Journal of Agricultural and Applied Economics (2024), **56**, 597–620
doi:10.1017/aae.2024.27

CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Does Adoption of Improved Variety Encourage Farmers to Invest in Modern Inputs and Use Good Practices? Evidence from Rice Farmers in Guinea

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Abstract
Iron toxicity is one of the constraints limiting rice production in Africa. This study used a randomized controlled trial to assess the impact of an iron toxicity-tolerant variety, named ARICA 6, on different outcomes and investment in modern inputs by smallholder farmers. Two rounds of data were collected from 520 rice-farming households in Guinea. Results showed that the use of ARICA 6 increased rice yield by 330 kg ha^{-1} and net income by US$ 120 ha^{-1}. However, adoption of improved variety may not be enough to crowd in investment in modern inputs because farmers face other constraints.

Keywords: Iron toxicity tolerance; field experiment; policy; food security; SSA

JEL classifications: Q12; O33; D13

Introduction

Estimated to cover over 190 million hectares in sub-Saharan Africa (SSA), lowlands could play a crucial role in achieving regional and global objectives for food security and poverty reduction due to high water availability and high soil fertility levels relative to the surrounding uplands and highlands (Rodenburg et al., 2014). Lowlands have been increasingly used for crop production, in particular for rice (Alemayehu et al., 2022). Regarding rice-based cropping systems, lowlands provide advantageous biophysical conditions for the expansion and intensification of sustainable rice production, particularly in the conditions of irregular rainfall caused by climate change. However, iron (Fe) toxicity is a major concern in acid sulfate soils and waterlogged conditions such as those in lowlands (Mahender et al., 2019). Although rice plants need several micronutrients, including Fe, for their growth, an excess of Fe in the soil hinders several physiological functions, causing significant losses in crop yield and quality (Bashir et al., 2014; Onyango et al., 2019). In SSA, lowlands especially non-irrigated ones have poor water drainage canals, creating favorable conditions to iron toxicity (van Oort, 2018).

Iron toxicity is among abiotic stresses reducing rice productivity in lowlands in SSA (Cherif et al., 2009) and about 60% of rice production are concerned in West and Central Africa. It reduces the fertility rate of rice panicles and results in a decrease in yield of 10% to 100% depending on the iron tolerance of the genotype, the intensity of the iron toxicity stress, and the fertility status of the soil (Sahrawat, 2010).

To address iron toxicity challenges, AfricaRice in partnership with national research institutes has developed improved rice varieties adapted to iron toxicity conditions (AfricaRice 2014). One of these improved named the Advanced Rice Varieties for Africa 6 (ARICA 6) was tested and released in many countries with high losses dues to iron toxicity, including Guinea, in 2017. ARICA 6 is expected to reduce production constraints by decreasing crop damage due to iron toxicity. Empirical evidence has shown that the adoption of improved rice varieties can contribute to productivity increase and food security improvements (e.g., Arouna et al., 2017; Asfaw et al., 2012; Mishra et al., 2022). However, not all improved varieties have a positive effect on yield and the livelihood of smallholder farmers. For instance, Yamano et al. (2017) found that the adoption of Sahbhagi Dhan, a drought-tolerant variety, had a negative effect on yield. In addition, improved varieties may lead to additional costs, which may reduce their profit and adoption (Emerick et al., 2016).

This study aims to assess the effects of the iron toxicity-tolerant rice variety ARICA 6 on various outcomes (productivity, net income, technical efficiency) and investment in good agricultural practices and modern inputs using a randomized controlled trial (RCT) approach. The contributions of this paper to the existing literature are threefold. First, this is the first attempt, to the best of our knowledge, to use an RCT approach to assess the impact of an improved rice variety adapted to iron toxicity conditions in SSA. Although extensive literature is available on the effect of improved high-yielding varieties (Arouna et al., 2017; Mishra et al., 2022) and short-duration varieties (SPIA 2019), little evidence exists on the effect of varieties with stress tolerance (Yamano et al., 2017). In addition, farmers' practices are different from the field experiments conducted in controlled breeding and agronomic trials before the release of varieties. Therefore, it is important to test the performance of newly released varieties under the real socioeconomic conditions of farmers prior to large-scale diffusion. This study fills this knowledge gap by assessing, under the farmers' conditions, the effect of a new variety that is tolerant to a major rice stress that is likely to become more severe with climate change. Second, this study analyzes the additional production costs related to the adoption of ARICA 6. In general, producers are reluctant to adopt new technologies because of the additional costs they may entail (Tufail et al., 2019). Thus, we attempt to address this concern by comparing production costs in both the control and treatment groups. Third, this study evaluates whether an improved variety can lead farmers to use high levels of modern inputs and to adopt improved cultivation practices for agricultural transformation in developing countries. Although improved technology may lead to the decision to invest in modern inputs (Emerick et al., 2016; Karlan et al., 2014), it is not obvious if a reduction in one constraint is enough to crowd in new investments in the presence of multiple constraints. Therefore, this paper tests whether the adoption of an improved variety crowds in other production investments under socioeconomic conditions characterized by multiple constraints (unpredictable rainfall and limited access to credit).

