the highest correlation sum. Additionally, RHB had significant effect on soil pH. The RHB application increases soil pH which helps in retention of water soluble nutrients in soil, thus increasing their availability for plant uptake [29]. pH-induced nutrient uptake is often considered as the process associated with the increase and decrease in yield and sustainable yield index, i.e. goal factor [30,31]. Therefore, pH was selected for MDS. The EC of the studied soils were in the range from 0.51 to 1.27 dS m^{-1}. Generally, influence of EC on crop productivity is not observed when it is less than 4 dS m^{-1}. Furthermore, EC levels have no direct relationship water and water-soluble nutrients available for plant uptake [32]. In our experimental soil, we did not consider EC to have an effect on the crop growth or yield substantially, similar to earlier reports [20]. Therefore, EC was dropped from the MDS, even though it had high correlation sum and factor loading. Selection of BD was inevitable as biochar is highly porous material and its continuous application is expected to reduce the BD of soil. Moreover, the BD is one of the input variables for hydrological pedotransfer functions [33], and vital for any study related to modelling for prediction of sustainable yield [34]. Therefore, BD was retained in MDS even though the factor loading was relatively low.

Among the chemical indicators, POC had the highest factor loading, followed by C_{tot}. Diovisalvi et al. (2014) [35] reported that, though POC is sensitive to agronomic management, its variation is highly correlated to C_{tot}. Their study concluded that POC can be satisfactorily obtained through variations in C_{tot} through models using content, particularly in cultivated loamy soils. C_{tot} is a key soil function with its prominent role as a nutrient reservoir and supplier, and stabilization of soil structure, apart from increasing grain yield [36]. Moreover, biochar addition directly contributes to C_{tot} in soil [37–39]. The changes in POC associated to agronomic management can be estimated through the variation of C_{tot} [35]. In the present experiment, C_{tot} also had a relatively high factor loading among the PC1 variables, and, therefore, C_{tot} was selected for MDS and POC was dropped. Biochar contains substantial amount of K in available form, and it has the potential to increase the available K content in soil over a period of time [40]. Therefore, available K was also retained in MDS. Other important variables viz., available N and Bray's P were not selected as they were highly correlated to pH. DTPA-Cu was the only highly weighted variable in PC2 and therefore retained in MDS. Similarly, in PC4, the only highly weighted variable was DTPA-Zn and it was retained in MDS. Earlier research showed, both the micronutrients (Zn and Cu) had their relative

Table 3
Results of principal component analysis (PCA) of soil quality indicators.

Principal components (PC)	PC1	PC2	PC3	PC4
Eigen value	9.185	1.660	1.451	1.124
% of total variance	0.540	0.098	0.085	0.066
Cumulative %	0.540	0.638	0.723	0.789
Factor loadings/Eigen vectors				
Physical indicator				
Bulk density (Mgm^{-3})	**−0.853**	0.084	0.307	0.087
Physico-chemical indicator				
pH	**0.938**	0.006	−0.019	−0.030
Electrical conductivity (dSm^{-1})	**0.891**	−0.008	−0.155	0.148
Chemical indicator				
Total organic carbon (g kg^{-1})	**0.918**	0.067	−0.278	−0.051
Particulate organic carbon (g kg^{-1})	**0.965**	−0.041	0.015	−0.007
Permanganate Oxidizable Carbon (g kg^{-1})	0.739	0.254	−0.288	−0.197
Available nitrogen (kg ha^{-1})	**0.893**	−0.097	0.176	0.158
Bray's phosphorus (kg ha^{-1})	**0.854**	−0.165	0.337	0.023
Available potassium (kg ha^{-1})	**0.845**	−0.152	0.271	−0.053
DTPA Zinc (mg kg^{-1})	−0.047	0.660	−0.099	**−0.517**
DTPA Copper (mg kg^{-1})	0.031	**0.756**	−0.060	0.207
DTPA Iron (mg kg^{-1})	0.747	−0.159	−0.223	−0.206
DTPA Manganese (mg kg^{-1})	0.073	0.178	−0.678	0.401
Biological indicator				
Fluorescein di acetate (μg fluroscein g^{-1} h$^{-1)}$	0.557	−0.071	0.272	0.242
Dehydrogenase (μg TPF g^{-1} h^{-1})	0.447	0.561	**0.425**	−0.106
β-glucosidase (μg *p*-nitrophenol g^{-1} soil h^{-1})	**0.908**	−0.094	−0.165	−0.222
Microbial biomass carbon (mg kg^{-1})	0.569	0.365	**0.387**	0.436

*Factor loadings in bold are considered highly weighted.

