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Change in Soil Chemistry and Rice Yield under Mineral Fertilizer and Organic Amendment as Occurring in Second Order Valley of Guinea Savanna: Evidence of Nonsymptomatic Iron Toxicity of Rice

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Abstract

Iron toxicity is a widespread abiotic constraint limiting drastically rice production in lowland and, it is advocated to establish more reliable characteristics of this constraint overcoming the shortage of rice production. Three cropping cycles of rice were conducted as on-farm experiment (split-plot) including mineral fertilizer – MF (N. P, K. Ca, Mg and Zn) and organic amendment – OA (rice straw) treatments in order to observe rice yields (straw and grain) in relation with changes in soil chemistry. Yield decreasing (6.3 – 2.99 t ha^{-1} for MF and 4.2 – 2.65 t $ha^{-1}$for OA) was observed subsequently with impoverishment of soil chemistry (C, N, K, Ca, Mg and ECC) against increasing of soil contents of available P and iron (421.36 ppm-614.33 ppm) as well as its acidity. Soil concentration of Fe was significantly contributing to the decreasing trend of grain yield regardless of the treatments while isomorphic substitution was observed between soil contents of K and Fe under MF treatment resulting highest yield declining (50%). This process was limited under organic amendment further releasing P for yield stabilization. In the light of these finding, iron toxicity was characterized by K deficiency while no visual symptom was observed.

Keywords: Iron toxicity, rice, isomorphic substitution, potassium deficiency, phosphorus

1. INTRODUCTION

Chemical toxicity in lowland soils is a major constraint for lowland use sustainability (Hodomihou *et al*., 2011). Iron (ferric form) as the most concentrated element in tropical upland soil (Audebert, 2002), in particular as Oxisoils and Alfisoils, may be drained by sorption flow in soil or run off toward the bottom valley. The submersion occurring in this ecology will promote the reversibility of Fe^{3+} into reduced form as Fe^{2+} that can be uptake by rice (Chérif *et al*., 2009). Uptaken iron may be toxic for rice plant according to Fe^{2+} concentration in soil (Dramé *et al*., 2010).

Iron toxicity is known as a nutritional trouble of lowland rice (Fageria *et al*., 2008) often encountered in West Africa. The soluble iron as Fe^{2+} in soil solution is absorbed by the roots and accumulated in the leaves that are discolored (bronzing). Consecutively, there is growth reduction characterized by tiller number reduction and drastic depreciation of yield (Audebert *et al*., 2009) in a range of 30 – 80% (Koné, 2014).

From the above analysis, it is advocated to tackle iron toxicity in the lowland of Africa in a way of self-sufficiency in rice. In fact, this aversive physiological process is constraining the objective of Africa to promote the lowland as a food basket in the future (Mohapatra, 2016).

Tolerant varieties were developed (Gnago *et al.,* 2017; Dramé *et al.,* 2010) as well as cropping practices including land and water management (Ethan *et al*., 2011) with limited impact in space and time: seasonal sensibility and ecological difference were observed in iron toxicity management. Therefore, there is a need to continue the investigation to generate knowledge of iron toxicity in rice production in order to promote new sustainable strategy of management.

The current study is initiated in this line targeting the comparative effects of fertilizer and organic amendment on soil and rice yield in a second order valley in the Centre of Côte d'Ivoire. The study is volunteer to i) identify soil parameters involved in grain yield variability, ii) point out the contribution of soil concentration of iron in yield trend across cropping seasons ii) to underline change in soil and plant mineral compounds under iron toxicity process.

Overall, potential toxicity of iron should be characterized with recommendation of potential management strategy.