Methodology

Experimental design and sampling

To assess the impact of the ARICA 6 on productivity and net income, we conducted an RCT in the Nzerekore region. This region is among the large rice-producing region in Guinea. In Nzerekore region (in Guinea), the impact of iron toxicity on yield is high: indeed, approximately 10% of the fields cultivated in the lowlands have been abandoned due to high stress related to iron toxicity (Cherif et al., 2009). An experiment with one treatment arm and a control group was designed. All farmers in the treatment group (T_1) received 4 kg of ARICA 6 seed to cover an area of approximately 0.10 ha and information on agricultural practices concerning the variety, such as the total quantity of fertilizer required, a fertilizer application plan, the appropriate seeding method, and the appropriate weeding period. The seeds were freely provided, but we did not provide any fertilizer or other inputs to the treated farmers to ensure that the effect would be solely due to the seeds and not to any other inputs. The control group (T_0) did not receive ARICA 6 seeds but received advice on good agricultural practices for the traditional varieties.

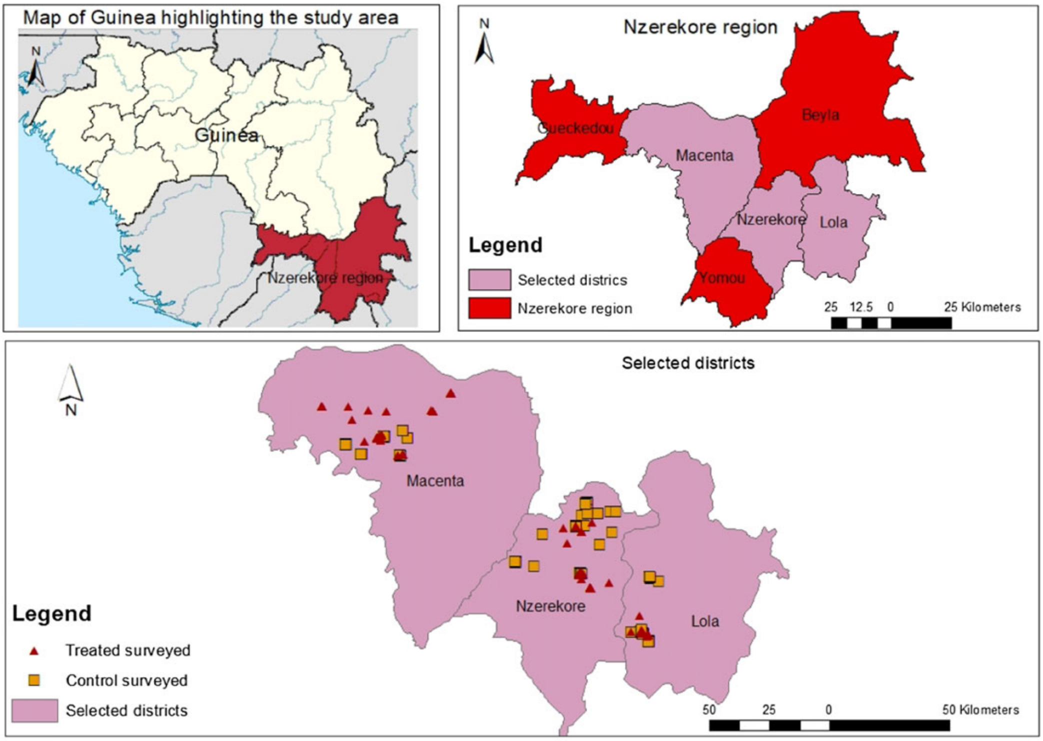

Figure 1. Map of the study area and selected villages.