Table 4

Correlation matrix (Pearson Correlation) for highly weighed variables under principle components with high factor loading.

Variables	pH	BD	EC	C_{tot}	POC	Avail N	Bray P	Avail K	BGLU
PC1									
pH	1.000								
BD	−0.957	1.000							
EC	0.972	−0.948	1.000						
C_{tot}	0.887	−0.973	0.914	1.000					
POC	0.989	−0.942	0.990	0.893	1.000				
Avail N	0.971	−0.940	0.988	0.921	0.988	1.000			
Bray P	0.942	−0.866	0.930	0.833	0.958	0.974	1.000		
Avail K	0.903	−0.807	0.905	0.767	0.926	0.939	0.940	1.000	
BGLU	0.976	−0.964	0.929	0.877	0.942	0.907	0.851	0.816	1.000
Correlation sums	6.684	−6.397	6.681	6.121	6.744	6.747	6.439	6.390	6.334
Variables									**DTPA-Cu**
PC2									
DTPA-Cu									1.000
Variables				**DHA**					**MBC**
PC3									
DHA				1.000					0.644
MBC				0.644					1.000
Correlation sums				1.644					1.644
Variables									**DTPA-Zn**
PC4									
DTPA-Zn									1.000

importance, thereby got selected as MDS-indicators in rice-wheat system [27]. The DHA and MBC recorded significant response to biochar application. Soil enzymes qualify as MDS indicators because these parameters are most sensitive to any change in soil quality [41].

Multiple regression analysis was done to select the indicators for final calculation of SQI (Table 5). From the nine indicators that qualified for MDS, three indicators, viz., EC, DHA and DTPA-Cu were dropped on the basis of multiple regression analysis. Finally, soil indicators viz., pH, BD, C_{tot}, MBC, Avail K and DTPA-Zn were considered for calculation of SQI on the basis of multiple regression equation. The calculated value of SQI ranged from 2.06 in the RDF to 2.39 in RDF +10 t ha^{-1} RHB treatment (Table 6, Supplementary Fig. 2). Overall, the indicators contributing towards SQI followed the order C_{tot} > DTPA-Zn > pH > BD > MBC > available K with 27.79, 26.61, 23.67, 14.47, 6.76 and 0.70% contribution, respectively. In the present study, C_{tot} was the main contributor to SQI (27.79%) similar to the results of Bera et al. (2016) [24] as they reported the highest weight for C_{tot} in biochar and manure amended soils. Several other reports also suggested increase in C_{tot} concentration in biochar-amended soil [42]. The second major contributor to SQI was DTPA-Zn above pH and BD. Fageria and Santos, 2014 [43], reported that micronutrient use efficiency of Cu is higher than Zn, also the solubility of Fe and Mn is high in lowland rice soil. Our results suggest that Fe and Mn do not contribute to SQI, and establishes the prominent role of Zn towards improvement in soil quality of biochar applied lowland rice soil. Similarly, effect of biochar on pH and BD is also well documented and discussed in many of the earlier studies [29,33,44]. Our study highlights that among the soil indicators, contribution of Zn is no less than pH, BD, microbes and macro nutrients in biochar applied lowland rice soil.

Table 5

Results of multiple regression of the minimum data set (MDS) components using management goal attributes at different probability (*P*) levels.

