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ORIGINAL RESEARCH

Improving soil silicon and selected fertility status for rice production through rice-mill waste application in lowland *sawah* rice field of southeastern Nigeria

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Abstract

Purpose Rice-mill wastes are generated in large amounts in Ishiagu, Ebonyi State, Nigeria. These wastes can potentially be utilized for rice production and in improving soil attributes. This study evaluated the effects of rice-mill wastes on soil chemical properties and rice yield in sawah rice management.

Methods A sawah rice field in an inland valley of southeastern Nigeria was used in 2014 and 2015 cropping seasons for the study. Sawah refers to an Indo-Malaysian term for rice paddy. It involves the manipulation of some soil physical properties in form of ecological engineering works, by bunding, puddling and leveling of lowland rice field for water control and management. Two rice-mill wastes [rice husk ash (RHA) and rice husk dust (RHD) applied at 0, 2.5, 5, 7.5, 10 and 12.5 t ha^{-1}] and the control were built into a split-plot in a randomized complete block design with three replications.

Results Bio-waste application had significant ($p < 0.05$) improved effects on the soil organic carbon, available P, soil available Si and total N compared with the unamended (control) treatment. There was significant ($p < 0.05$) increase in rice grain yield from 5.05 to 5.80 t ha^{-1} (for RHA) and 6.17–6.96 t/ha (for RHD) compared with 2.35–2.8 t ha^{-1} (control treatment) in both cropping seasons.

Conclusion RHD and RHA treatments had significantly higher rice grain yield compared with the control treatment. Overall, rice grain yield was higher under RHD treatment compared with RHA treatment. This result demonstrated that RHA and RHD are potential agricultural resource for rice production in the study area.

Keywords Rice-mill wastes · *Sawah* · Soil amendments · Chemical properties · Rice grain yield

Introduction

Silicon (Si) and NPK are important nutrients for rice production (Ma et al. 2001). Adequate available Si uptake enhances the growth of rice by increasing rice tolerance to both abiotic and biotic stresses (Liang et al. 2007; Guntzer et al. 2012). Si availability is key to sustainable rice production, thus inadequate Si can limit rice yield production (Klotzbücher et al. 2014). Generally, tropical soils have low available nutrients including Si due to soil degradation such as erosion, sediment transportation and leaching process (Meena et al. 2014; Li et al. 2014;). Intensive rice crop production can deplete soil available Si (Cornelis and Delvaux 2016) due to high uptake by rice plants (Ma et al. 2001; Makabe et al. 2009). Soil acidification in rice paddies can cause Si deficiency since pH affects Si availability in the soil (Tavakkoli et al. 2011).

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A *sawah* lowland farming, which has a small-scale irrigation scheme adapted for an integrated watershed management, was suggested as a promising strategy to tackle soil erosion and sediment transportation in inland valleys (Hirose and Wakatsuki 2002; Hayashi and Wakatsuki 2002). *Sawah* is an Indo-Malaysian word for paddy. It is a lowland rice management system that involves bunding, puddling, leveling of soil to ensure good water management via irrigation and drainage (Wakatsuki et al. 2005). *Sawah* system ensures that certain water level is maintained in field plots during the plant growing period, restores and replenishes soil nutrients through geological fertilization and soil erosion control. The mechanisms of nutrient replenishments in *sawah* system encourage rice growth and enhance microbial populations, which improve biological nitrogen fixation.

Study has shown that rice-mill wastes can serve as source of Si fertilizer to mitigate Si deficiency in rice-based agriculture (Song et al. 2014b). In southeastern Nigeria, chemical fertilizers are scarce and when available are often very costly for most resource-poor farmers. The use of chemical fertilizers to replenish lost nutrients in cultivated soil is negligible because most low-income farmers cannot afford the costs (Agbede and Kalu 1995).

Application of organic waste is recommended due to the potentials of organic waste to increase soil pH and nutrients and thus reduce heavy mineral fertilizer application to agricultural soils (Unagwu et al. 2013; Unagwu 2014, 2019; Nessa et al. 2016; Joardar and Rahman 2018). Under intensive agriculture, continuous chemical fertilizer application is reported to increase soil acidity which creates nutrient imbalance in the soil (Ojenyi 2000) and consequently reduces crop yield. The possible alternative for smallholder farmers to increase crop yield and achieve sustainable soil productivity is via organic amendment application (Okenmuo et al. 2018; Unagwu et al. 2019). Crop residues improve soil nutrient availability, crop yields (Singh and Singer 2006), improve the overall ecological balance of the crop production (Song et al. 2014b) and enhance soil–water relations of degraded soils (Nwite and Okolo 2016). Lal (2003) observed increased crop yield following organic waste application. Application of crop residues such as rice-mill wastes to agricultural soils improves soil fertility (Lehmann and Joseph 2009), nutrient use efficiency, nutrient cycling, and increases crop yield in rain-fed lowland rice systems (Seng et al. 2004; Song et al. 2014a). Rice-mill wastes can be applied to degraded soils to improve their fertility status (Nwite et al. 2012).