A stratified random sampling approach was used to select the households. For the field experiment, the Nzerekore region was selected because it is one of the major rice-producing areas (around 38% of national rice production). Rice production is concentrated in the lowlands presenting favorable conditions to iron toxicity (Cherif et al., 2009). In Nzerekore region, we selected randomly three districts namely Lola, Macenta and Nzerekore (see Fig. 1). In each district, we randomly selected rice-producing villages with access to lowlands (where iron toxicity is prevalent according to farmers perception) as the primary sampling units. The number of villages selected per district was proportional to the total number of rice-growing villages with access to lowlands in each district. In total, 36 villages were selected (Table 1), and they were randomly classified into 15 treated villages and 21 controls. To increase the balance of the sample, both treated and control villages were selected from each district. Fifteen households were selected from each village as secondary sampling units by using the list of farmers growing rice in the lowlands. During data collection, we observed some attrition from initial sampling to baseline.[1] Of the 540 farmers sampled for the experiment, 520 households (216 treated and 304 control) were interviewed (Table 1). This accounts for a 3.7% rate of attrition at baseline. In general, the main reason for attrition at baseline in our sample was the travel or migration of households out of the study area. There was full compliance because all households in the treated group accepted and grew the new seeds. There was no contamination, likely due to the experimental design separating the control and treated villages. Moreover, there was no attrition when comparing the baseline and the follow-up surveys: all households in our baseline sample were surveyed in the follow-up.

[1]Attrition in a randomized controlled trial study is the loss of participants during the study. The main evaluative robustness of RCTs lies in the propensity of each group to present balanced characteristics. However, in many trials, participants are lost to follow-up. In this study, travel and migration were the main reason, and the rate of attrition (4%) is acceptable.

https://doi.org/10.1017/aae.2024.27 Published online by Cambridge University Press

Table 1. Sample size and attrition at baseline

	Total sample		Treatment		Control	
	Num. of villages	Num. of farmers	Num. of villages	Num. of farmers	Num. of villages	Num. of farmers
Intended experimental design						
Pooled	**36**	**540**	**15**	**225**	**21**	**315**
Lola	7	105	2	30	5	75
Macenta	14	210	6	90	8	120
Nzerekore	15	225	7	105	8	120
Realized design or intent-to-treat						
Pooled	**36**	**520**	**15**	**216**	**21**	**304**
Lola	7	102	2	30	5	72
Macenta	14	208	6	89	8	119
Nzerekore	15	210	7	97	8	113

Note: "Num. of villages" represents the number of villages and "Num. of farmers" is the number of farmers.

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We used two rounds of household-level surveys data in our analysis. First, a baseline survey was conducted in 2016 to collect information on farm production before the treatment. We then conducted our intervention ahead of the rice growing season. Finally, we conducted an endline survey one year later, in 2017 rice season to analyze the behavior of households following the intervention. We used a structured and pretested questionnaire that included modules on household demographic characteristics and production details such as the area of the rice plot, input use, output, price, and household living conditions. The survey questionnaire also asked about farmers' perceptions of the effects of iron toxicity and other abiotic stresses on rice fields in lowland environments.

Baseline balance checks

Table 2 presents the pretreatment differences between the baseline conditions of both randomized groups. Column (1) the mean value of each variable for the treated group and its standard deviation (column 2), column (3) indicates the mean value of each variable for the control group and its standard deviation (column 4), column (5) indicates the presents the before treatment differences in the means between the treated T_1 group (who received ARICA 6 seeds) and the T_0 group (who produced other rice varieties) using t and Khi-deux tests.

The reported coefficients suggest a good balance for almost all variables capturing household and institutional characteristics. Characteristics such as household size, marital status, and number of household members of working age were well balanced between the two groups except for age, where the control group averaged 2 years older than the treated group. Similarly, except for being in contact with extension agents, all other institutional covariates, such as the education level of the rice farmer, the main activity of the farmer, access to credit and experience in rice production, were well balanced.

The variables related to farm management were also well balanced between the treated and control groups ex-ante. There were no differences in the area of the rice plot, quantity of fertilizer used, use of a transplantation sowing method or methods used for production. Among the main outcome variables, there was a difference between the treated and control groups in technical efficiency only, and the significance level was low (p-value <0.10). The unbalanced variables were used as covariates in the estimation models.

Intention-to-treat (ITT) estimation

Randomization allows for simple estimation strategies to be used to assess the impact of the ARICA 6 on productivity, net income and technical efficiency. Because we were able to observe each household in our sample before and after treatment, we employed three different estimators to calculate the intent-to-treat (ITT) effects, which measure the average effects of growing the new variety, irrespective of actual treatment participation. These estimators are i) a simple mean difference (MD) estimator that uses only the postintervention data, ii) a difference-in-differences (DD) estimator that uses the difference in baseline and difference in the endline data, and iii) a kernel propensity-score matching difference-in-differences (KD) estimator that compare only the treated and nontreated who are similar in the baseline. The DD uses all the sample while KD use only the treated and nontreated that match. We expect the treatment effects (ρ) of the use of ARICA 6 rice to be positive.

