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Determination of Kaolin Optimum Dose to Inhibit Iron Toxic Effect on Rice Plant in Lowland Rice Cultivation

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

In tropical areas, lowland rice cultivation with or without water control is often faced with iron toxicity constraint. This problem causes a drop of the rice grain yield when the iron concentration in soil solution is more than 300 ppm. To resolve iron toxicity problem, drainage and fertilizers as industrial silicon applying have been recommended. However, the used of industrial silicon is not adopted by the farmers because of his high cost and his accessibility. Kaolin contains 54.7% of SiO_2 the aim of

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this research is to explore the potential of kaolin as a natural substitute of industrial silicon. A pot test was carried in 900 ppm iron toxicity condition. of Fe^{2+} the condition out for two successive rice cultivation cycles by applying 900ppm of Fe^{2+}. Five kaolin treatments were analyzed (T0 = 0, T1 = 366, T2 = 735, T3 = 1097 and T4 = 1465 kg kaolin ha^{-1}) in a complete randomized block design with 5 repetitions. The dose of 366 kg ha^{-1} reduced the symptoms of iron toxicity on rice plant. kaolin applying improved the grain yield of rice (0 tha^{-1} to 1.8 tha^{-1}). The dose of 1465 kg kaolin ha^{-1} gave the best grain yield (1.08 t ha^{-1}). The response of rice to kaolin doses was an equation RDG = 0.98 ×Dose more linear than quadratic and the dose of 1465 kg kaolin ha^{-1} was recommended as the optimal dose in the conditions of 900 ppm Fe^{2+}.

Keywords: Kaolin; iron toxicity; lowland; rice cultivation; response curve; Côte d'ivoire.

1. INTRODUCTION

Rice is the main food for more than half of the world's population (Nguu, 2004). In sub-saharan africa, the need for rice is increasingly growing. in fact, local production is struggling to meet demand due to several factors, including iron toxicity. This nutritional disorder appears in rice plants when the concentration of iron in the soil solution reaches the threshold of 300 ppm (Akassimadou et al., 2014). The iron toxicity manifests itself in plants through stunted growth, browning of leaves and reduced yields. the solution proposed by research is drainage and the use of fertilizers such as industrial silicon ((Epstein, 1994, Ma et al., 2001, Gerami & Rameeh, 2012). however, the yield of lowland rice depends on the level of water in the rice-growing plot. also, the cost of industrial silicon far exceeds the financial income of rice growers. kaolin is a clay that contains up to 54.7% SiO_2 (Kim et al., 2002, Ma, 2004). It has been mined in an artisanal way since 1960 in the south of Ivory Coast, and is only used for body painting during ceremonies or in traditional medicine, because of its therapeutic virtues. Only a small quantity is used in the paint industry (Kouadio, 2008).

In Côte d'Ivoire, the rice deficit amounts annually to 750,000 tons of milled rice (Sehi, 2021) while good practice in the lowlands could increase yields by 50%. This is why we should face the most widespread constraint which is iron toxicity in the lowlands. Audebert and Fofana (Audebert & Fofana, 2009) tested the effect of zinc fertilizers in the Korhogo lowlands as well as that Sanogo (Sanogo et al., 2010) in the Gagnoa lowlands. with the current rise in the cost of chemical fertilizers and its corollary of water pollution and soil acidification, the use of kaolin would be a good alternative given its rapid dissolution in water (Sehi, 2021). There are kaolin deposits almost everywhere in Côte d'Ivoire, including that of Bingerville in the south of Côte d'Ivoire. Bingerville kaolin (54.7% SiO_2) can serve as a natural source of silicon in rice cultivation. The oxidative power of Si in the rice rhizosphere should lead to the conversion of ferrous ion to ferric ion. It is for this purpose this research activity was carried out to analyze the effect of kaolin on rice yield parameters and determine the optimal dose of kaolin for a better response of rice under iron toxicity conditions.

2. MATERIALS AND METHODS

2.1 Experiment Site

The study took place at the experimental site of Félix Houphouet-Boigny University located in the town of Bingerville at 05°21'25.6''N 03°54'11.5''W at 2 m of altitude in the south of Côte d'Ivoire during two successive rice cultivation cycles. The temperature of this site is 26.05 °C with an annual rainfall average of 2008.8 mm (Traoré et al., 2016).