2. METHODS

2.1 Site description

An on-farm trial was conducted in the irrigable valley of M'be II (8˚06N, 6˚00W, 180 m) about 24 km from the locality of Bouaké. The site is semi-developed lowland in the centre of Côte d'Ivoire including irrigation facility with minimum land leveling and missing drainage channel. The ecology is a Guinea savanna zone with a bimodal rainfall pattern including a specific dry, cool and dusty period of *harmattan* (December- February). The average annual temperature, rainfall and evapo-transpiration were 28˚C, 1200 mm and about 100 mm respectively. Intensified rice-rice cropping is adopted by local farmers as two cycles per year with maximum yield of 3-4 t ha^{-1}. The experiment was conducted in a second order lowland (100 – 120 m in wide) developed on granite-gneiss bed-rock with Fluvisol characterized by pH_{water}, C-organic and total-N of 5.5, 3.12 g kg^{-1} and 0.31 g kg^{-1} respectively. The content of available P (Olsen) was high (150 mg kg^{-1}) contrasting with the low content of K (0.08 cmol kg^{-1}). High contents of Ca (3.05 cmol kg^{-1}) and Mg (2.26 cmol kg^{-1}) are also determined for a ECC (Exchangeable Cation Capacity) of 2.02 cmol kg^{-1}. The ratios of C:N and [(K:ECC)×100] account for 10.06 and 3.9%. A five years old fallow dominated by *Lersiahexandra* (Poaceae) and *Frimbristulis* spp (Poaceae) was preceding the experiment.

2.2 Characteristics of the rice cultivar

One of the popular lowland rice cultivar named NERICA L19 (New Rice for Africa Lowland 19) was used as interspecific (*Oryza glaberrima* × *Oryza sativa*) released by Africa Rice Center in 2008. Its relative high weight of grain is among the quality required by farmer in addition to its weed competitiveness resulting to its high vegetative growth. Panicle length is about 30 cm for a potential yield of 6 – 8 t ha^{-1} in research station. The cultivar is tolerant to iron toxicity with high performance of ratoon.

2.3 Nutrient sources

The straw of newly harvested rice was kept for sun drying during 3-4 weeks. Dried straw was weighted in the basis of 3, 6, 9, 12 and 15 t ha^{-1}. Straw concentrations of the studied nutrients are given in Table 1. Commercial mineral fertilizers were used as urea ($CO(NH_2)2$, 46% N), triple super phosphate ($Ca(H_2PO_4)2•H_2O$, 18–22% P), chloridic potassium (KCl ; 50% K), carbonate of calcium ($CaCO_3$; 40% Ca), sulfate of magnesium ($MgSO_4.H_2O$, 17% Mg) and sulfate of zinc ($ZnSO_4H_2O$, 36 % Zn).

2.4 Experiment design

About 1200 m^2 of bush fallow was manually cleaned and debris was taken out of the plot before setting the experiment. Forty-two (42) microplots of 3 × 5 m in individual dimension were laid and each of them was limited by 4 surrounding bounds with canals for irrigation and drainage. Different ratios (3 t ha^{-1}, 6 t ha^{-1}, 9 t ha^{-1}, 12 t ha^{-1} and 15 t ha^{-1}) of dried rice straw were laid randomly in specific microplot before applying slight irrigation. After a week period, the straw was incorporated in 0 – 20 cm depth of the soil during manual tillage for initial decomposition during two weeks. Mineral fertilizers were applied in the other plots: 30 kg N ha^{-1}, 60 kg P ha^{-1}, 50 kg K ha^{-1}, 50 kg Ca ha^{-1}, 50 kg Mg ha^{-1} and 10 kg Zn ha^{-1} as basal fertilizers. Mineral fertilizer treatment was composed of NPK, NPKCa, NPKMg, NPKZn, NPKCaMg, NPKCaZn and NPKCaMgZn. The plot with no fertilizer and no incorporation of straw accounted for the control treatment. The experiment was laid in a split-plot design (main plot: source of nutrients; sub-plot: rates). Twenty-one days old seedlings of NERICA L19 were transplanted per hill of two stands with 20 × 20 cm arrangement between rows and plants. At tillering and panicle initiation stages, hand weeding was done before applying 25 kg N ha^{-1} respectively. Except for the period of N application, the plot was maintained flooded with 3-5 cm water depth. The first trial started in April 2012 and it was repeated twice every six months.

2.5 Data collection

Soil was sampled in 0 – 20 cm depth before the trial using augur and this operation was repeated after each trial. The soil samples were dried, ground and sieved (2 mm) before the laboratory analyses were carried out. Soil pH water (1/2,5) and its contents of carbon-C (Wakley and Black), total nitrogen-N (Kjeldahl), exchangeable K, Na, Ca, and Mg (1 N NH_4OAc (pH 7.0)) were determined as described by the American Society of Agronomy-ASA and the Soil Sciences Society of America-SSSA described by Pages *et al*. (1996). Soil content of NH_4^+ was also determined accordingly. Fe-free was determined by the method of Tamm (1922).