We estimated the ITT effect (ρ) for household h in village v and district g using the simple MDX with covariate as (Arouna et al., 2020):

$$S_{hvg} = \lambda + \rho^{MDX} T_{hv} + X_{hvg}\beta + \sigma_g + \varepsilon_{hvg} \tag{1}$$

where S_{hvg} is the observed outcome variable, and T_{hv} is a household-level indicator that equals one if the household was randomly offered the treatment (T_1) and zero otherwise (T_0). Additionally, σ_g

Table 2. Baseline characteristics and differences of both randomized groups

	Treated group (n = 216)		Control group (n = 304)		
	Mean	St. Dev	Mean	St. Dev	Diff (treated minus control)
Variables	(1)	(2)	(3)	(4)	(5)
Household characteristics					
Age of rice farmer (years)	43.958	8.830	45.474	11.167	−1.515*
= 1 if rice farmer is male (%)	0.449	0.499	0.477	0.500	−0.028
= 1 if rice farmer is household head (%)	0.981	0.135	0.990	0.099	−0.009
= 1 if rice farmer is married (%)	0.903	0.297	0.911	0.285	−0.008
Household size	9.412	4.318	9.148	3.861	0.264
Household members of working age	5.319	2.625	5.579	2.743	−0.260
Institutional characteristics					
= 1 if rice farmer has a formal education (%)	0.315	0.466	0.263	0.441	0.052
= 1 if main activity is crop production (%)	0.986	0.117	0.990	0.099	−0.004
= 1 if member of a farmer group (%)	0.991	0.096	0.970	0.170	0.020
= 1 if credit access (%)	0.069	0.255	0.082	0.275	−0.013
Experience in rice production (years)	15.722	8.080	15.734	8.829	−0.011
= 1 if contact with extension agent (%)	0.444	0.498	0.299	0.459	0.145***
Distance to extension service (km)	7.541	7.127	6.903	5.801	0.638
Price of kg of paddy rice (US$/kg)	0.346	0.052	0.351	0.032	−0.005
Farm management					
Total quantity of NPK (kg/ha)	4.516	24.939	2.423	17.761	2.094
Total quantity of urea (kg/ha)	2.703	16.047	2.143	14.651	0.560
= 1 if transplantation sowing (%)	0.250	0.434	0.286	0.453	−0.036
= 1 if irrigated lowland (%)	0.005	0.068	0.013	0.114	−0.009

(*Continued*)

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Table 2. (*Continued*)

Variables	Treated group (n = 216) Mean (1)	Treated group (n = 216) St. Dev (2)	Control group (n = 304) Mean (3)	Control group (n = 304) St. Dev (4)	Diff (treated minus control) (5)
= 1 if rain-fed lowland (%)	0.995	0.068	0.987	0.114	0.009
= 1 if rice farmer uses certified seed (%)	0.037	0.189	0.066	0.248	−0.029
= 1 if rice farmer uses traditional seed (%)	0.968	0.177	0.967	0.179	0.000
Rice area (ha)	1.163	0.589	1.242	0.696	−0.079
Rice production (kg)	1521.833	914.583	1513.990	1020.913	7.843
Outcome variables					
Rice yield (t/ha)	1.311	0.403	1.261	0.472	0.050
Net income (US$/ha)	276.627	165.810	268.535	212.206	8.092
Technical efficiency	0.808	0.117	0.787	0.134	0.021*

Note: Column 5 is the value of the treated group minus the one of the control group. *** $p < 0.01$; * $p < 0.1$.

is a district fixed effect that accounts for variation across the districts, and ε_{hvg} is an idiosyncratic error term that is orthogonal to the ITT effect because of the randomization. X_{hvg} represents the vector of household characteristics, including the age of the household head, household size, number of household members of working age, distance to an extension service, number of years of experience in rice production, and binary variables indicating whether the household head received a formal education, and whether crop production is the main household activity. The simply MD without covariate was estimated using the equation 1 with the exclusion of the X_{hvg} term.