2.2 Experiment Pot and Growing Substrate

This research was carried out in a greenhouse in plastic pots with a surface area of 706.5 cm^2 at the opening, 30 cm in upper diameter, 20 cm in lower diameter and 40 cm in height. Sand (quartz grains) colluvium by runoff was used as culture substrate. This sand was sieved using a 2 mm sieve in order to eliminate other elements, like organic and coarse particles. Then, it was washed with tap water several times until a clear supernatant was obtained before being dried in an oven at a temperature of 120°C for 24 hours, then 5 kg of this sand were took to fill the pots.

2.3 Plant Material

With a cycle of 120 days, an average yield of 6 t ha^{-1} with a potential of 10 t ha^{-1}cycle, WARA-IITA 9 was used as plant material. The paddy grains of this variety are long and fine. The characteristics are presented in the Table 1.

Table 1. Characteristics of the WARA-IITA 9 variety

Parameters	
Height (cm)	92 cm
Tillers / m^2	205
Flowering 50 % time (day)	80 à 85
Potential yield	10 t ha^{-1}
Grain lenght	3.5 mm
Iron toxicity	sensitive
Genetic Parents	IR 2042-178-1 x CT 19

2.4 Inputs and Source of Iron

Kaolin from Bingerville deposit (130g) was used as silicon source after drying during 24 hours at 120°C in an oven. Monohydrate iron sulfate (FeSO4 H2O) (112 g) was used as iron source to create the iron toxicity (900 pp/pot). Triple super phosphate (Ca(H2PO4), 2H2O) (114 g), of chloride of potassium (K2OCl) (50g) and of urea ((CO(NH2)2) (61 g) were used as fertilizer applied at doses of 60 kg P ha^{-1}, 60 kg K ha^{-1} and 80 kg N ha^{-1} respectively.

Table 2. Characteristic of Bingerville kaolin (Kouadio, 2008)

	Oxides	Mass percentages
Main oxides	SiO_2	54.7
	Al_2O_3	36.80
	Fe_2O_3	5.32
	MgO	0.26
	MnO	0.03
	K_2O	1.26
	CaO	0.02
	TiO_2	1.18
	P_2O_3	0.10
	Na_2O	0.29
Characteristic mineral	kaolinite	
Secondary mineral	quartz, micas, feldspars	
Color	Pink (5YR 7/3)	
Family	Phyllosilicate 1:1	

2.5 Calculation of the Quantity of Silicate (SiO_2) and Iron

Bingerville kaolin contains 54.7% silicate (SiO_2). However, According to sehi, (Sehi, 2021), an average of 200 kg ha^{-1} of SiO_2 is required to resolve deficiency and disease problems in rice cultivation. The pots used in our work having a surface area of 1413 cm^2, the corresponding quantities of kaolin and iron sulfate were calculated according to the following formulas:

> Q kaolin = (pot surface area × dose) / conversion coefficient, the surface area being expressed in m^2 and the dose in kg ha^{-1}.
> Q iron sulfate = (M iron sulfate x total dose per pot) /M iron

The quantity of iron sulfate provided to reach 900 ppm is 13.66 g. This quantity was calculated taking into account that the molar mass of iron sulfate is 170 g mol^{-1} for a molar mass of iron of 56 g mol^{-1}. 1 ppm is equivalent to 1 mg kg^{-1} so for a pot containing 5 kg of sand, you need 4500 mg of Fe for the dose of 9070

$Q900ppm= (170 \times 4500.10^{-3}) /56 = 13.66$ g.

2.6 Treatments

Five treatments were analyzed counteract iron negative effect. There are

- T0 (control): 0 g of kaolin
- T1: 5.16 g of kaolin
- T2: 10.33 g of kaolin
- T3: 15.49 g of kaolin
- T4: 120.66 g of kaolin

Used in a completely randomized complete block design with treatments and five repetitions.

2.7 Experimental Device

Two pot tests were carried out consecutively using the same practices. WITA 9 rice variety which sensitive to iron toxicity was used as plant material. The dry sand (5kg) was mixed with iron sulfate (13.66 g) and 21 day old plants were transplanted into pots at the rate of one plant per pot placed in a hole dug in the center of each pot. The nitrogen supply was divided into two urea contributions, i.e. 0.5 g at tillering and 0.5 g at the panicle heading stage. The pots were kept flooded with a water height of approximately 3 cm above the surface of the substrate, condition favorable for maintaining the iron in the form Fe^{2+}.

