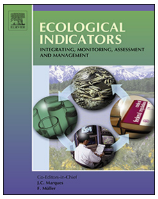
ARTICLE IN PRESS

Ecological Indicators xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Original Articles

Impact of rice-husk ash on the soil biophysical and agronomic parameters of wheat crop under a dry tropical ecosystem

Rishikesh Singh[a,*], Pratap Srivastava[b], Pardeep Singh[c], Archana Kumari Sharma[d], Hema Singh[e], Akhilesh Singh Raghubanshi[a,*]

[a] Integrative Ecology Laboratory (IEL), Institute of Environment & Sustainable Development (IESD), Banaras Hindu University, Varanasi 221005, India
[b] Department of Botany, Shyama Prasad Mukherjee Government Degree College, Phaphamau, Allahabad 211013, India
[c] Department of Environmental Studies, PGDAV College, University of Delhi, New Delhi 110065, India
[d] Center for Environmental Science and Technology, Central University of Punjab, Bathinda 151001, India
[e] Department of Botany, Institute of Science, Banaras Hindu University, Varanasi 221005, India

ARTICLE INFO

Keywords:
Agronomic practices
Biochar
Fertilizers
Organic manure
Sequestration
Soil quality

ABSTRACT

Several alternative amendments like organic manure and biochar have been proposed for revitalizing the degrading soil viability and fertility for sustainable agriculture, globally. However, detailed field-scale studies focussing on the soil and agronomic parameters of crops under these amendments are limited in dry tropical ecosystems. Therefore, we studied the impact of various soil amendments viz., rice-husk ash (RHA) and farmyard manure (FYM) along with mineral fertilizer on soil biophysical and agronomic parameters of wheat crop. We specifically explored the impact of the amendments on soil CO_2 efflux (SCE, under different growth stages) and the harvest index of wheat crop, which are considered as the key indicators of soil viability and agronomic efficiency, respectively. SCE, soil moisture, soil temperature, soil N, microbial biomass and soil pH were found significantly varying under different treatments ($P < 0.05$). SCE was found maximum under sole FYM applied and minimum under mineral fertilizer applied treatments, whereas RHA application lowered the SCE as compared to sole FYM application. Moreover, SCE showed variation with plant growth stages, and found maximum during stem elongation followed by heading stage whereas minimum during ripening stage. Soil moisture was found to have considerable regulation for the overall variation in SCE ($r^2 = 0.17$; $P = 0.04$). In contrast to the soil properties, agronomic parameters (except harvest index) were found higher under mineral fertilizer applied treatments followed by sole FYM and combined FYM + RHA treatments, whereas sole RHA applied treatment showed minimum values. However, significant variations were observed only for harvest index, aboveground dry matter, grain and straw yields ($P < 0.05$). Further, harvest index was found highest under sole and combined FYM and RHA applied treatments whereas lowest in mineral fertilizer applied treatments. Soil C/N ratio ($r^2 = 0.16$; $P = 0.04$) and panicle length ($r^2 = 0.18$; $P = 0.03$), respectively as soil and agronomic parameters, have been found to have considerable control over harvest index. The findings revealed that soil viability is higher under sole FYM and combined FYM + RHA treatments whereas mineral fertilization enhances agronomic performance. Based on the studied two indicators, we conclude that both soil and agronomic sustainability can be maintained by using a combination of organic (FYM and RHA) fertilization with reduced inputs from mineral fertilizers. However, it further needs exploration for various soil and plant eco-physiological parameters of different crops at field level for wider adaptation in the dry tropical region.

1. Introduction

Generation of surplus crop residue and husk biomass is of greater concern worldwide (Haefele et al., 2011). In Asian countries, about 30% of the total ~4000 MT yr^{-1} lignocellulosic waste is generated from 27 major cereal crops, mainly from rice-wheat cropping system (Lal, 2008). The crop residues are rich in plant available nutrients which can be utilized for improving soil properties (Westeman and Bicudo, 2005; Tang et al., 2013). However, a major portion of it is burnt in the field due to short time difference between two crops, resulting into several environmental issues (Jain et al., 2006). In contrast, husks (associated with grains) constitute about 20–33% of paddy yield (Lim et al., 2012; Shafie et al., 2012), and generally excluded from open burning. Husks are generally consist of cellulose, hemicellulose and

---

* Corresponding authors.
E-mail addresses: rishikesh.iesd@gmail.com (R. Singh), asr.iesd.bhu@gmail.com (A.S. Raghubanshi).

https://doi.org/10.1016/j.ecolind.2018.04.043
Received 30 June 2017; Received in revised form 14 April 2018; Accepted 16 April 2018
1470-160X/ © 2018 Elsevier Ltd. All rights reserved.

Please cite this article as: Singh, R., Ecological Indicators (2018), https://doi.org/10.1016/j.ecolind.2018.04.043

lignin in different proportions (McKendry, 2002; Muhammad et al., 2013); and have a considerable amount of minerals like silica (especially rice husks) and other macro- and micro-nutrients (Della et al., 2002; Koyama et al., 2016). Thus, the rice husks are utilized in various value-added products such as extractions of various minerals and raw material for bio-energy generation via thermo-chemical decomposition (Della et al., 2002; Singh et al., 2015a; Quispe et al., 2017). After bioenergy production and mineral extractions (especially silica), some solid remains are generated which have no or negligible use for the industries (Shackley et al., 2012a). The solid remains are carbonaceous in nature and rich in plant nutrients (Muhammad et al., 2013; Quispe et al., 2017). These remains (termed as crop residue ash or biochar) have been explored for managing soil fertility and productivity in several studies (Abrishamkesh et al., 2015; Gamage et al., 2016; Nguyen et al., 2016).

Biochar, the carbonaceous remains of bio-energy production, have a significant amount of plant nutrients and can be used for soil amelioration (Singh et al., 2015a). In addition, its multifaceted potential for soil carbon sequestration and waste management led to its wider application as soil ameliorant (Lehmann and Joseph, 2009; Singh et al., 2015a). It has ash content of 0.4% to 88.2% (depending upon the heating process) consisting of various macro- and micro-nutrients (Enders et al., 2012), and engrossed the wider attention because of its ability to improve the basic soil physico-chemical and biological properties (Sohi et al., 2010; Jeffery et al., 2011; Lehmann et al., 2011; Enders et al., 2012). Several studies have shown the variable effects of biochar derived from various sources on soil properties (Mukherjee and Lal, 2013; Prendergast-Miller et al., 2014; Hussain et al., 2017; Jeffery et al., 2017; Mohan et al., 2018). Recently, several studies assessed the impact of biochar on the agronomic benefits and risks for various crops (Carter et al., 2013; Liu et al., 2013; Kuppusamy et al., 2016; Hussain et al., 2017). However, the identification and evaluation of agronomic benefits as compared to the soil related observation is quite difficult (Enders et al., 2012). The studies reported both positive and negative responses of crops under biochar applied soils (Atkinson et al., 2010; Major et al., 2010; Spokas et al., 2011; Kuppusamy et al., 2016). Moreover, biochar application is being assessed in combination with organic manure and composts (Agegnehu et al., 2016a,b, 2017). However, several agronomic benefits reported at laboratory scale studies may not be observed in field scale studies due to different soil-crop-climate interactions (Jones et al., 2012; Kuppusamy et al., 2016; Agegnehu et al., 2017; Jeffery et al., 2017). Therefore, biochar application (either sole or in combination) with other amendment needs to be evaluated for different ecosystems before wider application.

Dry tropical ecosystems are characterised by variable precipitation and temperature regimes (Allen et al., 2017), and are under the intensive agriculture (Srivastava et al., 2016a). These ecosystems are facing the major challenges such as the loss of soil C (Houghton, 1994) and declining soil fertility, and are under intensive application of mineral fertilization for achieving food security (Srivastava et al., 2016a; Singh et al., 2016). Organic amendments have been extensively proposed by several studies for restoring the soil organic C (SOC) pool in these ecosystems (Srivastava et al., 2015, 2016a,c, 2017a). It alone or in combination with mineral fertilizers have significant impact over SOC pool (Srivastava et al., 2017a,b). However, soil CO_2 emission from the organically amended system is one of the major concerns in the present climate change scenario (Yang et al., 2015; Srivastava et al., 2017a). Thus, organic amendment with mineral fertilization is proposed for the reduced soil CO_2 emission (Wilson and Al-kaisi, 2008; Srivastava et al., 2016c, 2017a). Alternatively, several studies showed the beneficial impact of biochar on soil properties (Sohi et al., 2010) and plant growth in combination with mineral fertilizers (Chan et al., 2007; Asai et al., 2009; Saarnio et al., 2013). Recently, Mohan et al. (2018) performed a pot experiment to observe the impact of rice husk and corn stover biochar over the soil CO_2 efflux (SCE) and plant biomass. They reported the decrease in SCE whereas an increase in plant biomass with biochar application as compared to the raw biomass application. Such studies showed the candidature of rice husk biochar for the improvement of various soil and agronomic parameters. However, most of the studies performed on rice-husk biochar application to soil are limited to incubation or pot levels. Thus, limited understanding exists on how biochar and several other agro-management practices govern the soil and the agronomic properties in the dry tropical agro-ecosystems. These ecosystems showed the strong adaptive mechanisms; and a proper organic management may lead to the mitigation of negative effects of present climate change (Srivastava et al., 2015). Therefore, it is important to evaluate the effect of biochar as sole as well as with organic amendment and mineral fertilizer based agricultural management practices on soil bio-physical and agronomic behaviour of cereal crops in these ecosystems.

Detailed field- or plot-scale studies considering integrated biochar and organic as well as mineral fertilizer application could be of greater importance for soil amelioration and carbon sequestration (Singh et al., 2015b). In the present plot-level study, we observed the effect of rice-husk ash (RHA, biochar) in integration with farm-yard manure (FYM) and mineral fertilizers on soil (soil respiration and biophysical properties) and agronomic parameters of wheat crop. We considered the SCE and harvest index as the indicators of soil and agronomic parameters, respectively, for evaluating the impact of RHA as sole and in combined form for agriculture sustainability in dry tropics. Studies reported the strong effect of crop phenology on SCE (Shi et al., 2006; Tong et al., 2017), therefore, we further assessed the variation in SCE along with crop growth stages of wheat crop. We hypothesized that application of RHA as sole or in combination to FYM or mineral fertilizers would help to negate the impact of: (1) organic amendment on SCE as well as soil biophysical properties, and (2) mineral fertilizer application for the agronomic parameters in the dry tropical environment. The objectives of the study were to observe: (1) the variation in SCE (overall and at different growth stages) and other basic soil biophysical properties; and (2) the variation in various agronomic parameters and harvest index of wheat crop under seven treatment combinations of RHA, FYM and mineral fertilizers.

2. Material and methods

2.1. Rice-husk ash and farm-yard manure

Rice-husk ash (RHA) was taken from a local power plant which was a by-product after energy production, whereas farm-yard manure (FYM) was procured from Banaras Hindu University farm. These materials were characterized by Fourier-Transformed Infra-Red (FTIR) spectroscopy, Scanning Electron Microscopy (SEM), Energy Dispersive X-ray spectroscopy (EDX) and elemental analyses for observing its structural and functional composition. The pH of the RHA and FYM was determined using 1:10 ratio (RHA:water) whereas 1:2.5 ratio (FYM:water) using a pH electrode. Organic carbon (C) and nitrogen (N) contents of the FYM were determined by using dichromate acid digestion method (Nelson and Sommers, 1982) and Kjeldahl method (Jackson, 1973), respectively.