Goal or function	R^2	Most significant MDS variables	*P*
SYI- Wet season	0.981[a]	pH, C_{tot}, K, MBC	<0.030,<0.001,<0.032
SYI-Dry season	0.966[a]	pH, BD, K, Zn, MBC	<0.0049, <0.037,<0.0416,<0.000
Yield-Wet season	0.285 (NS)	pH	<0.032
Yield-Dry season	0.154 (NS)	–	
Regression equation			
SYI-Wet season = 0.576 + 0.067 pH + $0.003C_{tot}$ + 0.001 K + 0.0002 MB C			
SYI-Dry season = 0.441 + 0.136 pH −0.369 BD + 0.001K-0.002Zn + 0.0004 MB C			
Mean yield over years- Wet season = −258.3 + 139.37 pH			
Mean yield over years- Dry season = 0			

[a] Significantly different at $P \leq 0.01$.

Table 6

Non-linear scoring results and effect of biochar application on soil quality index (SQI). The difference between the means of treatment is separated by least significant difference (LSD) at 5% level of significance.

Treatments	pH	BD	C_{tot}	MBC	Avail K	DTPA-Zn	SQI
RDF	0.83^{D}	0.47^{B}	0.99	0.05^{CD}	0.01^{C}	0.95	2.06^{D}
RDF +0.5 t ha^{-1} RHB	0.83^{CD}	0.48^{B}	1.00	0.23^{BCD}	0.01^{C}	0.96	2.16^{C}
RDF +1.0 t ha^{-1} RHB	0.84^{C}	0.52^{A}	1.00	0.27^{BC}	0.02^{C}	0.96	2.21^{BC}
RDF +2.0 t ha^{-1} RHB	0.86^{B}	0.54^{A}	1.00	0.03^{D}	0.02^{C}	0.97	2.16^{C}
RDF +4.0 t ha^{-1} RHB	0.86^{AB}	0.54^{A}	1.00	0.20^{CD}	0.03^{B}	0.97	2.24^{B}
RDF +8.0 t ha^{-1} RHB	0.87^{AB}	0.55^{A}	1.00	0.46^{AB}	0.04^{AB}	0.94	2.35^{A}
RDF +10.0 t ha^{-1} RHB	0.87^{A}	0.55^{A}	1.00	0.53^{A}	0.05^{A}	0.94	2.39^{A}
SE(d)	0.005	0.014	0.002	0.110	0.006	0.013	0.038
LSD ($P \leq 0.05$)	0.0105	0.0298	NS	0.2399	0.0125	NS	0.082

RDF, Recommended dose of fertilizers; Bulk density (Mg m^{-3}); C_{tot}, Total organic carbon (g kg^{-1}); Avail K, Available potassium (kg ha^{-1}); DTPA-Zn, DTPA extractable zinc (mg kg^{-1}).
*means with same letter are not significantly different at $P \leq 0.05$.

4. Conclusion

This is first of a kind study to identify the most sensitive physico-chemical and biological soil quality indicators in a biochar treated, lowland rice soil. Substantial response on SQI was observed on sequential application of RHB at higher doses, after four years. The following conclusions may be drawn from the present study: (i) substantial improvement in soil quality of a well-managed, lowland rice soil is possible even with application of rice husk derived biochar at lowest dose (0.5 t ha^{-1}), (ii) Contribution of soil indicators followed the order C_{tot} > DTPA-Zn > pH > BD > MBC > available K and (iii) Zn is one of the most important indicators that contribute towards soil quality of biochar applied lowland rice soil.

Author contribution statement

A.K. Nayak and S. Munda: Conceived and designed the experiment.
S. Munda, A.K. Nayak, M. Shahid: Performed the experiments.
S. Munda, R. Tripathi, A. Kumar, U. Kumar, D Bhaduri, S. Mohanty: Analyzed and interpreted the data.
D Bhaduri, D. Chatterjee, N. Jambhulkar, A.K. Nayak, R. Khanam: Contributed reagents, materials, analysis tools or data.
S. Munda, A.K. Nayak, D. Bhaduri, D. Chatterjee: Wrote the paper.

Data availability statement

Data included in article/supp. Material/referenced in article.

Additional information

Supplementary content related to this article has been publish online at [URL].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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