Standard procedures for laboratory quality control of measurements, including the use of blanks, replicates and internal reference samples, were followed.

At maturity, rice was cut just above the soil surface in 8 m² per micro-plot by leaving two border lines. The rice was threshed and the grains and straw were separately dried and weighed. The moisture content of the grain was measured and grain yield (GY) was determined at a moisture content of 14%. Straw yield (SY) was also determined after the weighing.

2.6 Statistical analyses

Mean values of soil chemical compounds measured were determined by descriptive analysis for each cropping cycle. Using a general linear model analysis (GLM), the mean values of GY and SY were generated per cropping cycle for each treatment (MF and OA). Pearson correlation analysis was also done to expose the relation between soil measured chemical compounds and yield parameters (GY and SY). Similar investigation was also done considering fertilizer treatment apart from organic amendment. The mean values were separated using the least significant difference (LSD) at a threshold of α = 0.05. The analyses were performed using the SAS software package.

3. RESULTS

3.1 Soil chemistry during the experiment

Measured soil chemical parameters before and after trials are presented in table 2. We observed a slight variation of soil acidity roughly about 0.1 in a decreasing trend while soil contents of C and N show important depletion.

The measured values of soil contents in Ca and Mg during the study were also decreased about twice compared to the initial value, while increasing trend characterized the contents of P, Fe and the soil ECC. Soil content of K also varied about 0.01 cmol kg^{-1} to be lower than the initial value after the third cropping cycle.

Significant differences of soil pH and its content of K were observed exclusively during the cropping cycle 1: the pH was higher by about 0.13 under MF treatment than that of OA treatment while the content of K is lower by about 0.02 cmol kg^{-1} reversely (Table 3).

Although not significant, negative differences were observed for soil contents of Fe-free and NH_4^+ during the cropping cycle 1 and 2, meaning lower contents of Fe-free under MF treatment. Similar results were observed for soil content of exchangeable K during three cycles.

The relationship of soil chemical parameters is described in table 4. There is positive and significant correlation between N-total et NH_4^+ indifferently to nutrient sources, while significant correlations of P are limited to OA due to the negative (-0.50) value of soil pH and the positive one (0.73) occurring with Fe. Negative (-0.44) significant correlation is also observed between soil contents of K and Fe under mineral fertilizer treatment while the correlation values of ECC are positive and significant with Fe and NH_4^{+}. Significant and positive value (0.60) is also observed between ECC and NH_4^+ under organic amendment treatment.

3.2 Rice yield and soil chemistry

Figure 1 is presenting the mean values of rice grain yield as recorded for mineral fertilizer (MF) treatments and for organic amendment (OA) respectively.

The yields recorded for MF were higher than that of OA during the first and second cropping seasons while they were almost similar during the third one with 2.99 t ha^{-1} (MF) and 2.65 t ha^{-1} (OA): there was significant difference between mean values from a cropping cycle to another with more pronounced decreasing trend for the mineral fertilizer treatments against observation of stable values of yield between the second cropping duration and the others (1 and 3).

According to the data recorded in the table 5, we have positive and significant correlation between rice grain yield (GY) and soil pH almost similarly to the straw yield (SY).

In the meantime (Table 5), we have highly significant negative correlation (-0.48) between soil content of Fe and grain yield while similar correlation (-0.32) accounts for the straw yield and soil content of NH_4^+ while no significant correlation is observed for N-total. Yet, table 6 shows that rice grain yield may be decreased by soil iron concentration only for mineral fertilizer treatment.

Table 1. Rice straw concentrations of N, P, K, Ca, Mg and Zn

Nutrient	Mean	Standard deviation (n=36)
N (gkg^{-1})	7.8	2.1
P (gkg^{-1})	0.8	0.3
K (gkg^{-1})	26.8	4.5
Ca (gkg^{-1})	3.0	0.7
Mg (gkg^{-1})	2.0	0.6
Zn (gkg^{-1})	0.12	0.07

Table 2. Soil chemistry as measured before and after each of the three cropping cycles