2.2. Study site and treatment details

The study was performed in the experimental plot of Banaras Hindu University, Varanasi, Uttar Pradesh, India (25°16′10.2″N and 82°59′20.6″E). The study site is a part of middle Indo-Gangetic plains, consisting of rich alluvial soils. The region is characterized by a typical dry tropical monsoonal climate with three distinct seasons, viz., summer (April to mid-June), rainy (mid-June to September) and winter (November to February). October and March constitute the transitional months between the rainy and winter seasons and between the winter and summer seasons, respectively (Srivastava et al., 2016b; Singh et al., 2017a). Average annual rainfall is ∼1100 mm, of which 80–85% occurs during the rainy season. Mean monthly minimum and maximum temperatures varied from 8.7 °C during winter and 45.0 °C during summer season, respectively (Afreen et al., 2017). During the study period (January to May 2016), the temperature ranged from 19 to 42 °C, revealing a hot year, however, occasional overcast conditions were observed. The soil is inceptisol, pale brown in colour with silty-loam texture (Afreen et al., 2017).

Total seven treatments viz., control (RC), sole mineral fertilizer (RI), sole FYM (RO), sole RHA (RB), RHA + mineral fertilizer (RIB), RHA + FYM (ROB), and RHA + FYM + mineral fertilizer (ROIB), showing a combination of RHA, FYM and mineral fertilizers were taken in a plot size of 2 × 1 m for each (*see*: Table S1 for more treatment details). The experiment was conducted in triplicate for all the treatment combinations with total 21 (7 × 3) plots distributed randomly. The RHA and FYM were applied at the rate of 5 t ha^{-1} for the crop grown/cycle. It signifies a moderate dose of application under tropical soils (Srivastava et al., 2016c). Mineral fertilizers were used as per the local application rate by farmers of the region as 100:50:50 ratio for nitrogen: phosphorus: potassium (NPK) using urea, single superphosphate and muriate of potash, respectively.

2.3. Soil mineralogical and biophysical properties

Soil mineralogical/elemental composition was identified by EDX spectroscopy. Soil CO_2 efflux was measured at different intervals throughout the wheat crop cycle (i.e. at different growth stages like one shoot, tillering, stem elongation, booting, heading, ripening onset, ripening and after harvest stages) by using an infra-red gas analyser (IRGA)-based portable photosynthetic system LICOR-6400XT (*see*: Srivastava et al., 2016b; Singh et al., 2017a). Soil temperature was measured using the attachment with LICOR-6400XT. Soil moisture was determined by gravimetric analysis as given in Singh et al. (2017a). SOC was determined by dichromate acid digestion method (Nelson and Sommers, 1982). Total Kjeldahl N (TKN) was determined by Kjeldahl method (Jackson, 1973). Soil microbial biomass (C and N) was measured by following chloroform fumigation-extraction method (Brookes et al., 1985; Vance et al., 1987). Soil pH was measured by taking soil and double distilled water in 1:2.5 ratio (Anderson and Ingram, 1993).

2.4. Agronomic parameters

Agronomic parameters such as tiller number, effective tiller number, tiller and panicle length were measured for the matured crop whereas grain and straw yields were measured just after the harvest. Harvest index (%) was calculated based on the grain and aboveground dry matter ratio by following Unkovich et al. (2010).

2.5. Statistical analysis

One-way Analysis of Variance (ANOVA) and Tukey's post hoc analyses were performed using SPSS package (ver. 16) to observe the variation in different soil biophysical and agronomic parameters of wheat crop under different treatment combinations. Correlation analysis was also performed using SPSS package to identify the interrelationship among different soil and agronomic parameters. Moreover, stepwise (bidirectional) regression analysis was performed to identify the key determinants of two major indicators (viz., soil CO_2 efflux and harvest index) of soil health and agronomic sustainability. Some parameters (viz., straw yield, grain yield and aboveground dry matter content) were excluded during the stepwise regression analysis performed for the harvest index as harvest index is directly derived from these parameters.

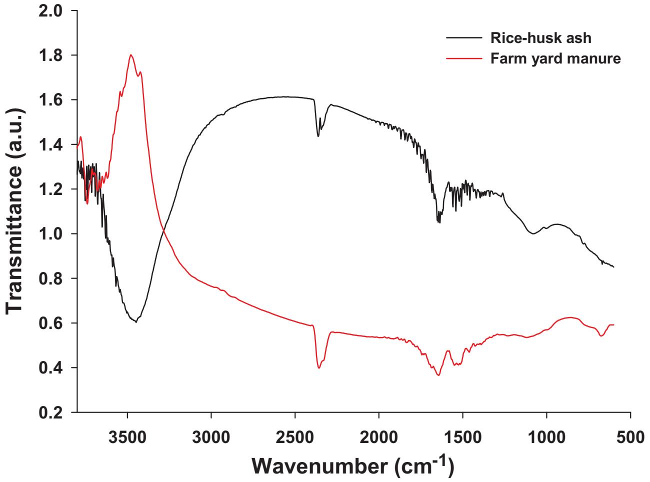


Fig. 1. Fourier-Transformed Infra-Red (FTIR) spectra of rice-husk ash and farmyard manure used for soil amelioration.

3. Results

3.1. Characterization of soil amendments

The ultimate analysis of RHA and FYM showed the carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) contents of 42.09%, 4.57%, 0.61% and 0.12%, respectively for RHA, and 53.37%, 7.60%, 2.87% and 0.30%, respectively for FYM. Moreover, organic C and total Kjeldhal N (TKN) contents of FYM was found as 28.59 ± 0.14% and 2.81 ± 0.09%, respectively. The FTIR spectra of RHA and FYM (Fig. 1) showed the presence of absorption bands at 3400–3600 cm^{-1}, 2900–2950 cm^{-1}, 2360–2380 cm^{-1}, 1300–2000 cm^{-1}, 1100 cm^{-1}, 980 cm^{-1}, 680 $cm^{-1}$and 661 cm^{-1}, revealing the presence of different functional groups (elaborated in discussion section). As observed in the SEM images (Fig. 2), the RHA showed some crystalline structures dominated by various macro- and micro-pores on its surface whereas FYM showed amorphous structure with comparatively less micro-pores. The EDX spectral analysis revealed the presence of different macro- and micro-nutrients including sodium (Na), K, calcium (Ca) and copper (Cu) on the surface of RHA. However, FYM showed several additional elements (Al, P, S, Cl and Fe) on its surface (Table 1). The pH was found moderately alkaline (10.54 ± 0.03) for RHA whereas neutral (7.07 ± 0.05) for FYM.

3.2. Variation in soil CO_2 efflux with treatments and plant growth stages

Soil CO_2 efflux was found to vary significantly ($F_{6,14} = 2.40$; $P < 0.05$) under the seven treatment combinations (Table S2). Tukey's post hoc results further grouped the seven treatments into three distinct groups (Fig. 3). Average SCE was found maximum (201.50 ± 4.35 μg CO_2-C m^{-2} s^{-1}) in FYM applied (RO) treatment whereas minimum (147.94 ± 14.31 μg CO_2-C m^{-2} s^{-1}) in mineral fertilizer applied (RI) treatment. RHA applied treatment showed moderate SCE lying in between RO and RI treatments (Fig. 3). Similarly, SCE was found varying with the plant growth stages (Fig. 4). It was found maximum during the stem elongation stage, followed by heading and tillering stages whereas minimum during ripening stage. RO treatment showed an overall highest SCE during all the growth stages whereas mineral fertilizer applied (RI) treatment showed minimum SCE during one shoot, booting, heading, ripening and after harvest growth stages. Control (RC) showed minimum SCE during tillering and stem elongation stages whereas rice-husk ash applied (RB) treatment during ripening onset stage (Fig. 4).

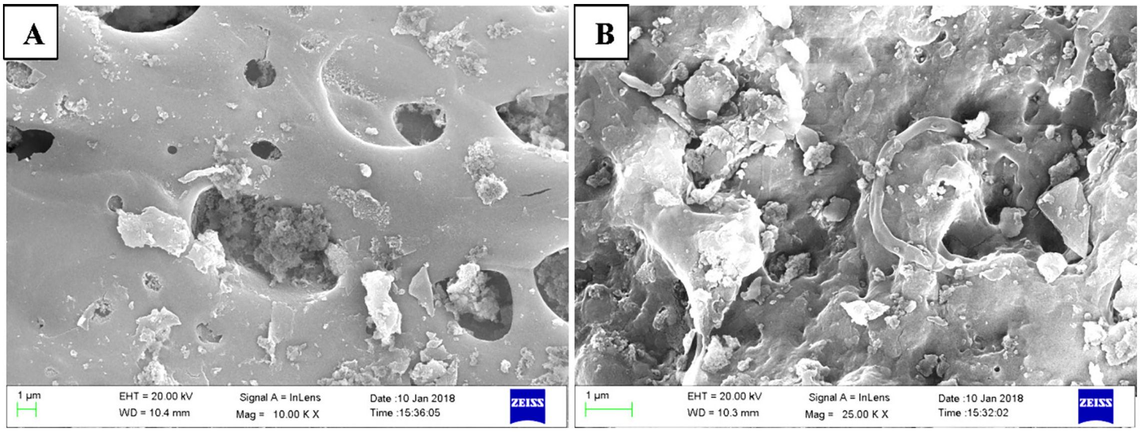


Fig. 2. Scanning Electron Microscopic (SEM) images of rice-husk ash (A) and farm-yard manure (B) used for soil amelioration.

3.3. Variation in soil mineral composition and biophysical properties

Energy Dispersive X-ray spectroscopic (EDX) analysis showed the presence of various macro- (C, O, Mg, Al, Si, K) and micro-nutrients (Fe and Cu) in all the seven treatment combinations (Table 1). It was observed that the C, O, Si, Al, K and Fe majorly contributed to the overall composition of soil system showing the alumino-silicate nature of soil system. Moreover, presence of Na was observed in FYM (RO) and RHA (RB and RIB) applied treatments. Presence of Ca was observed in control and combined FYM + RHA + mineral fertilizer applied (ROIB) treatment (Table 1).

Analysis of variance (ANOVA) showed significant variation in soil moisture ($F_{6,14} = 4.22$; $P < 0.01$), soil temperature ($F_{6,14} = 3.72$; $P < 0.05$), TKN ($F_{6,14} = 4.40$; $P < 0.01$), soil C/N ratio ($F_{6,14} = 6.12$; $P < 0.001$), microbial biomass C (MBC, $F_{6,14} = 23.44$; $P < 0.001$), microbial biomass N (MBN, $F_{6,14} = 10.62$; $P < 0.001$), microbial C/N ratio ($F_{6,14} = 7.90$; $P < 0.001$) and soil pH ($F_{6,14} = 3.22$; $P < 0.05$), except soil organic C (SOC, $P > 0.05$) (Table S2). Tukey's post hoc analysis also showed the variation among treatments for various studied soil biophysical properties (Table 2). Sole RHA applied treatment showed minimum soil moisture, TKN, MBC and MBC/N ratio whereas it showed maximum values of these properties in combination with FYM, except soil moisture which was found maximum under sole FYM treatment (Table 2). Soil C/N ratio was found maximum in RIB treatment whereas minimum in ROB treatment. MBN was found maximum in ROIB treatment whereas minimum in control (RC). Soil temperature and pH were found maximum in sole RHA applied (RB) treatment whereas minimum in RIB and RI treatments, respectively (Table 2).