Ebonyi state, southeastern Nigeria, has numerous rice milling industries. These mills produced large quantities of fresh and partially burnt rice-mill wastes (bio-wastes). Despite the huge rice-mill wastes generated and the potential negative effects these wastes can have on the environment, the only means of disposing these wastes is by burning at the various dump sites (Nwite et al. 2012). Thus, this work evaluated the possibility of using the available rice-mill wastes to increase rice production, evaluated the effects of rice-mill wastes on some soil chemical properties and the relationship between the Si nutrient uptake and grain yield of rice.

Materials and methods

Description of the study area

A field study was conducted in lowland and undulating area of Ishiagu, Ebonyi State, Southeastern Nigeria, in 2014 and 2015 cropping seasons. The study area is within latitude 05°56′N and longitude 07°41′E of the derived savannah zone of the Southeastern Nigeria. The area has a wet and dry climate, with a mean annual temperature of about 30 °C and rainfall of 1350 mm, which spans from April to October while the dry season spans from November to March each year. The geology of the study area comprises sandy shales and has fine-grained micaceous sandstones and belongs to the Asu River Group (Ezeh and Chukwu 2011). The soils are Aeric Tropoaquent (USDA 1998) or Gleyic Cambisol (FAO 1988) and have moderate soil organic carbon (SOC), low pH and cation exchange capacity (CEC).

Field preparation

The experimental field was divided into two different main plots. Two rice-mill wastes [rice husk ash (RHA) and rice husk dust (RHD)] constituted the main plots. The main plots were demarcated by a 0.6-m raised bund. Six different levels (0, 2.5, 5.0, 7.5, 10.0 and 12.5 t/ha) of RHA and RHD constituted the sub-plots. The treatments were replicated three times. Poultry dropping (PD) was applied as basal application at 10 t/ha to provide additional N since N content of rice-mill wastes was insufficient for adequate rice growth and yield performance (Nwite et al. 2011). Each sub-plot (6 m × 6 m) was demarcated with a raised 0.6-m bunds, plowed, puddled, leveled, and bunded with inlet and outlet channels for irrigation and drainage. Water was supplied, controlled and maintained via the inlets and outlets channels from 2 weeks after transplanting to the grains ripening stage. RHA and RHD were incorporated manually in the sub-plots at 20 cm soil depth, 2 weeks before transplanting. *Oryza sativa var* FARO 52 (WITA 4), a high-tillering rice variety, was used as the test crop in this study. The rice seedlings were first raised in the nursery. After 3 weeks, the seedlings were transplanted to the plots (spacing distance was 20 cm × 20 cm) at two seedlings per row. At maturity, rice grains were harvested dry and the grain yield was determined by weight.

Soil sampling and laboratory analyses

Bulk soil samples were collected from 0 to 20 cm depth before treatment application for pre-planting soil analysis (Hence, the reason why PD was added as basal application.). Similarly, after each cropping season (after harvest), soil samples were taken from the amended plots, air-dried and sieved through 2.0-mm mesh and taken to laboratory for chemical analyses. The soil pH was determined in distilled water and 0.1 N KCl solution using a soil solution of 1:2.5 (Mclean 1982). SOC was determined by wet oxidation method (Walkley and Black 1934) as modified by Nelson and Sommers (1982). Total nitrogen (TN) was determined using semi-micro-Kjeldahl methods (Bremner and Mulvaney 1982). Soil available Si was determined in a 1 mol L^{-1} acetate buffer (pH 4.0) at a 1:10 ratio for 5 h at 40 °C while shaking, occasionally (Imaizumi and Yoshida 1958). Bray II method was used in determining available P (Bray and Kurtz 1945). More so, the nutrient contents of the rice-mill wastes were determined following the above methods.

Statistical analysis

Data generated from the study were analyzed using GENSTAT 3 7.2 Edition. Significant treatment means were separated and compared using least significant difference (LSD) at 5% probability level.

Table 1 Physico-chemical properties of the soil (0–20 cm) before rice-mill waste application

Soil properties	Values
Clay (%)	20.0
Silt (%)	23.0
Fine sand (%)	53.0
Coarse sand (%)	4.00
Textural class	Sandy clay
SOC (g kg^{-1})	11.4
TN (g kg^{-1})	0.84
pH (H_2O)	4.80
Soil bioavailable Si (mg kg^{-1})	31.0
Available P (mg kg^{-1})	5.60

TN total nitrogen, *SOC* soil organic carbon

Results and discussion

Soil analysis

Some basic physical and chemical properties of the soil used in the present study as the medium for plant growth before rice-mill waste application are shown in Table 1. The test soil was sandy clay and was associated with low pH (4.8), SOC (11.4 g kg^{-1}) and available Si (31 mg kg^{-1}). The low nutrient status observed for the test soil is attributed to continuous cropping, increased land use intensity and inadequate application of organic amendments.

Organic amendment analysis

The composition of rice-mill waste and poultry manure is presented in Table 2. The RHD had the highest SOC, followed by RHA, while PD recorded the lowest SOC. The TN was higher in poultry dropping than for RHA (Table 2). Except for available Ca, the result showed that RHA had higher available K, Mg and P compared with PD and RHD, respectively.