Table 3. Quantities of kaolin and their content in SiO_2

Doses of SiO_2 (kg ha^{-1})	Quantity of kaolin (g)	Dose of kaolin (kg ha^{-1})
200	5.16	366
400	10.33	736
600	15.49	1097
800	20.66	1465

Test

2.8 Data Collection

At 30, 75, 90 and 120 days after transplanting, an iron toxicity rating was carried out according to the standard method for evaluating rice systems of the International Rice Research Institute (IRRI). At maturity, the panicles number, the average panicle length, the average number of full and empty grains per panicle were determined per pot. After harvest, the grain and straw yield were determined per pot and for each treatment.

To determine the effect of kaolin on the soil and rice roots. At 30 and 60 days after sowing, a rice plant was dug up from each pot for notations of hue (Hue), purity of hue (Chroma) and luminance of hue (Value) using of a Munsell code.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Effect of kaolin on Iron toxicity parameters

Table 4 presents the average values of the iron toxicity score on the rice plant. We see that the highest iron toxicity score (9) on plants and leaves was obtained with treatments T0, while T3 and T4 have the lowest score (1). Additionally, there is a significant difference between the four treatments. Kaolin applying had a very significant effect on the iron toxicity score, both on the leaves and on the plant. There is a very significant difference between the number of browned plants and T4 has the lowest number of browned plants as well as that of empty grains per panicle. Treatments T3 and T4 had practically the same effect on the parameters considered. Kaolin applying had a very significant effect on the number of browned plants and the number of empty grains per panicle.

3.1.2 Effect of treatments on agronomic parameters

The results recorded in Table 5 is the yield parameters average values by treatment. panicle length remains practically identical for all treatments. However, the grains number on the panicle varies by treatment. T3 gives the highest number on the panicle compared to a higher number of empty grains (20 grains) in the T1 treatment. The grain yield of 1.08 t ha^{-1} was obtained with treatment.

Table 4. Average values of Iron toxicity parameters measured

	Plant score	Score sheet	Browned	Yellow	Nber of Gr.V/pani
T_0	9a	9a	-	**-**	**-**
T_1	5b	5b	11a	1a	13a
T_2	3c	3c	9a	0,9a	15a
T_3	1d	1d	3b	0,1a	13a
T_4	1d	1d	1b	0a	11a
ppds.05	0	0	-	-	3,02
MG	3.60	3.60	6.07	0,48	16.79
CV (%)	0	0	44.46	198.63	13
P>F	<0.0001	<0.0001	<0.0001	0.08	0.16

Browned. = Browning, Juni.: Yellowing Nber: Number, Gr. V: Empty grain, Pani: Panicle MG: general average, CV: coefficient of variation, P: probability NB: The averages of a column followed by the same letter are not statistically different by the Newmann-Keuls test at the 5% threshold

Table 5. Yield parameters average values by treatment

Test	parameters	T_0	T_1	T_2	T_3	T_4
	Panicle length (cm)	-	25.3±0.7	24.7±0.7	28.6±0.7	26.9±0.7
	Number of grains per panicle	-	148±9.2	162±9.2	198±9.2	187±9.2
	Number of empty grains / panicles	-	20±0.6	14±0.6	11±0.6	10±0.6
	Number of panicles/pots	-	19±0.3	14±0.3	16±0.3	17±0.3
	Straw/pot yield (t ha-1)	-	1.20±0,02	1.44±0.02	3.60±0.02	3.42±0.02
	Grain/pot yield (t ha-1)	-	0.18±0.01	0.53±0.01	0.63±0.01	1.08±0.01

-: *undetermined; ±: standard deviation*

Table 6. Agronomic parameters Average values

	Nber. Grain /pan.	Nber. Empty grain /Pan.	Grain yield (tha^{-1})	Straw yield (tha^{-1})
T0	138a	14b	1.26a	4.62a
T1	144a	13b	1.26a	4.61a
T2	153ab	13b	2.44ab	5.33a