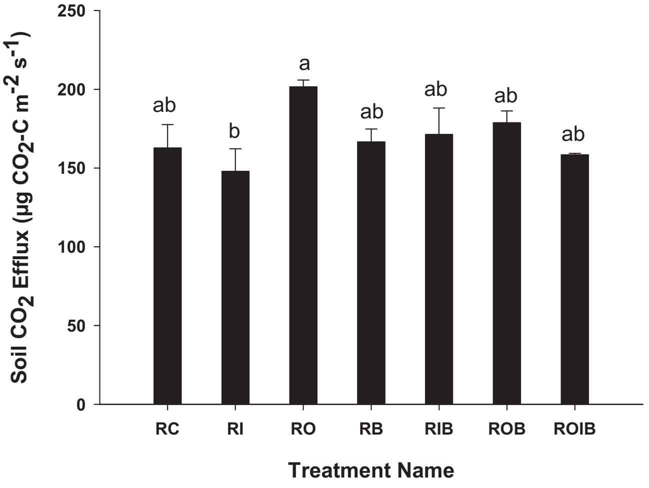


Fig. 3. Soil CO_2 efflux (average) observed under different treatment combinations of rice-husk ash, farm-yard manure and mineral fertilizer applied soil systems. Values are given as Mean ± 1SE and n = 24. Values with different letters indicates significance at $P < 0.05$. RC = Control, RI = Mineral fertilizer, RO = Farm-yard manure, RB = Rice-husk ash, RIB = Mineral fertilizer + Rice-husk ash, ROB = Farm-yard manure + Rice-husk ash, ROIB = Farm-yard manure + Mineral fertilizer + Rice-husk ash applied treatment combinations.

Table 1

Electron Dispersive X-ray (EDX) spectroscopic analysis of rice-husk ash, farm-yard manure and soils having a combination of rice-husk ash, farm-yard manure and mineral fertilizer applied treatments. RC = Control, RI = Mineral fertilizer, RO = Farm-yard manure, RB = Rice-husk ash, RIB = Mineral fertilizer + Rice-husk ash, ROB = Farm-yard manure + Rice-husk ash, ROIB = Farm-yard manure + Mineral fertilizer + Rice-husk ash applied treatment combinations.

Treatment name	Rice-husk ash	Farm-yard manure*	RC	RI	RO	RB	RIB	ROB	ROIB
Elements	%Weight								
Carbon	21.12	48.12	7.78	8.80	8.19	7.28	8.14	7.12	40.03
Oxygen	50.23	36.54	50.21	50.03	51.01	48.76	53.53	56.30	45.05
Sodium	1.14	nd	nd	nd	0.25	0.21	0.43	nd	nd
Magnesium	0.31	2.70	4.80	0.18	0.52	0.64	0.64	nd	0.42
Aluminium	nd	0.87	8.99	1.25	13.72	14.24	13.45	0.58	2.26
Silicon	26.31	7.42	13.04	38.26	17.78	18.66	17.09	35.36	9.98
Potassium	0.26	0.41	0.93	0.30	6.52	7.42	5.44	0.22	0.73
Calcium	0.31	1.67	0.28	nd	nd	nd	nd	nd	0.11
Iron	nd	0.62	13.38	0.89	1.58	1.77	0.91	0.26	1.15
Copper	0.30	0.14	0.28	0.30	0.22	0.21	0.18	0.16	0.15
Titanium	nd	nd	0.14	nd	0.21	0.82	0.18	nd	0.11

nd = not detected.

* Also showed peaks for Phosphorus (1.09%), Sulphur (0.36%) and Chlorine (0.07%) which were not observed in other EDX spectra.

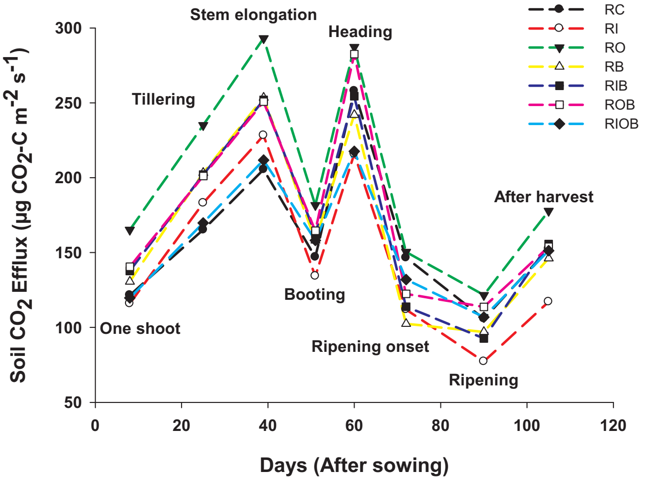


Fig. 4. Soil CO_2 efflux observed at different wheat crop growth stages under different treatment combinations of rice-husk ash, farm-yard manure and mineral fertilizer applied soil systems. Values are given as Mean ± 1SE and n = 3. RC = Control, RI = Mineral fertilizer, RO = Farm-yard manure, RB = Rice-husk ash, RIB = Mineral fertilizer + Rice-husk ash, ROB = Farm-yard manure + Rice-husk ash, ROIB = Farm-yard manure + Mineral fertilizer + Rice-husk ash applied treatment combinations.

3.4. Variation in agronomic parameters of wheat crop

Analysis of variance (ANOVA) showed significant variation in grain weight ($F_{6,14} = 9.27$; $P < 0.001$), straw weight ($F_{6,14} = 7.24$; $P < 0.001$), aboveground dry matter ($F_{6,14} = 10.38$; $P < 0.001$) and harvest index ($F_{6,14} = 2.58$; $P < 0.05$) whereas tiller number, effective tiller number, panicle and tiller lengths did not show significant variation under different treatment combinations (Table S2). Tukey's post hoc analysis also showed the variation among treatments for various studied agronomic parameters (Table 3). Aboveground dry matter, grain and straw yields were found maximum in RI treatment whereas minimum in RB and control treatments (Table 3). Harvest index was found maximum (0.38 ± 0.01) under ROB treatment followed by sole RHA (RB) applied treatment (0.36 ± 0.01) whereas minimum (0.32 ± 0.01) under the ROIB treatment (Fig. 5). Tukey's post hoc results further grouped the seven treatments into three distinct groups based on harvest index (Fig. 5).

4. Discussion

4.1. Candidature of RHA and FYM as soil ameliorant for improving soil and plant properties

Based on EDX analysis (Table 1), it was found that RHA is majorly composed of silicate minerals having carbon (C) and oxygen (O) with a small amount of magnesium (Mg), potassium (K), calcium (Ca) and copper (Cu). FYM was found rich in carbonaceous components with a moderate amount of silica and minimal amounts of Mg, aluminium (Al), phosphorus (P), sulphur (S), chloride (Cl), K, Ca, iron (Fe) and Cu. The presence of these minerals as well as significant amount of C, N and S contents showed their credential as soil ameliorants. Based on SEM-EDX analysis, RHA was found to have several macro- and micro-pores with the presence of various minerals on its surface which might help in providing nutrients to plants as well as the pores will help in improving the soil physico-chemical properties (Singh et al., 2015a). In addition, it would also help in the retention of adsorbed nutrients on its surface (Taghizadeh-Toosi et al., 2011; Spokas et al., 2011). The pH of RHA was moderately alkaline which suggest its suitability for the application in neutral to acidic soils. However, the studied soil had a slightly basic pH, thus, it may not have significant changes in soil pH. The higher pH of RHA is possibly due to the presence of carbonates formed during the heating process. In addition, additional lime treatment was applied for washing the rice-husk ash after silica extraction which might be resulted into the increase in its pH. It is also reflected by the presence of carbonate related peaks (1100 and 980 cm^{-1}) in the FTIR spectra of RHA. The FTIR spectra of RHA and FYM showed the presence of broad absorption bands at 3400–3600 cm^{-1} which corresponds to the presence of hydroxyl groups of various organic and inorganic compounds. Further, the small absorption bands at 2950–2900 cm^{-1} corresponds to the C–H bond stretching and CO_2 from the aliphatic compounds, and broad absorption bands at 2380–2360 cm^{-1} is assigned to C═C and C─N bonds of aromatic structures, respectively. Moreover, several unsymmetrical absorption bands were observed for RHA at region 1300–2000 cm^{-1}, whereas broad and symmetrical bands for FYM in the range of 1400–1750 cm^{-1} revealed the presence of different C═O, C─O, C═C and H─C─H bending. The absorption bands at wavelength of 1750 cm^{-1}, 1685 cm^{-1}, 1540 cm^{-1} and 1460 cm^{-1}, were formed due to different aliphatic and aromatic groups such as benzene rings, ketones, carboxylic acid, esters and anhydrides. Smooth or distinct peaks in the FYM as compared to RHA may reflect more amorphous and aliphatic nature of FYM as compared to RHA (Fig. 1). Further broadening of band at 1100 cm^{-1} and small absorption band at 980 cm^{-1} (corresponding to ─C─O bond and carbonates, respectively) was observed in RHA which showed the high concentration of calcite or carbonate minerals in RHA as compared to FYM (Mohan et al., 2018). Moreover, broad peak at 661 cm^{-1} in FYM and narrow peak at

Table 2
Soil properties observed in different rice-husk ash, farm-yard manure and mineral fertiliser applied treatment combinations. Values are as Mean ± 1SE and n = 9. Values with different letters indicate significant difference at $P < 0.05$. RC = Control, RI = Mineral fertilizer, RO = Farm-yard manure, RB = Rice-husk ash, RIB = Mineral fertilizer + Rice-husk ash, ROB = Farm-yard manure + Rice-husk ash, ROIB = Farm-yard manure + Mineral fertilizer + Rice-husk ash applied treatment combinations.