Further, the C:N in PD was lower than that of RHD and RHA. The high C:N associated with RHD and RHA can negatively affect soil N availability for plant uptake due to N immobilization by the soil microbes. Hence, the reason why PD was added as basal application.

Effects of bio-waste and application rates on soil chemical properties

Soil pH

The soil pH was significantly affected following rice-mill waste application across the cropping seasons (Table 3). In both 2014 and 2015 cropping seasons RHD and RHA had significantly higher soil pH compared with the unamended treatment (0 t ha^{-1}) The amended plots had 2.1–23.2% increase in soil pH when compared with the initial soil pH

Table 2 Properties of the organic amendment used in the study

Amendments	OC	TN (%)	Available K (%)	Available Ca (%)	Available Mg (%)	Available P (%)	C:N
PD	16.5	2.10	0.48	14.4	1.20	2.55	7.86
RHD	33.7	0.70	0.11	0.36	0.38	0.49	48.1
RHA	23.9	0.06	0.65	1.00	1.40	11.9	398.3

PD poultry droppings, *RHD* rice husk dust, *RHA* rice husk ash, *OC* organic carbon, *TN* total nitrogen, *C:N* carbon to nitrogen ratio

Table 3 Effect of treatments and application rates on soil pH and soil organic carbon

Treatments	Treatments rates (t ha^{-1})						Mean
	0	2.5	5.0	7.5	10.0	12.5	
Soil pH (H_2O)							
Year 1 (2014 cropping season)							
RHA	4.73	5.5	5.63	5.93	5.47	4.90	5.36
RHD	4.53	4.97	4.90	5.23	5.30	5.37	5.05
Mean	4.63	5.23	5.27	5.58	5.38	5.13	5.21
LSD $_{(0.05)}$ soil treatments = 0.276; $p = 0.040$							
LSD $_{(0.05)}$ soil treatment rates = 0.371; $p < 0.001$							
LSD $_{(0.05)}$ interaction = 0.495; $p = 0.027$							
Year 2 (2015 cropping season)							
RHA	4.87	5.20	5.67	5.80	5.63	5.97	5.52
RHD	4.97	5.43	5.60	5.20	6.07	5.30	5.43
Mean	4.92	5.32	5.63	5.50	5.85	5.63	5.48
LSD $_{(0.05)}$ soil treatments = NS; $p = 0.568$							
LSD $_{(0.05)}$ soil treatment rates = 0.395; $p = 0.002$							
Soil organic carbon (g kg^{-1})							
Year 1 (2014 cropping season)							
RHA	6.27	7.97	7.87	9.31	7.27	8.20	7.81
RHD	8.27	10.3	9.37	7.6	9.13	10.4	9.17
Mean	7.27	9.12	8.62	8.46	8.20	9.30	8.49
LSD $_{(0.05)}$ soil treatments = NS; $p = 0.158$							
LSD $_{(0.05)}$ soil treatment rates = 0.837; $p < 0.001$							
LSD $_{(0.05)}$ interaction = 2.009; $p < 0.001$							
Year 2 (2015 cropping season)							
RHA	7.38	9.37	9.68	10.13	9.65	9.25	9.24
RHD	7.63	8.73	9.07	10.3	10.07	9.67	9.24
Mean	7.38	9.37	9.68	10.13	9.65	9.25	9.24
LSD $_{(0.05)}$ soil treatments = NS; $p = 1.00$							
LSD $_{(0.05)}$ soil treatment rates = 0.915; $p < 0.001$							

RHA rice husk ash, *RHD* rice husk dust, *LSD* least significant difference, *NS* non-significant

(Table 1). The high soil pH in the amended plots is attributed to high Ca, Mg and K associated with the rice-mill waste whose effect on the soil can be likened to that of lime (Lickaz 2002). Mbah et al. (2017) reported that soil pH increases following organic waste application.

Soil organic carbon (SOC)

Overall, there was significant effect on the SOC with rice-mill waste application. In 2014 and 2015 cropping seasons, SOC in RHA ranged from 6.27–8.20 to 7.38–10.1 g kg^{-1} and from 8.27–10.4 to 7.63–10.3 g kg^{-1} for RHD, respectively. The RHA and RHD treatments did not significantly ($p < 0.05$) affect their SOC content in both cropping seasons (Table 3). Increase in treatment application rates significantly increased the SOC, across both cropping seasons (Table 3). This is due to the high SOC associated with rice-mill waste.

Total nitrogen (TN)

All the amended plots significantly improved the TN relative to the unamended plot. Across treatment application rate, RHA and RHD did not significantly ($p > 0.05$) differ in their TN content in the first year of application (2014 cropping season), but significantly improved the soil TN in 2015 (Table 4). As anticipated, increase in RHD and RHA application rates significantly ($p > 0.05$) increased the TN across both cropping seasons (Table 4). The TN in the amended plots was higher than the initial TN (Table 1). This is due to organic amendment applied and due to the *sawah* system mechanisms that encourage replenishment of nutrients for rice growth, as well as enhance microbial population help in nitrogen fixation (Nwite et al. 2016a). In 2015 cropping season, increase in treatment application rates beyond 10 t ha^{-1} significantly reduced the TN by 22% and 63%, for RHA and RHD, respectively.