The second estimator is a DDX estimate of the ITT:

$$S_{hvgt} = \lambda + \alpha P_t + \gamma T_{hv} + \rho^{DD} P_t * T_h + X_{hvg}\beta + \sigma_g + \varepsilon_{hvgt} \tag{2}$$

Here, P_t is an indicator for the posttreatment period, and ρ^{DD} is the coefficient of the DD estimate of the ITT. Other variables are defined as in equation 1. The DDX estimator removes any time-invariant unobserved heterogeneity captured in the MDX, making it more efficient than the MDX estimator. Similar to the MD estimates, we also estimated the DD without covariates (ρ^{DD}) by removing the X_{hvg} term.

Finally, since a comparison within the region of common support increases the efficiency of the DDX estimator, we incorporated kernel propensity-score weights into the ITT estimates. We used the observed baseline characteristics to estimate the propensity score (the likelihood of being treated) and calculated the kernel weights following Heckman et al. (1998). After matching the treated and control households according to their propensity scores, we estimated the DD kernel (ρ^{KD}) and the DD kernel with covariates (ρ^{KDX}). ρ^{KDX} is estimated with equation 2 considering only the treated and control households that match. Although randomization means that the simple MD estimator provides unbiased estimates of the ITT, the DD and KD estimators are preferred because they take advantage of the panel nature of the data (Wooldridge, 2010). Similar to Arouna et al. (2020), we also used the analysis of covariance (ANCOVA) method, but we obtained results similar to those for the DD. The results from the ANCOVA analysis are not reported here.

Sampling weights and multiple hypothesis testing

As previously described, we used a multilevel stratified sampling approach. We sampled 15 households per village regardless of the village population, so with this sampling approach, different households had different probabilities of being sampled. This means that a same probability of being sampled is used and this could bias population estimates (Ksoll et al., 2016). Therefore, in our regression, we used sampling weights calculated as the inverse probability of being selected in any given village for each observation. The sample weights were calculated as the inverse of the ratio (sample size per village)/(total household population) for each village. Similar to Arouna et al. (2020) and Ksoll et al. (2016), we use the weighted data in all the regressions throughout the paper, though our results are also robust using the raw data.

Because in our stratification, the final sampling units (households) were clustered within the village, serial correlation in a village might be an issue. Although the intracluster correlation coefficients (ICC) for the outcome variables were relatively low (see Appendix Table 9), ignoring the clustered design may lead to standard errors that are too small and t-values that are too large. Even when individual behavior can generate homoscedastic regression functions within a cluster, there is heterogeneity between villages, and there may be heteroscedasticity in the overall regression (Cameron and Miller, 2015). Therefore, we used heteroscedasticity-robust standard errors clustered at the village level for all inferences.

When making inferences on many hypotheses, it is possible for significant results to emerge from the analysis due to chance rather than to actual treatment effects. This multiple-inference issue is well known in the literature, and several approaches exist to address it. In our approach, we

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followed Arouna et al. (2020) and adjusted the p-values in a number of different ways. The sharpened q-values were calculated as in Anderson (2008), and Bonferroni, Holm, and List adjusted p-values were calculated as suggested by List et al. (2019). The results are presented in the Appendix (Table 10 and Table 11). The q- and p-values are consistent with the significance level of the ITT, showing that the multiple hypotheses do not affect our estimates.

Measurement

Socioeconomic data was collected through household interviews. Interview data may have some bias due to recall information. To reduce the bias, we used the second round of data collection (endline) to crosscheck some data. In addition, local units for area measurement and product measurement (bag) were standardized with actual measurement. Although these strategies have helped to reduce measurement errors, we agree that bias can still exist. Future survey should add as much as possible actual measurements in the socioeconomic data collection.

The yield (t/ha) is measured by the ratio between the production rice volume (in tons) and the rice area (in ha). Gross income is calculated by multiplying yield (in tons per hectare) by the average unit price of paddy rice (in US$ per ton) in the data. The quantity of fertilizer (NPK and urea) was self-reported for those in the information-only treatment and control households. Technical efficiency was estimated using the Cobb-Douglass function.

Results

We present the results of the impact of ARICA 6 on the outcomes (yield, net income and technical efficiency) at two levels. First, we present the results at the farmer level (based on the total production of each farmer) and second, at the plot level (comparing ARICA 6 plots with non-ARICA plots).

Treatment effect on direct outcomes

The impact of the ARICA 6 on the direct outcomes (yield, net income, and technical efficiency) are presented in this section. As presented in the methodology section, six estimates of the ITT effect were calculated for each outcome. In the tables of this section, odd-numbered columns are from regressions without covariates while even-numbered columns include covariates, i.e., columns 1–2 present the simple MD estimates, columns 3–4 present the DD estimates, and columns 5–6 present the kernel propensity score matching DD estimates. We focus the analysis on both the DD and kernel approach estimates because they remove any time-invariant unobserved heterogeneity that is correlated with the ITT from our models, unlike the simple MD.