Soil properties	Unit	Treatment name						
		RC	RI	RO	RB	RIB	ROB	ROIB
Soil Moisture	%	3.30 ± 0.18^{ab}	2.08 ± 0.44^{b}	3.79 ± 0.43^{a}	2.16 ± 0.24^{b}	3.20 ± 0.08^{ab}	2.92 ± 0.36^{ab}	2.80 ± 0.18^{ab}
Soil temperature	°C	28.76 ± 0.37^{ab}	29.54 ± 0.26^{ab}	28.45 ± 0.27^{ab}	29.97 ± 0.19^{a}	28.35 ± 0.09^{b}	29.43 ± 0.38^{ab}	29.48 ± 0.50^{ab}
Soil organic C	%	1.20 ± 0.01^{a}	1.13 ± 0.02^{a}	1.21 ± 0.07^{a}	1.18 ± 0.01^{a}	1.27 ± 0.11^{a}	1.14 ± 0.04^{a}	1.34 ± 0.11^{a}
Total Kjeldahl N	%	0.14 ± 0.01^{ab}	0.16 ± 0.02^{ab}	0.16 ± 0.01^{ab}	0.15 ± 0.01^{ab}	0.11 ± 0.01^{b}	0.18 ± 0.02^{a}	0.12 ± 0.01^{b}
C/N ratio		8.78 ± 0.61^{abc}	7.31 ± 0.80^{c}	7.75 ± 1.08^{bc}	8.07 ± 0.41^{abc}	12.04 ± 1.21^{a}	6.38 ± 0.58^{c}	11.64 ± 1.16^{ab}
Microbial biomass C	µg C g^{-1} soil	245.72 ± 11.61^{d}	322.25 ± 16.64^{cd}	499.14 ± 57.72^{b}	192.97 ± 17.47^{d}	255.11 ± 1.72^{d}	671.94 ± 64.63^{a}	457.95 ± 25.21^{bc}
Microbial biomass N	µg N g^{-1} soil	17.35 ± 0.50^{c}	20.99 ± 2.02^{c}	33.97 ± 2.53^{ab}	25.63 ± 2.05^{bc}	33.25 ± 3.51^{ab}	26.32 ± 2.75^{abc}	36.91 ± 0.80^{a}
Microbial C/N ratio		14.21 ± 4.99^{b}	15.41 ± 5.20^{b}	14.72 ± 3.12^{b}	7.54 ± 5.76^{b}	7.68 ± 0.47^{b}	25.56 ± 4.30^{a}	12.41 ± 5.75^{b}
Soil pH		7.85 ± 0.10^{ab}	7.70 ± 0.07^{b}	7.88 ± 0.02^{ab}	8.14 ± 0.08^{a}	7.91 ± 0.10^{ab}	8.04 ± 0.04^{ab}	7.84 ± 0.11^{ab}

Table 3
Agronomic parameters of wheat crop observed in different rice-husk ash, farm-yard manure and mineral fertiliser applied treatment combinations. Values are as Mean ± 1SE and n = 9. Values with different letters indicate significant difference at $P < 0.05$. RC = Control, RI = Mineral fertilizer, RO = Farm-yard manure, RB = Rice-husk ash, RIB = Mineral fertilizer + Rice-husk ash, ROB = Farm-yard manure + Rice-husk ash, ROIB = Farm-yard manure + Mineral fertilizer + Rice-husk ash applied treatment combinations.

Agronomic Parameter	Unit	Treatment name						
		RC	RI	RO	RB	RIB	ROB	ROIB
Tiller number	Per plant	5.28 ± 0.29^{a}	5.67 ± 0.57^{a}	5.40 ± 0.12^{a}	5.07 ± 0.41^{a}	5.47 ± 0.13^{a}	5.53 ± 0.57^{a}	5.67 ± 0.35^{a}
Effective tiller number	Per plant	4.48 ± 0.06^{a}	4.33 ± 0.35^{a}	4.60 ± 0.42^{a}	4.13 ± 0.35^{a}	4.40 ± 0.31^{a}	5.03 ± 0.32^{a}	4.20 ± 0.42^{a}
Panicle length	cm	7.23 ± 0.49^{a}	8.03 ± 0.43^{a}	7.21 ± 0.17^{a}	7.17 ± 0.04^{a}	7.85 ± 0.15^{a}	6.73 ± 0.31^{a}	7.97 ± 0.53^{a}
Tiller length	cm	62.23 ± 3.13^{a}	67.00 ± 2.67^{a}	64.73 ± 2.60^{a}	60.60 ± 3.10^{a}	66.60 ± 3.03^{a}	58.53 ± 3.74^{a}	64.53 ± 2.37^{a}
Grain weight	$g\ m^{-2}$	156.83 ± 4.10^{bc}	193.67 ± 7.97^{a}	163.50 ± 4.32^{bc}	154.50 ± 1.45^{c}	164.67 ± 4.13^{bc}	176.00 ± 3.78^{ab}	169.50 ± 1.26^{bc}
Straw weight	$g\ m^{-2}$	294.40 ± 0.95^{bc}	398.09 ± 20.12^{a}	296.34 ± 35.03^{bc}	270.63 ± 12.12^{c}	337.25 ± 6.08^{abc}	289.79 ± 7.04^{bc}	358.90 ± 12.22^{ab}
Aboveground dry matter	$g\ m^{-2}$	451.24 ± 4.43^{bc}	591.75 ± 24.74^{a}	459.84 ± 35.39^{bc}	425.13 ± 10.78^{c}	501.92 ± 5.08^{bc}	465.79 ± 3.41^{bc}	528.40 ± 11.05^{ab}

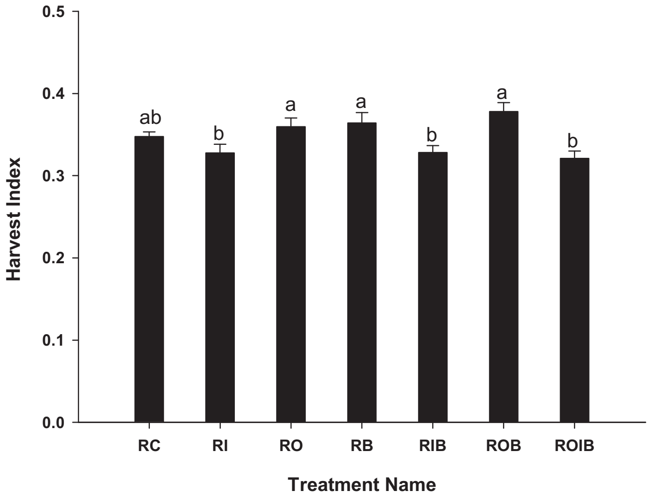


Fig. 5. Harvest index of wheat crop under different combinations of rice-husk ash, farm-yard manure and mineral fertilizer applied treatments. Values are Mean ± 1SE and n = 3. Values with different letters indicates significance at $P < 0.05$. RC = Control, RI = Mineral fertilizer, RO = Farm-yard manure, RB = Rice-husk ash, RIB = Mineral fertilizer + Rice-husk ash, ROB = Farm-yard manure + Rice-husk ash, ROIB = Farm-yard manure + Mineral fertilizer + Rice-husk ash applied treatment combinations.

680 cm^{-1} in RHA, are assigned to the Si-O-Si stretching and the presence of alkyl-halides in the FYM (Fig. 1). Based on the FTIR spectra, it can be inferred that the RHA is composed of more aromatic structures whereas FYM is dominated by aliphatic components. It can also be inferred from the SEM structures and elemental composition (EDX results) of RHA and FYM. Moreover, based on the characteristics observed for the RHA, it revealed its behaviour as similar to the rice-husk biochar, therefore, it is further discussed in relation to the biochar applied under different systems in previous studies. Both RHA and FYM showed the presence of several functional groups on its surface which further help in improving the soil properties such as nutrient retention, soil water holding capacity, pH, cation exchange capacity and microbial community structure and function. Thus, based on the different characteristics reported here, the RHA and FYM showed its candidature as a suitable soil ameliorant.

4.2. Variation in soil CO_2 efflux (overall and with plant growth stages)

Soil CO_2 efflux is one of the indicators for soil biological activities, and is of vital concern in the present climate change scenario. Researches are being carried out to reduce the SCE from agro-ecosystems on one hand whereas improving the soil viability on the other hand. In the present study, SCE was found maximum under FYM applied treatment. Several studies reported higher SCE under treatments receiving FYM (Agegnehu et al., 2016a; Srivastava et al., 2016b,c) which limit the sole FYM application as soil nourishing agent. On the contrary, the application of mineral fertilizer led to the short term increase in plant growth and yield, however, decrease in soil quality in the long term (Foley et al., 2005). Therefore, application of biochar or crop residue ash is recently considered as one of the alternative for reducing the greenhouse gas emissions from soil and improving the soil basic properties (Sohi et al., 2010; Jeffery et al., 2011). However, several studies reported both positive and negative responses of greenhouse gas emissions from biochar applied soils (Spokas and Reicosky, 2009; Taghizadeh-Toosi et al., 2011; Aguilar-Chávez et al., 2012; Zhang et al., 2012; Angst et al., 2013). We observed that the application of RHA as sole and in combination with FYM, mineral fertilizer and combined FYM + mineral fertilizer applied treatment showed 17%, 15%, 11% and 21%, respectively, less SCE than sole FYM applied treatment. Moreover, RHA application showed *at par* SCE with control and comparatively higher SCE than mineral fertilizer applied treatment.

In general, SCE is a combined efflux contributed by roots and microorganisms residing at different soil depths. It may be regulated by a variety of factors such as soil properties and plant growth and their interactions (Litton et al., 2003; Epron et al., 2004). Thus, plant phenology may have an important role in regulating SCE through its influence on rhizospheric activities (Shi et al., 2006). We observed variation in SCE with different plant growth stages. Previous studies also showed variation in SCE with crop phenology (Shi et al., 2006; Tong et al., 2017). As suggested previously, phenological changes in crop affect the SCE by modulating soil bio-physical processes. The SCE was found increasing initially during tillering and stem elongation stages possibly due to improved soil water conditions and plant root development. Moreover, a drop in SCE during booting stage revealed the less rhizospheric activity and higher plant development (i.e. greater nutrient allocation to plant) during this stage whereas a sudden increase during the heading/flowering stage revealed the increased microbial activity. In addition, a drop in soil moisture content during booting stage (Fig. S1A) may possibly lead to decrease in microbial activities. Whereas later increases in SCE may possibly be due to higher root respiration as compared to the heterotrophic respiration as well as indirectly by crop phenological changes such as increase in leaf area and photosynthetic activities (Shi et al., 2006).

Soil moisture and temperature are reported as the major regulatory variables of SCE as it is observed that an increase in soil water content with a suitable soil temperature conditions improved soil biological activities resulting into higher SCE (Srivastava et al., 2015, 2016b,c, 2017a). We also observed the variation in soil moisture and temperature with plant growth stages (Fig. S1). SCE coincided positively with the variation in soil moisture and soil temperature up to heading stage (Fig. 4 and Fig. S2). Irrigation is applied at different intervals of the plant growth stages which may lead to the improved root development and activities resulting into higher SCE at different growth stages. However, there was a sudden increase in soil temperature after booting stage which may led to the decrease in soil moisture (as no irrigation was applied). In addition, onset of ripening revealed the reduced plant activity which coincided with reduced soil moisture and increase in soil temperature, thus, a reduction in SCE was observed. The role of soil moisture in SCE at different growth stages can also be inferred from the positive and significant relationship ($r^2 = 0.39$; Fig. S2A) observed between SCE and soil moisture. Moreover, moderate soil temperature (20–30 °C) also showed positive ($r^2 = 0.49$; Fig. S2B) regulation over SCE at early growth stages (till maturity) whereas mature crop phenology and increased soil temperature (30–40 °C) did not show significant relationship (Fig. S2B). Such variations led to enhanced microbial activities and soil C mineralization resulting into higher SCE (Sainju et al., 2010; Tong et al., 2017). Previous studies also suggested that the soil temperature had its impact over SCE when soil moisture is not limited (Curiel-Yuste et al., 2004; Jassal et al., 2008; Tong et al., 2017). However, dry tropical ecosystems are nutrient and moisture limited (Singh et al., 1989; Singh et al., 2017b), therefore, soil moisture showed pronounced impact over SCE as compared to the soil temperature throughout the crop cycle possibly by mediating soil nutrient dynamics (Srivastava et al., 2015; 2016b, 2017a,b). Moreover, crop phenology also led to nullifying the impact of soil temperature in later stages with increase in leaf area, photosynthetic rate and root activities (Shi et al., 2006; Tong et al., 2017).