Table 4 Effect of treatments and application rates on total nitrogen, available P and soil available Si

Treatments	Treatments rates (t ha^{-1})						Mean
	0	2.5	5.0	7.5	10.0	12.5	
Soil total nitrogen (g kg^{-1})							
Year 1 (2014 cropping season)							
RHA	0.81	0.90	1.08	1.09	1.20	1.07	1.02
RHD	0.91	0.93	1.10	1.09	1.11	1.21	1.06
Mean	0.86	0.92	1.09	1.09	1.16	1.14	1.04
LSD $_{(0.05)}$ treatments = NS; $p = 0.130$							
LSD $_{(0.05)}$ treatment rates = 0.038; $p < 0.001$							
Year 2 (2015 cropping season)							
RHA	1.13	2.24	1.32	1.53	1.58	1.24	1.51
RHD	1.12	7.57	10.3	14.1	18.3	6.86	9.71
Mean	1.13	4.9	5.81	7.83	9.93	4.05	9.71
LSD $_{(0.05)}$ treatments = 2.05; $p = 0.003$							
LSD $_{(0.05)}$ treatments rates = 2.67; $p < 0.001$							
Available P (mg kg^{-1})							
Year 1 (2014 cropping season)							
RHA	10.8	12.3	10.9	12.7	11.8	12.8	11.9
RHD	9.38	9.87	10.7	10.7	11.9	11.6	10.7
Mean	10.1	11.1	10.8	11.7	11.8	12.2	11.2
LSD $_{(0.05)}$ treatments = 0.3482; $p = 0.005$							
LSD $_{(0.05)}$ treatment rates = 0.4465; $p < 0.001$							
Year 2 (2015 cropping season)							
RHA	11.4	13.3	15.4	14.4	15.4	15.8	14.3
RHD	11.8	16.3	14.2	16.6	16.4	16.9	15.4
Mean	11.6	14.8	14.8	15.5	15.9	16.3	14.8
LSD $_{(0.05)}$ treatments = 0.157; $p = 0.001$							
LSD $_{(0.05)}$ treatment rates = 1.03; $p = 0.001$							
Soil available Si (mg kg^{-1})							
Year 1 (2014 cropping season)							
RHA	30.7	53.0	58.7	48.0	88.3	73.0	58.6
RHD	25.7	37.0	44.7	90.7	78.7	56.7	55.6
Mean	28.2	45.0	51.7	69.3	83.5	64.8	57.1
LSD $_{(0.05)}$ treatments = NS; $p = 0.172$							
LSD $_{(0.05)}$ treatment rates = 9.75; $p = < 0.001$							
Year 2 (2015 cropping season)							
RHA	120	163	148	192	175	146	157
RHD	146	158	168	170	157	134	155
Mean	133	160	158	181	166	140	156
LSD $_{(0.05)}$ treatments = 1.45; $p = 0.041$							
LSD $_{(0.05)}$ treatment rates = 2.06; $p < 0.001$							

RHA rice husk ash, *RHD* rice husk dust, *LSD* least significant difference, *NS* non-significant

Available P

In both 2014 and 2015 cropping seasons, RHA and RHD application significantly affected available P. Relative to the initial available P (5.6 mg kg^{-1}) associated with the test soil (Table 1), in 2014, RHA and RHD treatments increased the mean available P from 5.6 to 11.9–10.7 mg kg^{-1}, respectively, and 14.6–15.4 mg kg^{-1} in 2015 (Table 4). Across the treatments and application rates, RHA and RHD had significantly higher available P than the unamended plot. The significant increases in available P associated with RHA and RHD compared with the unamended plot is due to high available P in the rice-mill wastes applied. The unamended plots (Table 4) record higher available P content relative to the initial available P (Table 1). This is linked to the contributions of *sawah* system in improving soil fertility status in lowland rice field. This is because pre-farm activities such as bunding, surface field leveling, irrigation and drainage modifications in the *sawah* system help in preventing erosion (Nwite et al. 2016b). *Sawah* system has been reported to have positive effect in restoring/replenishing lowland with nutrients due to geological fertilization (Wakatsuki et al. 2005).