	Nber. Grain /pan.	**Nber. Empty grain /Pan.**	**Grain yield (tha^{-1})**	**Straw yield (tha^{-1})**
T3	179b	11b	4.67b	8.28b
T4	176b	9a	4.70b	8.43b
CV (%)	11.08	20.18	24.68	12.65
MG	89.02	12	3.58	6.25
ppds.05	**0.005**	**0.0004**	**0.001**	**<0.0001**

Nber: Number; Pan.: panicle, MG: General average

3.1.3 Determination of the optimal dose of kaolin

3.1.3.1 Kaolin dose response curve

Table 7. Characteristic of the linear regression of grain yields following the doses of kaolin

	Regression	**DDL**	**Sum of squares**	**R^2**	**P>|r|**
TEST	Linear	1	3.61	0.79	0.005
	Quadratic	1	0.29	0.06	0.004
	Product	0	0	0.00	-
	Total model	2	3.90	0.74	0.0001

DOF: Degree of freedom; R2: coefficient of determination; P: probability

Table 8. Quadratic regression of yield in trial 1

	Parameters	**DOF**	**Coefficient**	**P>|r|**
	Constant	1	0,05	0,47
Test	Dose	1	0,001	0,0001
	$Dose^2$	1	$-4{,}80.10^{-7}$	0,004
	Critical value	1,04		
	Optimal dose (unit)	496,99		

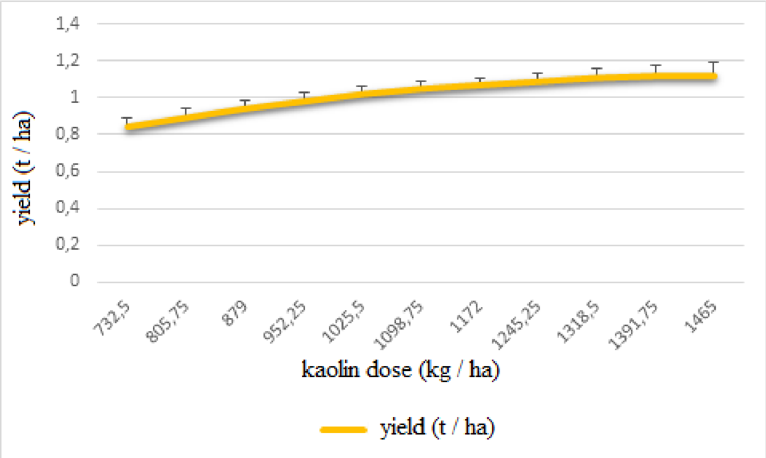

Fig. 1. Regression curve of rice response surface to increasing doses of kaolin (Error bar = standard deviation)

The characteristics of the response of rice to doses of kaolin are represented in Tables 7 and 8 and in

The equation obtained for the response of rice to doses of kaolin is

$$Y = 1.04 \times X.$$

We note a linear pattern in the response of rice to doses of kaolin (Fig. 1).

Tables 7 and 8 reveal that the linear pattern of the rice response is highly significant (p = 0.005 and R2=0.79) as is the quadratic pattern (p=0.004) but with a low value of R2= 0.06 (Table 7). The response curve shows the absence of significant difference between the yields of doses of 1391.75 kg ha^{-1} (1.12 ±0.06 t ha^{-1}) and 1465 kg ha^{-1} (1.12±0.07 t ha^{-1}). This makes it possible to adjust the optimal dose to 1496.99 kg ha^{-1} of kaolin as noted in Table 8.

Table 9. Rice plant root colour evolution after 30, 75 and 120 days after sowing

	Hue	Chroma	value
30 jours semis			
T0	5YR	1	8
	5YR	8	6
T1	5YR	1	8
	5YR	8	7
T2	5YR	1	8
	5YR	6	7
T3	5YR	1	8
	5YR	3	8
T4	5YR	1	8
	5YR	6	5
75 jours après semis			
T0	5YR	1	2.5
T1	5YR	1	3
	5YR	1	2.5
T2	5YR	1	8
	5YR	1	4
T3	5YR	1	8
	5YR	3	3
T4	5YR	1	8
	5YR	3	3
120 jours après semis			
T0	5YR	1	2.5
T1	5YR	1	3
	5YR	1	2.5
T2	5YR	1	8
	5YR	1	4
T3	5YR	1	8
	5YR	3	3
T4	5YR	1	8
	5YR	3	3

Table 9 shows the evolution of rice plant root colour after 30, 75 and 120 days after sowing. We that very not variation of the Hue (5YR). In each of the treatments. However, the change is in purity (Chroma) and clarity (Value).