Further, SCE was found higher under FYM applied treatment in all the growth stages which suggest suitable micro-environment under FYM treatment. Moreover, RHA application initially showed higher SCE, however, a reduction in the overall SCE as well as under different growth stages of wheat crop was observed later under RHA applied treatment as compared to the FYM applied treatment. Smith et al. (2010) also observed higher SCE initially under biochar applied systems which get reduced after one week of application. Higher SCE observed from soils receiving organic amendments (FYM and RHA) as compared to the mineral fertilizer applied treatment is in accordance with the results of some previous studies (Wilson and Al-kaisi, 2008; Smith et al., 2010; Zhang et al., 2012; Lentz et al., 2014; Shen et al., 2014; Agegnehu et al., 2016a; Srivastava et al., 2016c). Usually higher C mineralization is observed in the biochar applied soils which may further get enhanced or diminished depending upon the availability of labile C sources (Jones et al., 2012; Bruun et al., 2014; Junna et al., 2014; Mohan et al., 2018). Thus, initial increase in SCE under RHA applied systems revealed the higher biological activities initially due to presence of labile C source which may get stabilized after a few days of application (Hussain et al., 2017). It can further be attributed to the improved microbial growth and nutrient turnover under these treatments which may get stabilized and led to soil C sequestration in different soil aggregate fractions in the medium to long terms (Mikha and Rice, 2004; Srivastava et al., 2016b).

Further, variation in SCE under organically amended systems was possibly attributed to the moisture availability in these treatments due to presence of pores on their surfaces (as observed in SEM-EDX analysis). In addition, higher organic C content of these amendments may also lead to improved soil physical properties. Moreover, higher pH under biochar applied treatments may favour the bacterial communities (Srivastava et al., 2016b). It led to the improved nutrient availability as well as habitats to the microbes catalysing higher microbial activities (Lehmann et al., 2011; Srivastava et al., 2016b). It can be inferred from the higher microbial biomass under FYM applied treatments revealing a labile C source for increased microbial activities. A positive relationship was observed for soil moisture and average SCE (Table S3) and stepwise regression analysis also revealed a considerable effect of soil moisture on overall SCE ($r^2 = 0.17$; $P < 0.05$; Table 4). Moreover, the presence of various nutrients (as in Table 1) also led to catalysing microbial activities in RHA and FYM applied treatments. These observations revealed that the organic treatments (FYM and RHA) have consistent effect over soil microbial activities whereas mineral fertilizers have occasional or temporary effect over microbial communities.

Table 4
Stepwise regression analysis data table showing major determinants of average soil CO_2 efflux and harvest index for wheat crop under different treatment combinations.

Parameter	Number of samples (n)	Primary determinant	Adjusted r^2	P
Soil CO_2 efflux (overall parameters)	21	Soil moisture	0.17	0.04
Harvest index (with soil properties)	21	Soil C/N ratio	0.16	0.04
Harvest index (with agronomic parameters)	21	Panicle length	0.18	0.03

4.3. Variation in soil bio-physical properties

Soil degradation is one of the most imperative constraints limiting agricultural productivity (Lal, 2015; Pender, 2009). Incorporation of mineral fertilizers led to improved crop yield; however, its excessive application has also been reported to deteriorate soil quality by rapid mineralization of native organic matter and SOC stocks (Palm et al., 2001; Foley et al., 2005; Liu et al., 2010). Sole organic amendment or in combination with mineral fertilizers in agro-ecosystems showed positive impact over the SOC dynamics. Thus, a regular application of organic amendments is suggested to improve the soil vitality and nutrient pools (Marinari et al., 2000; Srivastava et al., 2016c, 2017a,b). On the other hand, biochar application has been reported to alter the soil physical properties especially soil aeration and water content in certain soils (Jeffery et al., 2011; Haefele et al., 2011). In this study, FYM and RHA application (sole as well as combined) led to increase in soil moisture, soil pH and microbial biomass (except sole RHA) as compared to mineral fertilizer application. Liu et al. (2012) also observed the improvement in soil nutrient levels and water content of a sandy soil under compost and biochar + compost applied field conditions. Moreover, RHA and FYM also led to improved soil N content which was *at par* with mineral fertilizer soils. However, variation in SOC was not found significant in the present study. It showed that biochar application may lead to long term increase in SOC content which might not be reflected in short term observation. In general, RHA application along with mineral fertilizer led to increase of 6–12% in SOC whereas 15–23% decreases in soil N content. In contrast, the increase in microbial biomass N was more (92–114%) under combined RHA and mineral fertilizer treatments which showed the improved microbial activity under RHA applied treatment leading to microbial immobilization of soil N, as compared to control. The C/N ratio (11–12) of RHA + mineral fertilizer applied soils revealed the presence of more labile organic matter source, thus, a higher biological activity. Thus, RHA may catalyse the higher microbial activities in presence of N source leading to reduction in soil N and its immobilization in microbial biomass. In addition, higher SOC content (though not significant) in RHA + mineral fertilizer applied soils showed that the combined application of RHA with mineral fertilization could be more sustainable approach for soil C sequestration in long term.

As observed, sole RHA application led to decrease in SOC content possibly due to enhanced microbial activities. However, sole RHA application led to increase in soil N and microbial N by 7% and 48%, respectively, as compared to control. A recent study also suggested that the partial or complete substitution of mineral fertilizers with organic amendments may lead to reduction in soil N losses from the agricultural soils which may improve the crop production (Wang et al., 2015). Previous studies reported that the application of biochar showed an increase in microbial biomass and composition (Lehmann et al., 2011;

Galvez et al., 2012; Biederman and Harpole, 2013; Thies et al., 2015; Wang et al., 2016), due to presence of various macro- and micro-pores on its surface acting as a suitable habitat for microbes (Thies and Rillig, 2009). In addition, FYM application as sole as well as along with RHA showed a substantial increase in soil N (16–32%), MBC (103–174%) and MBN (52–96%) as compared to control soil. Higher soil microbial biomass in FYM amended system as compared to RHA and mineral fertilizer applied treatments in the present study is consistent with several previous studies (Dalal and Mayer, 1986; Kaur et al., 2008; Banger et al., 2009). The lower microbial biomass in RHA and mineral fertilizer applied treatments than FYM amended system may be attributed to N fertilization (Omay, 1997). Organic matter decomposition is found to be related with the variation in soil microbial biomass (Schnurer et al., 1985) which can be observed as an increase in microbial biomass under FYM and combined RHA applied systems.

Improvement in soil nutrient properties under RHA and RHA + FYM combined system along with mineral fertilization was in accordance with previous studies (Schulz and Glaser, 2012; Agegnehu et al., 2016a). Such improvement in soil properties is crucial for the improvement of agronomic performance and agricultural productivity (Bationo et al., 2007; Vanlauwe et al., 2010). However, combined application of mineral and organic fertilizers may show varying results depending upon local environmental conditions (Vanlauwe et al., 2010). For example, rapid mineralization of organic matter under tropical environment is one of the aspects to be considered for suggesting any ameliorant. It is the major constraints for sole FYM application under dry tropical environment as rapid decomposition is observed in several studies (Kaur et al., 2008; Srivastava et al., 2014). Thus, application of biochar may hold the rapid mineralization and led to soil C accumulation in these ecosystems by microbial mediated processes. It can also be inferred by the significant increase in soil N and microbial biomass under RHA and FYM treatments in the present study. Increased nutrient availability (especially N) is reported from biochar applied soils under combined application of biochar and compost (Sanchez et al., 2001; Fischer and Glaser, 2012; Schulz and Glaser, 2012). It is attributed by the modified stoichiometric relationship of soil N dynamics under biochar (Anderson et al., 2011) and organic manure (Srivastava et al., 2016b) applied soils. Moreover, RHA application (sole or combined with FYM and mineral fertilizer) led to increase in soil pH as compared to the control and inorganic treatments. It is in accordance with the previous studies showing an increase in soil pH with the application of alkaline biochar (Laird et al., 2010; Zhang et al., 2010; Anderson et al., 2011; Shackley et al., 2012b). However, FYM application showed a moderate change in soil pH. The increase in pH of biochar applied soils may led to the solubilisation and availability of nutrients to the microbes from the biochar ash itself or from the adjacent labile nutrient source (Shackley et al., 2012b; Carter et al., 2013). The alkaline pH range of RHA favours soil bacterial communities responsible for rapid mineralization of organic matter on one hand and its microbial sequestration on the other hand, thus, improved soil viability under RHA and FYM applied systems (Nardi et al., 2004). Overall, organic amendment improved the soil biophysical properties and may led to the soil C accumulation in the long term in contrast to the mineral fertilizer applied soils.

4.4. Variation in agronomic parameters of wheat crop

The capacity of a soil to perform various agronomic and environmental functions such as biomass productivity and responses to various biotic and abiotic stresses under different management practices refers to the soil health (Doran and Zeiss, 2000; Srivastava and Ngullie, 2009). As discussed earlier, the improvement in soil bio-physical properties under organic amended (RHA and FYM) systems as sole as well as combined with mineral fertilizers revealed the improved soil health under these systems as compared to the sole mineral fertilizer applied treatment. It showed one dimension of soil health improved by the organically amended systems. However, evaluation of agronomic benefits under different management system would help in holistic understanding of the agricultural sustainability. The benefits of mineral fertilizers in terms of agronomic performance and agricultural productivity have been well established since last few decades (Vanlauwe et al., 2010). On the contrary, rapid organic matter mineralization in presence of N fertilizers leading to the deteriorating soil quality is also an imperative aspect for the sustainable management of agriculture (Palm et al., 2001; Foley et al., 2005; Liu et al., 2010). Therefore, evaluating the responses of mineral fertilizers along with organic amendments could be of vital importance for maintaining the soil productivity and viability in the long term.

In this study, agronomic performance of wheat crop in terms of tiller and panicle length and number was not significantly varied under different management systems. Though the differences were not significant statistically, the mineral fertilizer (either complete or partial) applied treatment showed higher tiller number, effective tiller number, tiller and panicle lengths as compared to the control and sole RHA and FYM applied treatments. Moreover, mineral fertilizer applied systems showed maximum aboveground dry matter, grain and straw yields. Control and sole RHA applied treatments showed lowest grain (19 and 20% low) and straw (26 and 32% low) yields, respectively, as compared to the mineral fertilizer applied treatment. However, partial addition of mineral fertilizers along with RHA or RHA + FYM led to improvement in yields by 10–20% as compared to the sole RHA and FYM application. Glazer et al. (2015) also found similar results for maize crop where sole mineral as well as combined mineral fertilizer with biochar showed higher yield and agronomic performance than sole biochar and organic manure receiving treatments. Agegnehu et al. (2016b) also found significant improvement in barley yield and soil fertility under combined organic amendment with N fertilizer treatment. Moreover, several studies showed higher crop yield under the combined application of biochar with compost or mineral fertilizer than the sole mineral fertilization (Yamato et al., 2006; Christoph et al., 2007; Steiner et al., 2007; Kaur et al., 2008; Meade et al., 2011; Blackwell et al., 2015), which stands in contrast with our results showing higher aboveground dry matter under sole mineral fertilizer applied treatment as compared to the combined treatments. This further supports the consensus that the sole application of RHA or biochar and organic fertilizer (FYM) may initially lead to a yield penalty.