Soil available Si

RHA and RHD treatments and their application rates had significant effect on soil available Si (Table 4). Soil available Si in the amended treatments was not significantly different in the first cropping year of study but differed significantly ($p < 0.05$) in the second cropping year. RHA treatment mean for soil available Si was significantly higher compared with RHD treatment (Table 4). As anticipated, soil available Si recorded for RHA and RHD in 2014 and 2015 cropping seasons was higher than the initial soil available Si (31.0 mg kg^{-1}). The present results corroborate the findings of Magale et al. (2011) and Lima et al. (2011) who reported that application of increasing amounts of Si-rich sources enhanced greater availability of Si in the soil. Across both cropping seasons, increase in treatment application rates significantly increased soil available Si (Table 4). Soil available Si range was 30.7–88.3 mg kg^{-1} and 25.7–90.7 mg kg^{-1} for RHA and RHD amended plots, respectively. RHA and RHD treatments applied beyond 10 t ha^{-1} significantly reduced the soil available Si. This result suggests that the optimum application level of RHA and RHD treatments required to enhance the soil available Si level in the study area is about 10 t ha^{-1}. The increase in soil available Si from 31 to 192 mg kg^{-1} following bio-waste application is comparable to the work of Song et al. (2014a) who reported a significant increase in soil available Si (130–270 mg kg^{-1}) after 10 years of manure treatment (rice crop residues) application in Eastern China. When incorporated into the soil, rice husk contains approximately 86% of Si which could be taken up by rice plants (Klotzbücher et al. 2015). Thus, RHA and RHD are potential alternative resources for improving soil available Si.

Rice grain yield (t ha^{-1}) as affected by organic treatments and application rates

Rice-mill wastes and their application rates had significant ($p < 0.05$) effect on rice grain yield in the 2014 and 2015 cropping seasons (Table 5). The grain yield mean values ranged from 5.05–6.17 to 5.80–6.96 t ha^{-1} in the 2014 and 2015 cropping seasons, respectively. The amended plots had 89.1–107.4% increased grain yield compared with the unamended plot. Overall, rice yield obtained in the two cropping seasons was above the usual < 2 t ha^{-1} often obtained by the local smallholder farmers under non-*sawah* farming system. The higher yield obtained can be attributed to improvement in available Si and soil fertility index following the application of RHA and RHD treatments. The results obtained corroborated to that of Datta and Shinde (1985), who reported that under upland and water-logged conditions, application of Si in rice field increased the rice grain yield. Further, Mukhtar et al. (2012) observed that Si nutrition significantly affected crop growth, physiological attributes and yield parameters.

In a similar study, Nwite et al. (2016a) reported that *sawah* tillage environments significantly increased rice

Table 5 Effect of treatments and application rates on rice grain yield (t ha^{-1})

Treatments	Treatments rates (t ha^{-1})						Mean
	0	2.5	5.0	7.5	10.0	12.5	
Year 1 (2014)							
RHA	2.56	5.43	5.74	4.84	6.62	5.12	5.05
RHD	3.67	5.28	6.56	7.61	7.11	6.79	6.17
Mean	3.11	5.35	6.15	6.23	6.87	5.96	5.61
LSD $_{(0.05)}$ soil treatments = 0.763; $p = 0.024$							
LSD $_{(0.05)}$ soil treatment rates = 1.210; $p < 0.001$							
LSD $_{(0.05)}$ interaction of treatments × rates = NS; $p = 0.228$							
Year 2 (2015)							
RHA	2.83	6.10	5.90	6.93	6.70	6.33	5.80
RHD	4.50	6.30	7.97	7.37	7.63	8.00	6.96
Mean	3.67	6.20	6.93	7.15	7.17	7.17	6.38
LSD $_{(0.05)}$ soil treatments = 0.172; $p < 0.001$							
LSD $_{(0.05)}$ soil treatment rates = 1.082; $p < 0.001$							
LSD $_{(0.05)}$ interaction of treatments × rates = NS; $p = 0.414$							

RHA rice husk ash, *RHD* rice husk dust, *LSD* least significant difference, *NS* non-significant