	Before ǂ	After cycle 1	After cycle 2	After cycle 3
pH_{water}	5.5	5.68 ± 0.312	5.42 ± 0.235	5.44 ± 0.235
C-org(g kg^{-1})	3.12	0.86 ± 0.222	0.95 ± 0.262	0.91 ± 0.319
N (g kg^{-1})	0.31	0.08 ± 0.021	0.09 ± 0.022	0.08 ± 0.022
P-available (ppm)	15	16.77 ± 7	17.36 ± 5	18.00 ± 5
Ca (cmol kg^{-1})	3.05	1.99 ± 0.478	2.13 ±0.381	1.83 ± 0.615
Mg (cmol kg^{-1})	2.26	1.42 ± 0.203	1.78 ± 0.156	1.27 ± 0.417
K (cmol kg^{-1})	0.08	0.07 ± 0.013	0.09 ± 0.011	0.06 ± 0.023
Fe_2O_3-free (ppm)	_	1207± 209	1353 ± 319	1789 ± 315
ECC (cmol kg^{-1})	2.02	8.35 ± 2.803	9.08 ± 2.116	9.07 ± 2.239

Table 3. Mean difference of soil pH and its contents of P, K, Fe_2O_3-free and NH_4^+ comparing mineral and organic sources of nutrients (treatment) during a cropping cycle

Cropping cycle	Treatment	Difference	Pr > |t|
		pH	
Cycle 1	MF-OA	0.13	0.021
Cycle 2	MF-OA	-0.07	0.600
Cycle 3	MF-OA	0.11	0.410
		NH_4^+	
Cycle 1	MF-OA	-0.10	0.141
Cycle 2	MF-OA	-0.10	0.117
Cycle 3	MF-OA	0.05	0.382
		Fe	
Cycle 1	MF-OA	-42.95	0.793
Cycle 2	MF-OA	-137.60	0.389
Cycle 3	MF-OA	151.49	0.344
		P	
Cycle 1	MF-OA	1.92	0.467
Cycle 2	MF-OA	4.29	0.110
Cycle 3	MF-OA	0.11	0.984

		K	
Cycle 1	MF-OA	-0.02	0.021
Cycle 2	MF-OA	-0.01	0.155
Cycle 3	MF-OA	-0.01	0.185

Table 4. Correlation of soil contents of N, P, K and ECC in relation to its pH and contents of Fe and NH_4^+ under different sources of nutrients

			Mineral fertilizer					
	N ($g\ kg^{-1}$)		P (ppm)		K ($cmol\ kg^{-1}$)		ECC ($cmol\ kg^{-1}$)	
	R	Pr. > |r|	R	Pr.> |r|	R	Pr > |r|	R	Pr > |r|
Ph	0.065	0.769	0.13	0.549	0.056	0.795	0.17	0.430
Fe-free (ppm)	0.26	0.225	-0.06	0.791	-0.42	0.044	0.41	0.050
NH_4^+($g\ kg^{-1}$)	0.71	0.000	0.09	0.691	0.09	0.688	0.74	<.0001
			Organic Amendment					
pH	0.20	0.423	-0.50	0.036	-0.08	0.747	0.03	0.897
Fe_2O_3-free (ppm)	0.03	0.887	0.73	0.001	-0.34	0.171	0.24	0.344
NH_4^+($g\ kg^{-1}$)	0.79	<.000	0.41	0.088	0.22	0.388	0.60	0.009

R : Correlation coefficient ; Pr > |r| : Probability

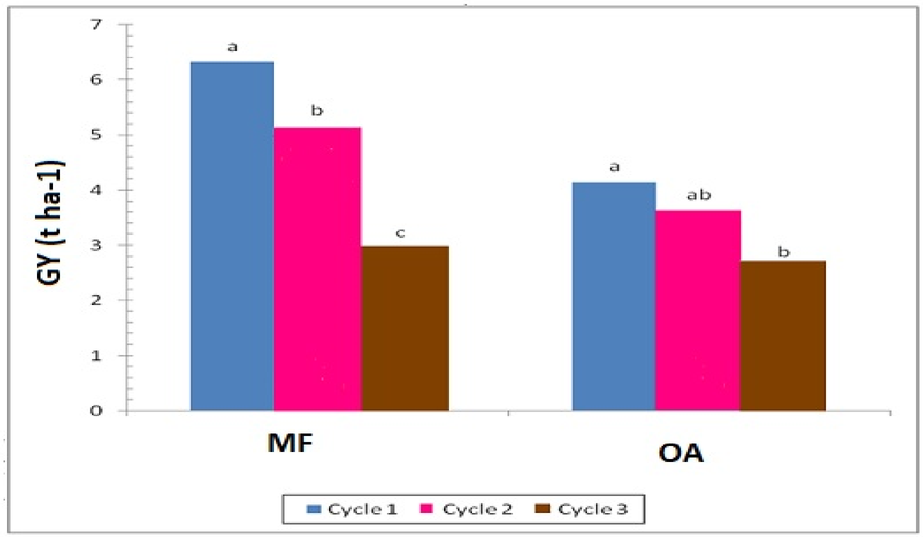
Table 5 . Correlation of rice grain yield (GY) and straw yield (SY) referring to soil measured chemical parameters