Treatment effect on yield

Panel A of Table 3 presents the impact of ARICA 6 on paddy yield using the total rice area and production of the treated and control farmers (farmer level). The results show that ARICA 6 increased paddy yield in 2017 after the intervention (Panel A of Table 3). In addition, there was a clear similarity across the estimates from different methods with and without the covariates implying consistency of the results. There was a difference between the yields of the treated and control farmers. The DD estimates (columns 3–4) show that the use of ARICA 6 increased paddy yield on average by 330 kg/ha, which represents an increase of 26% compared to the yield at baseline. The kernel estimates also suggest a similar effect that are statistically significant (p-value <0.01).

To check the results obtained in Panel A of Table 3, we evaluated the yields obtained at the plot level. That is, the yield of the ARICA 6 plots was compared to that of the other plots. The results

Table 3. Effect on rice yield (t/ha) at farmer and plot level

	MD	MDX	DD	DDX	KD	KDX
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Treatment effect on yield (farmer level)	0.373***	0.346***	0.326***	0.326***	0.342***	0.320***
	(0.079)	(0.075)	(0.075)	(0.075)	(0.077)	(0.078)
Mean of the dependent variable in the control farmers	1.290					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	520	520	1040	1040	1040	1040
R-squared	0.098	0.132	0.104	0.135	0.099	0.087
Panel B: Treatment effect on yield (plot level)	1.527***	1.508***	1.502***	1.502***	1.576***	1.568***
	(0.142)	(0.139)	(0.153)	(0.154)	(0.129)	(0.128)
Mean of the dependent variable in the control farmers	1.418					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	810	810	1620	1620	1620	1620
R-squared	0.412	0.420	0.433	0.442	0.528	0.525

Note: The odd and even columns show the regressions without and with covariates, respectively . Columns 1–2 present the simple mean-difference estimates (ρ^{MD} and ρ^{MDX}), columns 3–4 present the DD estimates (ρ^{DD} and ρ^{DDX}), and columns 5–6 present the kernel propensity-score matching DD estimates (ρ^{KD} and ρ^{KDX}). Values in brackets are clustered village-level robust standard errors. For simplicity, the coefficients on the household covariates are not included in the table, but the full results can be obtained from the author. *** $p < 0.01$. FE stands for fixed effect.

obtained are consistent across columns and significant with a p-value <0.01 (Panel B of Table 3). We found evidence from all estimates considered (MD, DD, and KD) that ARICA 6 had a positive effect, and as expected, the plot-level effect is larger than the effect at the farmer level. This can be explained by the size of the ARICA 6 plots, which represent only 8% of the rice area of the average farmer (Table 2). This means that treated farmers cultivated both ARICA 6 and traditional varieties. Therefore, the plot effect is expected to be more important than the farmer effect. The real effect is at the farmer level, while the plot level is the potential effect if the intensity of adoption at the farmer level were 100%. Specifically, ARICA 6 helped the treated farmers significantly increase their yield per plot by 1.5 ton/ha.

The results confirm our hypothesis that ARICA 6, which is iron-toxicity tolerant, increases rice yield. The evidence from the results shows that ARICA 6 variety had a positive effect (significant at 1%) on the rice yield of farmers. However, the average yield in the ARICA 6 plots (2.9 t/ha) of the treated group (Panel B of Table 3) is below the potential yield of 10 t/ha obtained with agronomic trials. This can be explained by the low level of fertilizer use in our study area. At baseline, the average farmer used on average 5 kg of fertilizer per hectare (Table 2), representing only 2% of the basic agronomic recommendations of 250 kg of fertilizer per hectare (150 kg of NPK fertilizer and 100 kg of urea fertilizer). Moreover, the median farmer in the sample uses no fertilizer. This reveals the difference between agronomic recommendations and actual farmers' conditions and highlights the importance of testing new varieties under the real socioeconomic conditions of farmers.

Treatment effect on net income from rice

We focus here on the effect of ARICA 6 on income gains. Panel A of Table 4 shows the ITT estimates of the adoption of the new variety on the net income per hectare calculated with the same estimation strategy used in Table 3. The net income is estimated as revenue minus all paid-out costs. For the treated group who received seeds of ARICA 6 for free, the cost of certified seeds in the survey area is used to evaluate the cost of ARICA 6 seeds, which are not yet available on the market.