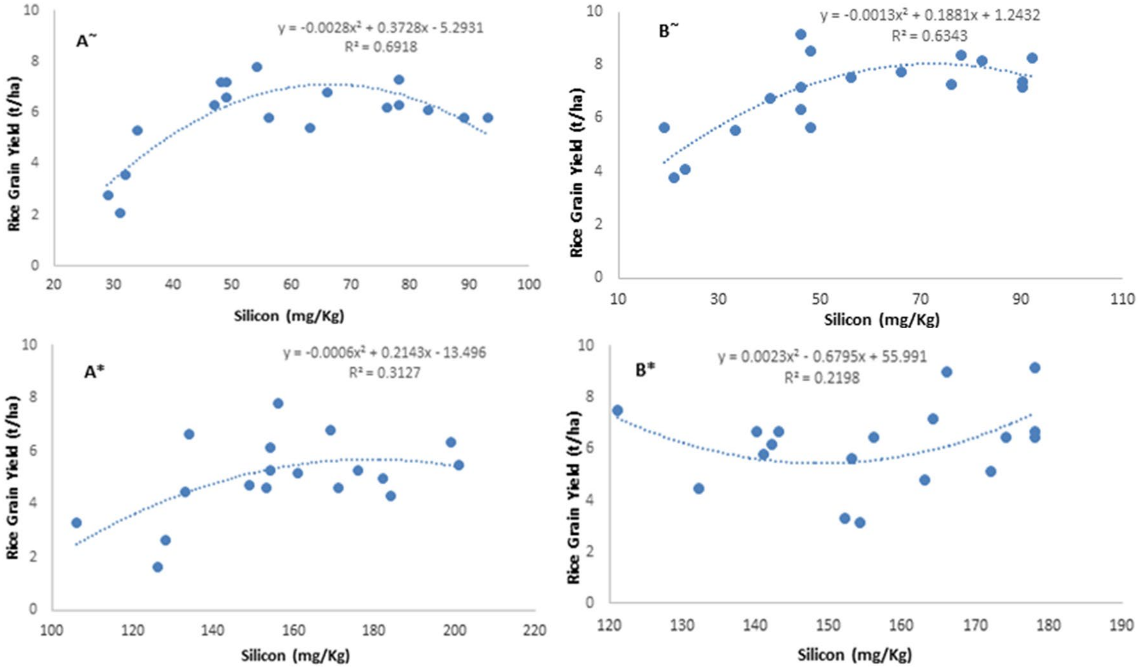

Fig. 1 Correlation between grain yield and soil bioavailable Si as affected by **a** RHA and **b** RHD at cropping seasons. $A^{\sim}$ and $B^{\sim}=2014$; A^{*} and $B^{*}=2015$ cropping season

grain yield than the farmers' growing environment in a 3-year study.

In 2014 cropping season, RHA applied at 10.0 t ha^{-1} had a significantly higher (6.62 t ha^{-1}) rice grain yield compared with the other RHA rates applied. Beyond 10 t/ha RHA application rates, there was significant reduction in rice yield. In 2015, the RHA applied at 7.5 t ha^{-1} had highest ($p < 0.05$) yield (6.93 t ha^{-1}). There was significant reduction in rice yield at increasing RHA application rates. For RHD, the highest yield (7.61 t ha^{-1}) was obtained at the application of 7.5 t ha^{-1} in 2014 and 5 t/ha in 2015. The yields obtained at these rates did not vary significantly with increasing RHD application rates. The regression analysis between the rice grain yield and soil available Si was significant at $p < 0.05$ (Fig. 1). Rice grain yields exhibited quadratic relationship with soil available Si. This result could suggest that the rates below 10 t ha^{-1} could be sufficient, although further long-time investigation is needed. The observed variations in the soil available Si in relation to rice grain yield across the two seasons following RHA and RHD application suggest that the treatments differ in their mineralization rate which resulted in the observed varied effect of rice grain yield (Klotzbücher et al. 2011). In addition to increasing soil NPK content, this study demonstrates that increasing the available Si of lowland soils can significantly improve rice yield.

Conclusion

The study evaluated the effects of RHA and RHD treatments on soil Si availability and other fertility indices on the growth and yield of rice in a *sawah*-based rice cropping system. Overall, RHA and RHD treatments had significantly higher yield compared with the unamended plot. For RHA, 5–7.5 t ha^{-1} application rate gave the highest rice grain yield while the highest yield from RHD was obtained between 10 and 12.5 t ha^{-1} application rates across the cropping seasons. The results obtained indicated that RHA and RHD application increased rice grain yield. These amendments can be a potential source of soil available Si and which can be replace mineral Si fertilizers which are costly and unaffordable to local smallholder rice farmers. Our investigations show that continuous rice-mill waste application can increase the soil available Si, other fertility index and consequently increase rice yield. The effect of rice-mill wastes on rice performance merits long-term studies to further understand the underlying mechanisms associated with Si release, mineralization and its subsequent uptake by rice plant in a *sawah* managed rice field and to ascertain the optimum bio-waste application rates to increase rice yield.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

References

Agbede OO, Kalu BA (1995) Constraints of small-scale farmers in increasing crop yield: farm size and fertilizer supply. Niger J Soil Sci 11:139–159

Bray RH, Kurtz LT (1945) Determination of total, organic and available forms of phosphorus in soils. Soil Sci 59:39–45

Bremner JM, Mulvaney CS (1982) Nitrogen-Total. In: Keeney DR, Nelson DW, Page AL (eds) Chemical and microbiological properties. American Society of Agronomy and Soil Science Society of America, USA, pp 595–624

Cornelis JT, Delvaux B (2016) Soil processes drive the biological silicon feedback loop. Funct Ecol 30(8):1298–1310. https://doi.org/10.1111/1365-2435.12704

Datta NP, Shinde JE (1985) Yield and nutrition of rice under upland and waterlogged conditions. Effect of nitrogen, phosphorus and silica. J Indian Soc Soil Sci 33:53–60

Ezeh HN, Chukwu E (2011) Small scale mining and heavy metals pollution of agricultural soils: the case of Ishiagu Mining District, South Eastern Nigeria. J Geol Min Res 3(4):87–104

Food and Agricultural Organization (1988) Soil map of the world: 1:5 million (Revised Legend). World Soil Resources Report, 60. Food and Agricultural Organization, Rome

Guntzer F, Keller C, Meunier JD (2012) Benefits of plant silicon for crop: a review. Agron Sustain Dev 32:201–213. https://doi.org/10.1007/s13593-011-0039-8