In a meta-analysis showing the impact of biochar application on crop productivity, Jeffery et al. (2011) found an overall small (~10%) improvement in grain yield under biochar applied systems possibly due to liming effect and increase in soil water holding capacity induced by biochar application. Moreover, several recent studies showed positive impact of biochar (as sole or combined with organic manure) addition on crop yield along with the improved nutrient dynamics (Van Zwieten et al., 2010; Galvez et al., 2012; Zhang et al., 2012; Biederman and Harpole, 2013; Agegnehu et al., 2017) depending upon the soil types. Agegnehu et al. (2017) suggested that biochar-compost mixture showed substantial economic gain under poor fertility soils due to replenishment of nutrient deficiency in soils by the compost source. Thus, a reduction in grain yield under RHA applied treatments may be due to poor fertility status of studied soil. The change in microbial community composition and activity in response to the organic amendments may resulted into the improved nutrient supply to the plants resulting into better yields (Kuzyakov et al., 2009; Liang et al., 2010). As observed in this study, several other studies suggested that combined organic manure and biochar only (i.e. without mineral fertilization) may lead to negative impact over agronomic parameters due to reduced bio-availability and binding of nutrients (especially N) on the surfaces of biochar and organic manure (Chan et al., 2007; Asai et al., 2009; Saarnio et al., 2013). Thus, a combined amendment can be viewed for agricultural sustainability

Moreover, harvest index is a measure of reproductive efficiency and crop C balance which can be used as an indicator of agronomic benefits.

It reflects the ability of crops to produce grain from dry matter (Unkovich et al., 2010). It is regulated by several factors and majorly by the soil water content, temperature, crop type and genotypes (Turner et al., 1999). The harvest index ranged from 0.32 to 0.38 in this study. Unkovich et al. (2010) also found an average harvest index of 0.37 for wheat crop after analysing a large dataset. Moreover, we observed that the sole FYM and RHA applied treatments showed higher harvest index followed by combined application whereas lower values were observed under mineral fertilizer applied treatments. A decrease in harvest index with the increase in mineral fertiliser is reported previously (Unkovich et al., 2010). The addition of N fertilisers led to the enhanced development of structural component (cellulosic structures) of crop due to allocation of photosynthate towards it whereas decrease in formation of water-soluble carbohydrate component which may not get mobilized into the grains later. Thus, it leads to increase in aboveground dry matter (mainly straw component) content resulting into decrease in harvest index (van Herwaarden et al., 1998; Adcock, 2006; Unkovich et al., 2010). It showed that higher photosynthetic activity under the mineral fertiliser applied treatments led to the improved structural development of wheat crop whereas nutrient limitation may lead to the production of water-soluble carbohydrate components which may get easily mobilize to the reproductive components (i.e., seeds/grains) under the RHA and FYM applied treatments as compared to the structural components. Comparatively higher soil water content might also lead to the improved harvest index under these treatments as compared to the mineral fertilizer applied treatment. Furthermore, we observed an overall negative correlation ($r = -0.45, P < 0.05$) between harvest index and soil C/N ratio (Table S3). Whereas, stepwise analysis results showed a considerable impact of soil C/N ratio over harvest index ($r^2 = 0.16$; $P < 0.05$; Table 4). It indirectly revealed that the soil N might not be the only major reason for the decrease in harvest index in the dry tropical region. Further, a positive but not significant relationship between SCE and harvest index revealed that the higher soil biological activities might led to the improved allocation of water soluble carbohydrate components to the seeds rather than the structural components. It may also be inferred from the positive relationship ($r = 0.45$, $P < 0.05$) between microbial biomass C/N and harvest index. Moreover, a sudden increase in temperature was observed after the booting period which may also led to the reduced allocation of photosynthates to the grain components later in the mineral fertiliser applied treatments (Stone and Nicholas, 1995). It can also be inferred from higher tiller number, panicle ($r = -0.47$, $P < 0.05$) and tiller length in mineral fertilizer applied treatment showing negative impact over harvest index. Effective tiller number was comparatively higher under the sole and combined FYM and RHA applied treatments. It showed positive relationship ($r = 0.44$, $P < 0.05$) with harvest index (Table S3). Moreover, stepwise analysis showed a considerable impact of panicle length ($r^2 = 0.18$; $P < 0.05$) on harvest index (Table 4). Thus, a combined application of RHA either with FYM or mineral fertilizer or both can be a viable approach under the dry tropical region for the sustainable management of agricultural productivity and soil health.

5. Conclusions

We observed the improved soil biophysical properties under the combined rice-husk ash (RHA), farm-yard manure (FYM) applied along with mineral fertilizer applied treatments. RHA addition initially showed higher soil CO_2 efflux, however, a reduction in it was observed later in different growth stages as well as overall SCE. It showed its potential for reducing greenhouse gaseous emissions from the dry tropical soils, which were nutrient poor and suggested for receiving a substantial amount of organic fertilizers for restoring soil viability. Moreover, the findings suggest that the soil biophysical properties can be optimized by organic (RHA + FYM) amendment whereas mineral fertilization improved the agronomic parameters. Agronomic properties were found higher under mineral fertilizer applied treatment, however, a combined (RHA + FYM + mineral fertilizer) fertilization approach showed *at par* or slightly reduced yields. As observed by the harvest index, a better agro-management would help in producing more grains and restoring soil viability by applying FYM and RHA along with an appropriate dose of mineral fertilizers. It showed that the combined application of mineral fertilizer with RHA and FYM may help in decreasing the initial yield penalty. Organic amendments will help in improving soil viability and health and it in combination with mineral fertilization can be a sustainable approach to produce *at par* grain yield as compared to the mineral fertilizer alone. It would help in reducing the amount of mineral fertilizer application in the long term under the dry tropical ecosystems. Moreover, the RHA left out after the energy production and mineral extraction can be used as a potential material for soil health and agronomic improvement in combination with FYM and mineral fertilizers. However, sole application of RHA, FYM or mineral fertiliser could not be promoted due to their direct impact over greenhouse gas emissions, agronomic parameters and soil properties, respectively. A combined approach needs to be explored further for other soil and plant eco-physiological parameters under the dry tropical ecosystems to promote their potential uses under the present climate change scenario.

Acknowledgements

Authors thankfully acknowledge the University Grants Commission (UGC) and DST-SERB, New Delhi, India, for providing funding to this research work. RS is thankful to Ms. Talat Afreen, Mr. Dharmendra Kumar Singh and Mr. Sanjay Maurya, Department of Botany, Banaras Hindu University, Varanasi for their support during sampling and data collection. RS also extends his thankfulness to the Handling Editors and anonymous reviewers for their thoughtful suggestions and criticisms for improving the article.

Authors' contribution

ASR and HS conceived the study which was further elaborated by PS and RS. Pardeep Singh provided the rice-husk biochar and performed its initial characterization whereas RS performed the detailed study on various soil and agronomic parameters. AKS helps in FTIR and EDX analysis and its explanation. RS drafted the initial manuscript in consultation with PS which was reviewed by all the co-authors and finalized by ASR.

Conflict of interests

Authors declare no potential conflicts of interests among them.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2018.04.043.

References

Abrishamkesh, S., Gorji, M., Asadi, H., Bagheri-Marandi, G.H., Pourbabaee, A.A., 2015. Effects of rice husk biochar application on the properties of alkaline soil and lentil growth. Plant Soil Environ. 61, 475–482.

Adcock, D., 2006. Soil Water and Nitrogen Dynamics of Farming Systems on the Upper Eyre Peninsula (Ph.D.). University of Adelaide, Adelaide, South Australia.

Afreen, T., Srivastava, P., Singh, H., Singh, J.S., 2017. Effect of invasion by Hyptis suaveolens on plant diversity and selected soil properties of a constructed tropical grassland. J. Plant Ecol. 1–10. http://dx.doi.org/10.1093/jpe/rtx045.

Agegnehu, G., Bass, A.M., Nelson, P.N., Bird, M.I., 2016a. Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. Sci. Total Environ. 543, 295–306.

Agegnehu, G., Nelson, P.N., Bird, M.I., 2016b. Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols. Soil Tillage Res. 160, 1–13.

Agegnehu, G., Srivastava, A.K., Bird, M.I., 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: a review. Appl. Soil Ecol. 119, 156–170.

Aguilar-Chávez, Á., Díaz-Rojas, M., del Rosario, M., Cárdenas-Aquino, D.L., Luna-Guido, M., 2012. Greenhouse gas emissions from a wastewater sludge-amended soil cultivated with wheat (*Triticum* spp. L.) as affected by different application rates of charcoal. Soil Biol. Biochem. 52, 90–95.

Allen, K., Dupuy, J.M., Gei, M.G., Hulshof, C., Medvigy, D., Pizano, C., Selgado-Negret, B., et al., 2017. Will seasonally dry tropical forests be sensitive or resistant tofuture changes in rainfall regimes? Environ. Res. Lett. 12, 023001.

Anderson, C.R., Condron, L.M., Clough, T.J., Fiers, M., Stewart, A., Hill, R.A., Sherlock, R.R., 2011. Biochar induced soil microbial community change: implications for biogeochemical cycling of carbon, nitrogen and phosphorus. Pedobiologia 54, 309–320.

Anderson, J.M., Ingram, J.S.I. (Eds.), 1993. Tropical Soil Biology and Fertility. A Handbook of Methods, second ed. CAB International, Wallingford, UK, pp. 22.

Angst, T.E., Patterson, C.J., Reay, D.S., Anderson, P., Peshkur, T.A., Sohi, S.P., 2013. Biochar diminishes nitrous oxide and nitrate leaching from diverse nutrient sources. J. Environ. Qual. 42, 672–682.

Asai, H., Samson, K.B., Stephan, M.H., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., Horie, T., 2009. Biochar amendment techniques for upland rice production in Northern Laos 1. Soil physical properties, leaf SPAD and grain yield. Field Crop Res. 111, 81–84.

Atkinson, C., Fitzgerald, J., Hipps, N., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337, 1–18.

Banger, K., Kukal, S., Toor, G., Sudhir, K., Hanumanthraju, T., 2009. Impact of long-term additions of chemical fertilizers and farm yard manure on carbon and nitrogen sequestration under rice-cowpea cropping system in semi-arid tropics. Plant Soil 318, 27–35.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric. Syst. 94, 13–25.

Biederman, L.A., Harpole, S.W., 2013. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. GCB Bioenergy 5, 202–214.

Blackwell, P., Joseph, S., Munroe, P., Anawar, H.M., Storer, P., Gilkes, R.J., Solaiman, Z.M., 2015. Influences of biochar and biochar-mineral complex on mycorrhizal colonisation and nutrition of wheat and sorghum. Pedosphere 25, 686–695.

Brookes, P.C., Landman, A., Pruden, G., Jenkinson, D.S., 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass N in soil. Soil Biol. Biochem. 17, 837–842.