We found that in addition to increasing yields, the treatment had positive and significant effects on the net income from rice production (Panel A of Table 4). On average, with DD estimates, the randomly treated farmers (T_1) increased their net income by approximately US$ 122 per hectare (significant at 1%), which is equivalent to an approximately 45% increase in net income (Panel A of Table 4). From the kernel estimates, columns 5–6 show a similar effect with similar significance, namely, US$ 124 per hectare, which is equivalent to an increase of 46%. The similarities among the different estimates and across estimators provides grounds for some confidence in the results.

Looking at the effect of the ARICA 6 variety on net income at the plot level (Panel B of Table 4), the results show that the use of ARICA 6 increased net incomes from rice production. Indeed, the DD estimators show an average effect of US$ 714 per hectare (columns 3–4). The kernel estimates in columns 5–6 also have a similar positive impact: an almost threefold increase in income compared to that in the baseline period.

To check the mechanism that explains the effect on net income, profit analysis was performed. Figure 2 shows the net income and the costs of rice establishment (input costs and labor costs), which includes the cost of the seeds, fertilizers, and herbicides used. In general, the costs of seeds and herbicides are the main factors and comprise up to 90% of the total rice establishment costs. The results suggest that establishment costs were not significantly different between the control and treated groups at baseline. However, the treated group had higher establishment costs at endline. The change between the endline costs of the control and treatment groups was mainly due to the cost of the seeds. The seed cost was not significantly different between the control and treated groups at baseline because all farmers used mainly noncertified seeds. However, the treated

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Table 4. Effect on net income (US$/ha) at farmer and plot level

	MD (1)	MDX (2)	DD (3)	DDX (4)	KD (5)	KDX (6)
Panel A: Treatment effect on yield (farmer level)	130.8***	122.4***	121.6***	121.6***	126.7***	122.3***
	(46.14)	(41.46)	(34.52)	(34.67)	(34.96)	(33.77)
Mean of the dependent variable in the control farmers	305.024					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	520	520	1040	1040	1040	1040
R-squared	0.074	0.126	0.078	0.128	0.081	0.079
Panel B: Treatment effect on yield (plot level)	605.830***	598.199***	598.143***	598.143***	617.926***	615.583***
	(44.484)	(42.266)	(46.296)	(46.397)	(47.257)	(46.953)
Mean of the dependent variable in the control farmers	369.507					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	810	810	1620	1620	1620	1620
R-squared	0.370	0.379	0.406	0.417	0.517	0.515

Note: The odd and even columns show the regressions without and with covariates, respectively . Columns 1–2 present the simple mean-difference estimates (ρ^{MD} and ρ^{MDX}), columns 3–4 present the DD estimates (ρ^{DD} and ρ^{DDX}), and columns 5–6 present the kernel propensity-score matching DD estimates (ρ^{KD} and ρ^{KDX}). Values in brackets are clustered village-level robust standard errors. For simplicity, the coefficients on the household covariates are not included in the table, but the full results can be obtained from the author. *** $p < 0.01$. FE stands for fixed effect.

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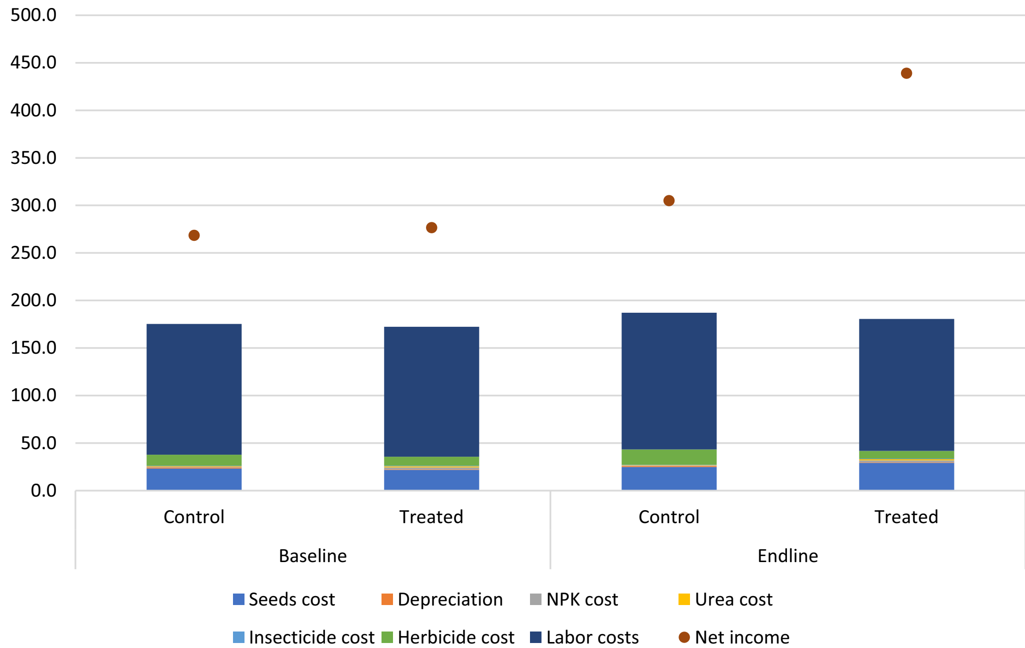