Hayashi K, Wakatsuki T (2002) Sustainable soil fertility management by indigenous and scientific knowledge in Sahel zone of Niger. In: CD- ROM transactions of the 17th World congress of soil science, symposium No. 15. Perceptions of soil management: matching indigenous and scientific knowledge systems, paper No. 1251

Hirose S, Wakatsuki T (2002) Restoration of inland valley ecosystems in West Africa. 56–86:222–2224. Association of agriculture and forestry statistics. Megro-Sumiya building, Tokyo

Imaizumi K, Yoshida S (1958) Edaphological studies on silicon supplying power of paddy fields. Bull Natl Inst Agric Sci [japan] Ser B Soils 8:261–304 (in Japanese with English summary)

Joardar JC, Rahman MM (2018) Poultry feather waste management and effects on plant growth. Int J Recycl Org Waste Agric. https://doi.org/10.1007/s40093-018-0204-z

Klotzbücher T, Kaiser K, Guggenberger G, Gatzek C, Kalbitz K (2011) A new conceptual model for the fate of lignin in decomposing plant litter. Ecology 92(5):1052–1062. https://doi.org/10.1890/10-1307.1

Klotzbücher T, Marxen A, Vetterlein D, Schneiker J, Türke M, van Sinh N, Manh NH, Chien HV, Marquez L, Villareal S, Bustamante JV, Jahn R (2014) Plant-available silicon in paddy soils as a key factor for sustainable rice production in Southeast Asia. Basic Appl Ecol 16(8):665–673. https://doi.org/10.1016/j.baae.2014.08.002

Klotzbücher T, Leuther F, Marxen A, Vetterlein D, Horgan FG, Jahn R (2015) Forms and fluxes of potential plant-available silicon in irrigated lowland rice production (Laguna, the Philippines). Plant Soil 16(8):157–165. https://doi.org/10.1007/s11104-015-2480-y

Lal R (2003) Influence of within and between row mulching on soil temperature, moisture, root development and yield of maize in a tropical soil. Field Crop Res 1:127–139. https://doi.org/10.1016/0378-4290(78)90016-3

Lehmann J, Joseph S (eds) (2009) Biochar systems for environmental management science and technology. Earthscan Books, London, pp 34–43

Li Z, Song Z, Cornelis JT (2014) Impact of rice cultivar and organ on elemental composition of phytoliths and the release of available bio-available silicon. Front Plant Sci 7(5):162–170. https://doi.org/10.3389/fpls.2014.00529

Liang YC, Sun WC, Zhu YG, Chrisie P (2007) Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants. A review. Environ Pollut 147:422–428. https://doi.org/10.1016/j.envpol.2006.06.008

Lickaz J (2002) Wood ash—an alternative liming material for agricultural soils. Agri-Facts, practical information for Alberta's agriculture industry. AGDEX 534-2, Alberta Agriculture, Food and Rural Development, p 6

Lima SPB, Vasconcelos RP, Paiva OA, Cordeiro GC, Chaves MRM, Filho RDT, Fairbairn EMR (2011) Production of silica gel from residual rice husk ash. Quim Nova 34:71–75. https://doi.org/10.1590/s0100-40422011000100014

Ma JF, Miyake YT, Takahashi E (2001) Silicon as a beneficial element for crop plants. In: Datnoff L, Snyder G, Korndorfer G (eds) Silicon in agriculture. Elsevier Science, New York, pp 17–39

Magale KDR, Andre LC, Daiane BB, Tiele MR, Luccelia AR, Gaspar HK, Ayrton FM (2011) Silica from rice husk ash as an additive for rice plant. J Agron 10(3):99–104. https://doi.org/10.3923/ja.2011.99.104

Makabe S, Kakuda KI, Sasaki Y, Ando T, Fujii H, Ando H (2009) Relationship between mineral composition or soil texture and available silicon in alluvial paddy soils on the Shounai Plain, Japan. Soil Sci Plant Nutr 55:300–308. https://doi.org/10.1111/j.1747-0765.2008.00352.x

Mbah CN, Njoku C, Okolo CC, Attoe E, Osakwe UC (2017) Amelioration of a degraded Ultisol with hardwood biochar: effects on soil physico-chemical properties and yield of cucumber (*Cucumis sativus* L). Afr J Agric Res 12(21):1781–1792. https://doi.org/10.5897/AJAR2016.11654

McLean EO (1982) Soil pH and lime requirement. In: Page AL, Miller RH, Keeny DR (eds) Methods of soil analysis, part 2. Am. Soc. Agron, Madison, pp 199–224

Meena VD, Dotaniya ML, Vassanda C, Rajendiran S, Ajay S, Kundu A, Subba R (2014) A case for silicon fertilization to improve crop yields in tropical soils. Proc Natl Acad Sci India Sect B Biol Sci 84(3):505–518. https://doi.org/10.1007/s40011-013-0270-y