	GY		SY	
	Pr > |r|	R	Pr > |r|	R
pH	0.33	0.036	0.34	0.028
P-avail (ppm)	0.19	0.229	0.20	0.207
ECC (cmol kg^{-1})	-0.09	0.557	-0.13	0.410
Ca^{2+} (cmol kg^{-1})	0.19	0.219	-0.07	0.669
Mg^{2+} (cmol kg^{-1})	0.22	0.165	-0.21	0.184
K^{+}(cmol kg^{-1})	0.17	0.284	-0.08	0.598
Na^{+}(cmol kg^{-1})	0.20	0.207	-0.25	0.112
Fe_2O_3-free (ppm)	-0.48	0.001	-0.16	0.301
Mn (ppm)	0.11	0.494	0.03	0.858
Cu (ppm)	0.07	0.639	0.06	0.713
C-org (g kg^{-1})	-0.14	0.382	-0.17	0.296
N (g kg^{-1})	-0.14	0.372	-0.21	0.194
NH_4^+ (g kg^{-1})	-0.26	0.093	-0.32	0.044

R : Correlation coefficient; Pr > |r|: Probability

Table 6 . Multiple regression of grain and straw yields with soil parameters

	GY			
	MF		**OA**	
	Coefficient	**Prob.**	**Coefficient**	**Prob.**
Constant	-3.56	0.594	10.69	0.200
pH	1.92	0.123	-0 .71	0.609
Fe_2O_3-free (ppm)	-0.00	0.003	-0.00	0.1810
NH_4^+(gkg^{-1})	5.92	0.171	-1.43	0.611
	SY			
Constant	-22.66	0.088	14.64	0.374
pH	6.35	0.012	-0.86	0.757
Fe_2O_3-free (ppm)	0.00	0.860	0.00	0.899
NH_4^+ (g kg^{-1})	-10.14	0.220	-7.49	0.196



Letters a, b and c are indicating the mean values with significant difference for α = 0.05; GY: grain yield; MF: mineral fertilizer; OA: organic amendment

Figure 1. Average grain yield for mineral fertilizer (MF) and organic amendment (OA) during the three cropping cycles (1, 2 and 3).

4. DISCUSSION

4.1 Valley suitability for rice cropping

Increase in soil contents of available P and iron oxide (Fe_2O_3) was observed coupled with global impoverishment of measured soil chemical parameters. The increase of soil content of Fe_2O_3 is likely an hint of iron toxicity (ADRAO, 2006; Fageria *et al*., 2002; Zro Bi *et al*., 2012) while it was not yet identified during previous studies (Konan, 2013; Akassimadou *et al*., 2014) in absence of symptom and soil data. Yield decreasing was observed across the three cropping cycles of current study. This observation was coupled with increasing of soil content of Fe_2O_3. In fact, soil content of Fe_2O_3 increased within the period of the three cropping cycles from 1206.65 ppm to 1788.36 ppm corresponding respectively to 421.36 ppm and 614.33 ppm of atomic Fe while, Koné (2014) indicated 300 ppm of atomic Fe as the threshold value for iron toxicity of rice. Therefore, we have a prove of the tolerance of NERICA L19 to iron toxicity as abiotic constraint regarding the yield (6.3 t ha^{-1}), harvested during the first cropping season while prevailing soil content of Fe over 300 ppm. Nevertheless, this constraint was likely limited under organic amendment practice since yield reduction across cropping cycles reached 50%. Hence, current finding is revealing a weakness of NERICA L19 which should be tackled by further study in a way of managing iron toxicity.