3.2 DISCUSSION

This study confirmed the sensitivity of Wita 9 to iron toxicity and identified the symptoms of iron toxicity on the rice plant, as well as kaolin's ability to inhibit the effect of iron toxicity on the rice plant. In addition to yellowing, leaf browning and grain sterility, the known symptoms of iron toxicity, root necrosis was observed in the rice plant. Indeed, in rice plants, in addition to the characteristic symptoms of bronzing and/or yellowing of leaves, iron toxicity also results in a reduction in rice growth (height and tillering) and an increase in panicle sterility (Gbeto et al., 2015, (Sehi, 2021) (Sehi et al., 2024). In addition to affecting the aerial part of the rice plant, toxicity also affects root development. Indeed, iron toxicity leads to root necrosis in the rice plant (Sehi et al. 2024). This root necrosis is reflected in variations in root color. The white color (5YR8/1) of the roots at 30 days after sowing in the T0 treatment changed to black (5YR2.5/1) at 75 and 120 days after sowing. The high concentration of iron inhibits the formation of new roots. Indeed, the high accumulation of $Fe2+$ ions in contact with the roots prevents the plant from absorbing nutrients such as P, whose deficiency weakens the plant's energetic state, and K, whose deficiency leads to the accumulation of monomeric carbonaceous substances in the plant's sap (Abdolzadeh et al., 2010). The deficiency of these two major elements in plant nutrition leads to an increase in exudation from the plant root, creating a favorable environment for the activity of iron-reducing microorganisms in the rhizosphere (Bongoua, 2009). Also, the absence of Ca in our culture medium could be a factor in the high $Fe2+$ uptake, as Ca deficiency is known to increase cell membrane permeability (Kilian, 2022). The 5YR3/1 and 5YR8/1 colors observed from kaolin inputs in treatments T1, T2, T3 and T4 at 75 and 120 days after sowing testify to root survival and the appearance of new roots under conditions of iron toxicity. The rice plant has a natural barrier against toxicity (Sehi, 2021) which, however, was breached in the control treatment. This barrier was progressively reinforced with the addition of kaolin, as shown by the progressive reduction in toxicity symptoms with increasing doses of kaolin, until they disappeared in treatments T3 and T4. The oxidation of reduced (Ducos, 2022) Iron at root level enabled the uptake of nutrients, which in the control treatment (T0) were not absorbed by the plant despite being available in the growing medium. Phosphorus uptake led to the appearance of new roots. In fact, the addition of phosphorus to a growing medium stimulates root elongation in plants (Da silva et al.2016, (Sehi et al. 2024). This root development is correlated with rice grain yield. The response curve for increasing doses of kaolin shows that rice grain yield increases linearly with the kaolin dose. One might think that the kaolin dose could always be increased to reach a peak in yield. However, there was no significant difference between the yields obtained with the 1097 and 1465 kg doses. Also, iron toxicity symptoms disappear 100% with the 1097 kg kaolin/ha dose. The optimum dose of kaolin could therefore be set at 1097 kg kaolin/ha versus 1176 kg SiO2 ha-1 chemical (Datnoff et al., 1997). The current cost of chemical silicon is US$5/kg, i.e. 3,528,000 FCFA for the 1176 kg chemical SiO2 ha-1, whereas with kaolin it would cost only 150,000 FCFA to overcome iron toxicity on the same surface area. The economic dose of kaolin to treat the effect of iron toxicity can therefore be set at 1097 kg kaolin/ha (Sehi et al., 2019).

4. CONCLUSION

This study revealed the ability of kaolin to inhibit the effect of iron toxicity under conditions of 900 ppm in a controlled environment. Analysis of the surface of the response and curve and the farmer's income level makes it possible to adjust the optimal dose to 1097 kg of kaolin ha^{-1} to obtain a grain yield of 0.98 t ha^{-1}.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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