Mukhtar A, Asif M, Goyal A (2012) Silicon the non-essential beneficial plant nutrient to enhanced drought tolerance in wheat crop plant. In: Goyal A (ed) crop plant. CBS Publishers & Distributors Pvt. Ltd, New Delhi. https://doi.org/10.5772/45647

Nelson DW, Sommers LE (1982) Total carbon, organic carbon, and organic matter. In: Methods of soil analysis. Part 2: chemical and microbiological properties. Agronomy Monograph no. 9 (2nd edition), pp 539–579

Nessa B, Rahman MM, Shammi M et al (2016) Impact of textile sludge on the growth of red amaranth (*Amaranthus gangeticus*). Int J Recycl Org Waste Agric 5:163–172. https://doi.org/10.1007/s40093-016-0126-6

Nwite JN, Okolo CC (2016) Soil water relations of an Ultisol amended with agro-wastes and its effect on grain yield of maize (*Zea*

Mays L.) in Abakaliki, Southeastern Nigeria. Eur J Sci Res 141(2):126–140

Nwite JC, Obalum SE, Igwe CA, Wakatsuki T (2011) Properties and potential of selected ash sources for improving soil condition and sawah rice yields in a degraded inland valley in Southeastern Nigeria. World J Agric Sci 7(3):304–310

Nwite JC, Essien BA, Anaele MU, Obalum SE, Keke CI, Igwe CA (2012) Supplementary use of poultry droppings and rice-husk waste as organic amendments in Southeastern Nigeria. 1: soil chemical properties and maize yield. Libyan Agric Res Center J Int 3(2):90–97. https://doi.org/10.5829/idosi.larcji.2012.3.2.538

Nwite JC, Essien BA, Keke CI, Igwe CA, Wakatsuki T (2016a) Effect of different land preparation methods for sawah system development on soil productivity improvement and rice grain yield in inland valleys of southeastern Nigeria. Adv Res 6(2):1–17. https://doi.org/10.9734/AIR/2016/20792

Nwite JC, Onunwa AO, Igwe CA, Wakatsuki T (2016b) Sawah rice farming eco-technology options for enhancing sustainable nutrient management and rice production in degraded inland valleys of southeastern Nigeria. Int J Plant Soil Sci 9(4):1–19. https://doi.org/10.9734/ijpss/2016/20783

Ojenyi SO (2000) Soil fertility management and plant nutrient source in Nigeria. In: Proceedings of the 30th annual conference of Agricultural society of Nigeria. Bauchi, pp 35–45

Okenmuo FC, Odii OU, Okolo CC (2018) Short-term amelioration of soil properties and maize yield enhancement using animal wastes in degraded hydromorphic soils of Southeastern Nigeria. J Soil Sci Environ Manag 9(6):91–97. https://doi.org/10.5897/JSSEM2018.0678

Seng V, Bell RW, Willet IR (2004) Amelioration of growth reduction of lowland rice caused by a temporary loss of soil-water saturation. Plant Soil 265:1–16. https://doi.org/10.1007/s11104-005-0694-0

Singh U, Singer K (2006) Effect of sulphur and zinc on yield and utilization of nutrients by wheat. Indian J Plant Physiol 29:219–224

Song Z, Wang H, Strong PJ, Shan S (2014a) Increase of available soil silicon by Si-rich manure for sustainable rice production. Agron Sustain Dev 34:813–819. https://doi.org/10.1007/s13593-013-0202-5

Song Z, Müller K, Wang H (2014b) Biogeochemical silicon cycle and carbon sequestration in agricultural ecosystems. Earth Sci Rev 139:268–278. https://doi.org/10.1016/j.earscirev.2014.09.009

Tavakkoli E, Lyons G, English P, Guppy CN (2011) Silicon nutrition of rice is affected by soil pH, weathering and silicon fertilization. J Plant Nutr Soil Sci 174:437–446. https://doi.org/10.1002/jpln.201000023

Unagwu BO (2014) Maize performance in a sandy loam ultisol amended with NPK 15-15-15 and poultry manure. Afr J Agric Res 9(12):1020–1024. https://doi.org/10.5897/AJAR2013.8313

Unagwu BO (2019) Organic amendments applied to a degraded soil: Short term effects on soil quality indicators. Afr J Agric Res 14(4):218–225. https://doi.org/10.5897/ajar2018.13457

Unagwu BO, Asadu CLA, Ezeaku PI (2013) Residual effects of organic and NPK fertilizers on maize performance at different soil pH levels. J Agric Vet Sci 5(5):47–53

Unagwu BO, Simmons RW, Rickson RJ (2019) Organic amendment and inorganic fertilizer addition: effect on soil nutrient, growth and yield of maize. Mid East J Agric Res 8(2):445–456

USDA (1998) Keys to soil taxonomy. Natural Resources Conservation Services, United States. Department of Agriculture, Washington, DC pp 36–66

Wakatsuki T, Buri MM, Fashola OO (2005) Ecological engineering for sustainable rice production and the restoration of degraded watersheds of West Africa. In: Proceedings of rice research conference, IRRI, pp 336–366

Walkley A, Black I (1934) An examination of methods for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 79:459–465