Over all, soil acidity was observed (pH<5.5) coupled with low contents of organic carbon (C), nitrogen (N) and potassium (K) somewhat differing to the moderate levels of phosphorus (P) and magnesium (Mg) resulting potential deficiencies in

N and K in studied agro-system. Yet, Konan (2013) underlined the importance of Mg for optimizing N nutrition of rice in addition to the response to P supplying during the work done by Akassimadou *et al.,* (2014). Consequently, fertilizer recommendation may be NPKMg for rice production in the valley of M'bé II (studied location) and by extension in similar valleys of second order in Centre Côte d'Ivoire.

4.2 Diagnosis of yield decreasing

Yield decreasing was observed with ongoing soil chemistry (C, N, K, Ca, Mg and ECC) impoverishment and increasing soil acidity. Meanwhile, increasing soil contents of P and Fe-free were observed likely for NH_4^+. Nevertheless, significant influence of soil chemistry on rice yield (GY) was limited to that of soil pH and its contents of Fe-free and NH_4^+: positive influence of soil pH on GY was observed contrasting with that of Fe-free and NH_4^+ in line of previous studies (Koné *et al*., 2009) supporting the effect of soil acidity on nitrogen availability for plant nutrition especially concerning NH_4^+ (Paillat, 2007) and the occurrence of iron toxicity in the studied agro-system.

More screening of these findings may point out the negative effect of soil content of Fe^{2+}, when inducing the decrease of rice grain yield (GY) and soil content of exchangeable K^+, under the treatment MF somewhat described by the multiple regression of grain yield. This parallelism may have sense when asserting isomorphic substitution (Jad, 2005) between K and Fe keeping K out of the soil cation exchangeable site while, this nutrient is essentially available for plant nutrition as exchangeable cation (Dunn and Stevens, 2005; Koné *et al.,* 2014). Therefore, the occurrence of iron toxicity in the studied agro-system is different from that previously described by Dufey *et al*. (2012) resulting from high concentration of iron in plant above ground biomass: disturbance of K uptake by the root of rice is characterizing the observed iron toxicity in absence of leaf symptoms. Thought K was already known to be involved in the occurrence of this constraint (Becker and Asch, 2005), its contribution was not established so far at sol-plant interaction. Definitively, the current study is supporting eluviation effect of K supplying on iron toxicity as suggested by Li *et al.,* (2015). Potassium requirement for the control of iron competition may be determined by calculation of K-nutrition index (Justes *et al*., 1997) of growing rice instead of basal fertilizer as currently practiced. Data of tillering and boosting stages may be compulsory for this innovative practice.

Well, there is evidence of the cause of yield declining under mineral fertilizer treatment while it may be more complex to be understood under organic amendment. In fact, the decreasing trend of yield occurred under OA was not significant in spite of the associated increase of soil content of Fe likely due to an elevation effect of added organic matter. Therefore, least decreasing of yield across cropping seasons was observed while, no significant difference of soil content of Fe was recorded between both nutrient sources (MF and OA). This elevation potential of OA may be relative to the increase of soil content in P due to the positive significant correlation between soil P and Fe. In fact, $P_2O_4^{2-}$ may be immobilized as $P_2O_4^{2-}(Fe^{2+})$ while the organic matter can react with this complex as $RCOO^-$ replacing $P_2O_4^{2-}$, hence, releasing P in soil solution while immobilizing Fe-free as $RCOO^-(Fe^{2+})$ as total iron (Tamm, 1992; Sorho *et al*., 2013). Regarding P importance in rice nutrition (Koné *et al.*, 2010), this process may have induced more stable grain yield under OA treatment during the 2nd and 3rd cropping cycles while controlling iron adverse effect by reducing its reactivity by K. This assertion is in line with the recommendation of organic matter application for iron toxicity management as promoted by some authors (Prade *et al*., 1989).

Overall, the current study revealed that the occurrence of iron toxicity was essentially induced by the displacement of exchangeable K from exchangeable site, hence, remaining deficient for rice nutrition. Therefore, iron toxicity may occur due to potassium deficiency or high concentration of iron in plant tissues. The current study revealed more declining trend of rice grain yield under mineral fertilizer which was more prone to iron toxicity. No visual symptomatic iron toxicity was identified as K deficiency due to Fe reaction in soil instead of high concentration of Fe in plant tissues. Although rice grain yield was limited during early cropping cycle under organic amendment, this practice was more of interest for sustaining rice production with more stable yield mainly by increasing soil content of available P and immobilizing Fe.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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