Bruun, S., Clauson-Kaas, S., Bobulska, L., Thomsen, I.K., 2014. Carbon dioxide emissions from biochar in soil: role of clay, microorganisms and carbonates. Eur. J. Soil Sci. 65, 52–59.

Carter, S., Shackley, S., Sohi, S., Suy, T.B., Haefele, S., 2013. The impact of biochar application on soil properties and plant growth of pot grown lettuce (*Lactuca sativa*) and cabbage (*Brassica chinensis*). Agronomy 3, 404–418.

Chan, K.Y., Van, Z.L., Meszaros, I., Downie, A., Joseph, S., 2007. Agronomic values of greenwaste biochar as a soil amendment. Aust. J. Soil Res. 45, 629–634.

Christoph, G.T., Wenceslau, L., Johannes, N., Thomas, M., de Vasconcelos, J.L., Winfried, E.H.B., Zech, W., 2007. Long-term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered central Amazonian upland soil. Plant Soil 291, 275–290.

Curiel-Yuste, J., Janssens, I.A., Carrara, A., Ceulemans, R., 2004. Annual Q10 of soil respiration reflects plant phonological patterns as well as temperature sensitivity. Glob. Change Biol. 10, 161–169.

Dalal, R.C., Mayer, R.J., 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland. IV. Loss of organic carbon from different density fractions. Aust. J. Soil Res. 24, 301–309.

Della, V.P., Kühn, I., Hotza, D., 2002. Rice husk ash as an alternate source for active silica production. Mater. Lett. 57, 818–821.

Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Appl. Soil Ecol. 15, 3–11.

Enders, A., Hanley, K., Whitman, T., Joseph, S., Lehmann, J., 2012. Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresour. Technol. 114, 644–653.

Epron, D., Nouvellon, Y., Roupsard, O., Mouyondy, W., Mabiala, A., Saint-André, L., Joffre, R., Jourdan, C., Bonnefond, J.M., Berbigier, P., Hamel, O., 2004. Spatial and temporal variations of soil respiration in a Eucalyptus plantation in Congo. For. Ecol. Manag. 202, 149–160.

Fischer, D., Glaser, B., 2012. Synergisms Between Compost and Biochar for Sustainable Soil Amelioration, Management of Organic Waste. In Tech, Shanghai, China, pp. 167–198.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., 2005. Global consequences of land use. Science 309, 570–574.

Galvez, A., Sinicco, T., Cayuelac, M.L., Mingorance, M.D., Fornasier, F., Mondini, C., 2012. Short-term effects of bioenergy by-products on soil C and N dynamics nutrient availability and biochemical properties. Agric. Ecosyst. Environ. 160, 3–14.

Gamage, D.N.V., Mapa, R.B., Dharmakeerthi, R.S., Biswas, A., 2016. Effect of rice-husk biochar on selected soil properties in tropical Alfisols. Soil Res. 54, 302–310.

Glaser, B., Wiedner, K., Seelig, S., Schmidt, H.P., Gerber, H., 2015. Biochar organic fertilizers from natural resources as substitute for mineral fertilizers. Agron. Sustain. Dev. 35, 667–678.

Haefele, S.M., Konboon, Y., Wongboon, W., Amarante, S., Maarifat, A.A., Pfeiffer, E.M., Knoblauch, C., 2011. Effects and fate of biochar from rice residues in rice-based systems. Field Crops Res. 121, 430–440.

Houghton, R.A., 1994. Land-use change and tropical forests. BioScience 44, 305–331.

Hussain, M., Farooq, M., Nawaz, A., Al-Sadi, A.M., Solaiman, Z.M., Alghamdi, S.S., Ammara, U., Ok, Y.S., Siddique, K.H.M., 2017. Biochar for crop production: potential benefits and risks. J. Soil Sediments 17, 685–716.

Jackson, M.L., 1973. Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi, India.

Jain, A.K., Tao, Z., Yang, X., Conor, G., 2006. Estimates of global biomass burning emissions for reactive greenhouse gases (CO, NMHCs, and NOx) and CO_2. J. Geophys. Res. 111, 1–12.

Jassal, R.S., Black, T.A., Novak, M.D., Gaumont-Guay, D., Nesic, Z., 2008. Effect of soil water stress on soil respiration and its temperature sensitivity in an 18-year-old temperate Douglas-fir stand. Glob. Change Biol. 14, 1–14.

Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric. Ecosyst. Environ. 144, 175–187.

Jeffery, S., Abalos, D., Prodana, M., Bastos, A.C., van Groenigen, J.W., Hungate, B., Verheijen, F., 2017. Biochar boosts tropical but not temperate crop yields. Environ. Res. Lett. 12, 053001.

Jones, D.L., Rousk, J., Edwards-Jones, G., DeLuca, T.H., Murphy, D.V., 2012. Biochar-mediated changes in soil quality and plant growth in a three year field trial. Soil Biol. Biochem. 45, 113–124.

Junna, S., Bingchen, W., Gang, X., Hongbo, S., 2014. Effects of wheat straw biochar on carbon mineralization and guidance for large-scale soil quality improvement in the coastal wetland. Ecol. Eng. 62, 43–47.

Kaur, K., Goyal, S., Kapoor, K.K., 2008. Impact of organic fertilizers with and without chemical fertilizers on soil chemical properties and the establishment of nitrogen-fixing bacteria in the rhizosphere. Microbes Environ. 23, 313–316.

Koyama, S., Katagiri, T., Minamikawa, K., Kato, M., Hayashi, H., 2016. Effects of rice husk charcoal application on rice yield, methane emission, and soil carbon sequestration in andosol paddy soil. Japan Agric. Res. Q: JARQ 50, 319–327.

Kuppusamy, S., Thavamani, P., Megharaj, M., Venkateswarlu, K., Naidu, R., 2016. Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions. Environ. Int. 87, 1–12.

Kuzyakov, Y., Subbotina, I., Chen, H.Q., Bogomolova, I., Xu, X.L., 2009. Black carbon decomposition and incorporation into soil microbial biomass estimated by C-14 labeling. Soil Biol. Biochem. 41, 210–219.

Laird, D.A., Fleming, P., Davis, D.D., Horton, R., Wang, B., Karlen, D.L., 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158, 443–449.

Lal, R., 2008. Crop residues as soil amendments and feedstock for bioethanol production. Waste Manage. 28, 747–758.

Lal, R., 2015. Restoring soil quality to mitigate soil degradation. Sustainability 7, 5875–5895.

Lehmann, J., Joseph, S., 2009. Biochar for Environmental Management. Earthscan, United Kingdom and United States.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – a review. Soil Biol. Biochem. 43, 1812–1836.

Lentz, R.D., Ippolito, J.A., Spokas, K.A., 2014. Biochar and manure effects on net nitrogen mineralization and greenhouse gas emissions from calcareous soil under corn. Soil Sci. Soc. Am. J. 78, 1641–1655.

Liang, B., Lehmann, J., Sohi, S.P., Thies, J.E., O'Neill, B., Trujillo, L., Gaunt, J., Solomon, D., Grossman, J., Neves, E.G., Luizão, F.J., 2010. Black carbon affects the cycling of non-black carbon in soil. Org. Geochem. 41, 206–213.

Lim, J.S., Manan, Z.A., Wan Alwi, S.R., Hashim, H., 2012. A review on utilisation of biomass from rice industry as a source of renewable energy. Renew. Sustain. Energy Rev. 16, 3084–3094.

Litton, C.M., Ryan, M.G., Knight, D.H., Stahl, P., 2003. Soil-surface CO_2 efflux and microbial biomass in relation to tree density thirteen years after a stand replacing fire in a lodgepole pine ecosystem. Glob. Change Biol. 9, 680–697.

Liu, E., Changrong, Y., Xurong, M., Wenqing, H., So, H.B., Linping, D., Qin, L., Shuang, L., Tinglu, F., 2010. Long term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in north-west China. Geoderma 150, 173–180.

Liu, J., Schulz, H., Brandl, S., Miehtke, H., Huwe, B., Glaser, B., 2012. Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions. J. Plant Nutr. Soil Sci. 175, 698–707.

Liu, X.Y., Zhang, A.F., Ji, C.Y., Joseph, S., Bian, R.J., Li, L.Q., Pan, G.X., Paz-Ferreiro, J., 2013. Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data. Plant Soil 373, 583–594.

Major, J., Rondon, M., Molina, D., Riha, S.J., Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant Soil 333, 117–128.

Marinari, S., Mascinadaro, G., Ceccanti, B., Grego, S., 2000. Influence of organic and mineral fertilizers on soil biological and physical properties. Bioresour. Technol. 72, 9–17.

McKendry, P., 2002. Energy production from biomass (part 1): overview of biomass. Bioresour. Technol. 83, 37–46.

Meade, G., Lalor, S., Cabe, T.M., 2011. An evaluation of the combined usage of separated liquid pig manure and inorganic fertiliser in nutrient programmes for winter wheat production. Europ. J. Agron. 34, 62–70.

Mikha, M.M., Rice, C.W., 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci. Soc. Am. J. 68, 809–816.

Mohan, D., Abhishek, K., Sarswat, A., Patel, M., Singh, P., Pittman, C.U., 2018. Biochar production and applications in soil fertility and carbon sequestration–a sustainable solution to crop-residue burning in India. RSC Adv. 8, 508–520.

Muhammad, S., Bakar, A., Titiloye, J.O., 2013. Catalytic pyrolysis of rice husk for biooil

production. J. Anal. Appl. Pyrol. 103, 362–368.
Mukherjee, A., Lal, R., 2013. Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy 3, 313–339.
Nardi, S., Morari, F., Berti, A., Tosoni, M., Giardini, L., 2004. Soil organic matter properties after 40 years of different use of organic and mineral fertilizers. Eur. J. Agron. 21, 357–367.
Nelson, D.E., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., Keeney, R.D. (Eds.), Methods of Soil Analysis Part 2: Chemical and Microbiological Properties. ASA, SSSA, Madison, Wisonsin, pp. 539–758.
Nguyen, D.H., Scheer, C., Rowlings, D.W., Grace, P.R., 2016. Rice husk biochar and crop residue amendment in subtropical cropping soils: effect on biomass production, nitrogen use efficiency and greenhouse gas emissions. Biol. Fert. Soils 52, 261–270.
Omay, A.B., 1997. Soil microbial and chemical property under long crop rotation and fertilization. Soil Sci. Soc. Am. J. 61, 1672–1678.
Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric. Ecosyst. Environ. 83, 27–42.
Pender, J., 2009. The World Food Crisis, Land Degradation, and Sustainable Land Management: Linkages, Opportunities, and Constraints. IFPRI, New York, USA.
Prendergast-Miller, M.T., Duvalla, M., Sohi, S.P., 2014. Biochar – root interactions are mediated by biochar nutrient content and impacts on soil nutrient availability. Eur. J. Soil Sci. 65, 173–185.
Quispe, I., Navia, R., Kahhat, R., 2017. Energy potential from rice husk through direct combustion and fast pyrolysis: A review. Waste Manage. 59, 200–210.
Saarnio, S., Heimonen, K., Kettunen, R., 2013. Biochar addition indirectly affects N_2O emissions via soil moisture and plant N uptake. Soil Biol. Biochem. 58, 99–106.
Sainju, U.M., Stevens, W.B., Caesar, T., Jabro, J.D., 2010. Land use and management practices impact on plant biomass carbon and soil carbon dioxide emission. Soil Sci. Soc. Am. J. 74, 1613–1622.
Sanchez, J., Willson, T., Kizilkaya, K., Parker, E., Harwood, R., 2001. Enhancing the mineralizable nitrogen pool through substrate diversity in long term cropping systems. Soil Sci. Soc. Am. J. 65, 1442–1447.
Schnurer, J., Clarholm, M., Rosswal, T., 1985. Microbial biomass and activity in agricultural soil with different organic matter contents. Soil Biol. Biochem. 17, 611–618.
Schulz, H., Glaser, B., 2012. Effects of biochar compared to organic and inorganic fertilizers on soil quality and plant growth in a greenhouse experiment. J. Plant Nutrit. Soil Sci. 175, 410–422.
Shackley, S., Carter, S., Knowles, T., Middelink, E., Haefele, S., Sohi, S., Cross, A., Haszeldine, S., 2012a. Sustainable gasification-biochar systems? a case study of rice-husk gasification in Cambodia Part I: Context, chemical properties, environmental and health and safety issues. Energy Policy 42, 49–58.
Shackley, S., Sohi, S., Ibarrola, R., Hammond, J., Mašek, O., Brownsort, P., Haszeldine, S., 2012b. Biochar as a tool for climate change mitigation and soil management. In: Meyers, R. (Ed.), Encyclopedia of Sustainability Science and Technology. Springer, New York, NY, USA, pp. 183–205.
Shafie, S.M., Mahlia, T.M.I., Masjuki, H.H., Ahmad-Yazid, A., 2012. A review on electricity generation based on biomass residue in Malaysia. Renew. Sustain. Energy Rev. 16, 5879–5889.
Shen, J., Tang, H., Liu, J., Wang, C., Li, Y., Ge, T., Jones, D.L., Wu, J., 2014. Contrasting effects of straw and straw-derived biochar amendments on greenhouse gas emissions within double rice cropping systems. Agric. Ecosyst. Environ. 188, 264–274.
Shi, P.L., Zhang, X.Z., Zhong, Z.M., Ouyang, H., 2006. Diurnal and seasonal variability of soil CO_2 efflux in a cropland ecosystem on the Tibetan Plateau. Agric. For. Meteor. 137, 220–233.
Singh, R., Babu, J.N., Kumar, R., Srivastava, P., Singh, P., Raghubanshi, A.S., 2015a. Multifaceted application of crop residue biochar as a tool for sustainable agriculture: An ecological perspective. Ecol. Eng. 77, 324–347.
Singh, J.S., Raghubanshi, A.S., Singh, R.S., Srivastava, S.C., 1989. Microbial biomass acts as a source of plant nutrients in dry tropical forest and savanna. Nature 338, 499–500.
Singh, R., Srivastava, P., Upadhyay, S., Singh, P., Raghubanshi, A.S., Babu, J.N., 2015b. Integrating biochar as conservation agriculture tool under climate change mitigation scenario. In: Proceedings of National Conference on Climate Change: Impacts, Adaptation, Mitigation Scenario and Future Challenges in Indian Perspective. New Delhi, India, pp. 9–18.
Singh, R., Srivastava, P., Singh, P., Upadhyay, S., Raghubanshi, A.S., 2016. Human overpopulation and food security: challenges for the agriculture. In: Singh, R.P., Singh, A., Srivastava, V. (Eds.), Environmental Issues Surrounding Human Overpopulation. IGI Global, Philadelphia, pp. 12–39.
Singh, R., Singh, H., Singh, S., Afreen, T., Upadhyay, S., Singh, A.K., Srivastava, P., Bhadouria, R., Raghubanshi, A.S., 2017a. Riparian land uses affect the dry season soil CO_2 efflux under dry tropical ecosystems. Ecol. Eng. 100, 291–300.
Singh, R., Sagar, R., Srivastava, P., Singh, P., Singh, J.S., 2017b. Herbaceous diversity and soil attributes along a forest-savanna-grassland continuum in dry tropical region. Ecol. Eng. 103, 226–235.
Smith, J.L., Collins, H.P., Bailey, V.L., 2010. The effect of young biochar on soil respiration. Soil Biol. Biochem. 42, 2345–2347.
Sohi, S.P., Krull, E., Lopez-Capel, E., Bol, R., 2010. A review of biochar and its use and function in soil. In: Sparks, D.L. (Ed.), Advances in Agronomy. Academic Press, Burlington, pp. 47–82 vol. 105.
Spokas, K.A., Cantrell, K.B., Novak, J.M., Archer, D.W., Ippolito, J.A., Collins, H.P., Boateng, A.A., Lima, I.M., Lamb, M.C., McAloon, A.J., Lentz, R.D., Nichols, K.A., 2011. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. J. Environ. Qual. 41, 973–989.
Spokas, K.A., Reicosky, D.C., 2009. Impacts of sixteen biochars in soil greenhouse gas production. Ann. Environ. Sci. 3, 179–193.
Srivastava, A., Ngullie, E., 2009. Integrated nutrient management: theory and practice. Dyn. Soil Dyn. Plants 3, 1–30.
Srivastava, A., Das, S., Malhotra, S., Majumdar, K., 2014. SSNM-based rationale of fertilizer use in perennial crops: a review. Indian J. Agric. Sci. 84, 3–17.
Srivastava, P., Raghubanshi, A.S., Singh, R., Tripathi, S.N., 2015. Soil carbon efflux and sequestration as a function of relative availability of inorganic N pools in dry tropical agroecosystem. Appl. Soil Ecol. 96, 1–6.
Srivastava, P., Singh, R., Tripathi, S., Raghubanshi, A.S., 2016a. An urgent need for sustainable thinking in agriculture–an Indian scenario. Ecol Ind. 67, 611–622.
Srivastava, P., Singh, P.K., Singh, R., Bhadouria, R., Singh, D.K., Singh, S., Afreen, T., Tripathi, S.N., Singh, P., Singh, H., Raghubanshi, A.S., 2016b. Relative availability of inorganic N-pools shifts under land use change: an unexplored variable in soil carbon dynamics. Ecol. Ind. 64, 228–236.
Srivastava, P., Singh, R., Bhadouria, R., Tripathi, S., Singh, P., Singh, H., Raghubanshi, A.S., 2016c. Organic amendment impact on SOC dynamics in dry tropics: A possible role of relative availability of inorganic N-pools. Agric. Ecosys. Environ. 235, 38–50.
Srivastava, P., Singh, R., Tripathi, S., Singh, H., Raghubanshi, A.S., Mishra, P.K., 2017a. A new insight into the warming potential of organically amended agro-ecosystems. Org. Agric. 1–10. http://dx.doi.org/10.1007/s13165-017-0188-4.
Srivastava, P., Singh, R., Tripathi, S., Singh, P., Singh, S., Singh, H., Raghubanshi, A.S., Mishra, P.K., 2017b. Soil carbon dynamics under changing climate—a research transition from absolute to relative roles of inorganic nitrogen pools and associated microbial processes: a review. Pedosphere 27, 792–806.
Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., Macedo, J., Blum, W.H., Zech, W., 2007. Long term effect of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291, 275–290.
Stone, P., Nicholas, M., 1995. A survey of the effects of high temperature during grain filling on yield and quality of 75 wheat cultivars. Aust. J. Agric. Res. 46, 475–492.
Taghizadeh-Toosi, A., Clough, T., Sherlock, R.R., Condron, L.M., 2011. Biochar adsorbed ammonia is bioavailable. Plant Soil 350, 57–69.
Tang, J., Zhu, W., Kookana, R., Katayama, A., 2013. Characteristics of biochar and its application in remediation of contaminated soil. J. Biosci. Bioeng. 116, 653–659.
Thies, J.E., Rillig, M.C., 2009. Characteristics of biochar: biological properties. In: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management: Science and Technology. Earthscan, London, UK, pp. 85–105.
Thies, J.E., Rillig, M.C., Graber, E.R., 2015. Biochar effects on the abundance, activity and diversity of the soil biota. In: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management: Science and Technology Implement. Earthscan, London, UK, pp. 327–388.
Tong, X., Li, J., Nolan, R.H., Yu, Q., 2017. Biophysical controls of soil respiration in a wheat-maize rotation system in the North China Plain. Agric. For. Meteor. 246, 231–240.
Turner, N., Wright, G., Siddique, K.H.M., 1999. Adaptation of grain legumes (pulses) to water-limited environments. Adv. Agron. 71, 193–229.
Unkovich, M., Baldock, J., Forbes, M., 2010. Variability in harvest index of grain crops and potential significance for carbon accounting: examples from Australian agriculture. Adv. Agron. 105, 173–219.
van Herwaarden, A., Farquhar, G., Angus, J., Richards, R.A., Howe, G., 1998. 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser. I. Biomass, grain yield and water use. Aust. J. Agric. Res. 49, 1067–1081.
Van Zwieten, L., Kimber, S., Morris, J., Chan, K., Downie, A., Rust, J., Joseph, S., Cowie, A., 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant Soil 327, 235–246.
Vance, E.D., Brookes, P.S., Jenkinson, D.S., 1987. An extraction method for measuringsoil microbial biomass C. Soil Biol. Biochem. 19, 703–707.
Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., Sanginga, N., 2010. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook Agric. 39, 17–24.
Wang, J., Zhu, B., Zhang, J., Müller, C., Cai, Z., 2015. Mechanisms of soil N dynamics following long-term application of organic fertilizers to subtropical rain-fed purple soil in China. Soil Biol. Biochem. 91, 222–231.
Wang, J., Xiong, Z., Kuzyakov, Y., 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8, 512–523.
Westeman, P.W., Bicudo, J.R., 2005. Management considerations for organic wastes use in agriculture. Bioresour. Technol. 96, 215–221.
Wilson, H.M., Al-kaisi, M.M., 2008. Crop rotation and nitrogen fertilization effect on soil CO_2 emissions in Central Lova. Appl. Soil Ecol. 39, 264–270.
Yamato, M., Okimori, Y., Wibowo, I.F., Anshori, S., Ogawa, M., 2006. Effects of the application of charred bark of *Acacia mangium* on the yield of maize, cowpea and peanut and soil chemical properties in South Sumatra, Indonesia. Soil Sci. Plant Nutr. 52, 489–495.
Yang, B., Xiong, Z., Wang, J., Xu, X., Huang, Q., Shen, Q., 2015. Mitigating net global warming potential and greenhouse gas intensities by substituting chemical nitrogen fertilizers with organic fertilization strategies in rice-wheat annual rotation systems in China: a 3-year field experiment. Ecol. Eng. 81, 289–297.
Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., Zheng, J., Zheng, J., Zhang, X., Han, X., Yu, X., 2012. Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: a field study of 2 consecutive rice growing cycles. Field Crops Res. 127, 153–160.
Zhang, A.F., Cui, L.Q., Pan, G.X., Li, L.Q., Hussain, Q., Zhang, X.H., Zheng, J.W., Crowley, D., 2010. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain. China. Agric. Ecosyst. Environ. 139, 469–475.