Figure 2. Cost of crop establishment and net income in US$ per ha.

group observed an increase in seed cost at endline. This difference may be due to the cost of ARICA 6 seeds (see also the details on the difference in input costs at the endline survey in Appendix Table 12). In general, certified seeds are costly compared to the noncertified seeds that farmers use. We also observed that the fertilizer costs were very low. This confirms that producers used very little fertilizer for production. Indeed, farmers are often face additional constraints in accessing fertilizer.

Net revenue is equal to gross revenue minus variables costs (crop establishment costs) and fixed costs (equipment's costs). In this study, the value of equipment depreciation (cost) is very low, almost nil, and net income is equal to gross income minus variable costs (input costs and labor costs). Indeed, producers use manual equipment such as hoes and reapers. These tools are used for many crops. Labor costs did not differ between the groups, but they represented most production costs. This may be due to the low use of agricultural machinery, which leads to intensive human labor requirements for production activities. The total cost of production and the net income of the control farmers were not significantly different between the baseline and endline periods (Fig. 2). This implies that the control farmers did not significantly change their production habits during the experiment. This increases the robustness of the results of the experiment. However, a change was observed in the trend of the treated group. There was a sharp increase in the net income of the treated group between baseline and endline, with just a slight (1%) increase in production costs. This confirms that the rice production of the treated group using ARICA 6 was more profitable than that of the control farmers.

Treatment effect on technical efficiency

We assessed the effect of the new variety (ARICA 6) on the technical efficiency of the farmers. We estimated technical efficiency by using the Cobb-Douglas frontier production function (Appendix Table 13). Table 5 shows the ITT estimates of ARICA 6 on technical efficiency. The evidence shows that using of ARICA 6 seeds made the treated producers more technically efficient than the

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Table 5. Effect on technical efficiency at farmer and plot level

	MD (1)	MDX (2)	DD (3)	DDX (4)	KD (5)	KDX (6)
Panel A: Treatment effect on yield (farmer level)	0.093***	0.091***	0.072***	0.072***	0.069***	0.078***
	(0.007)	(0.006)	(0.023)	(0.023)	(0.023)	(0.025)
Mean of the dependent variable in the control farmers	0.787					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	520	520	1040	1040	1040	1040
R-squared	0.467	0.512	0.175	0.219	0.165	0.164
Panel B: Treatment effect on yield (plot level)	0.141***	0.142***	0.130***	0.130***	0.130***	0.133***
	(0.007)	(0.007)	(0.014)	(0.014)	(0.017)	(0.017)
Mean of the dependent variable in the control farmers	0.787					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	810	810	1620	1620	1620	1620
R-squared	0.596	0.608	0.217	0.231	0.269	0.272

Note: The odd and even columns show the regressions without and with covariates, respectively. Columns 1–2 present the simple mean-difference estimates (ρ^{MD} and ρ^{MDX}), columns 3–4 present the DD estimates (ρ^{DD} and ρ^{DDX}), and columns 5–6 present the kernel propensity-score matching DD estimates (ρ^{KD} and ρ^{KDX}). Values in brackets are clustered village-level robust standard errors. For simplicity, the coefficients on the household covariates are not included in the table, but the full results can be obtained from the author. ** $p < 0.05$; *** $p < 0.01$. FE stands for fixed effect.

nontreated farmers (Panel A of Table 5). On average, the technical efficiency of the farmers who received ARICA 6 seeds was 0.09 points higher than that of the control group according to the MD estimators. The DD and kernel estimates in columns 3 to 6 also show a similar, but smaller, positive effect. Although the size of the effect is still low, the effect of ARICA 6 on the technical efficiency of rice farmers varies between 7% and 8%. In addition, when we consider the estimates of the effect with and without covariates, the results are consistent. Considering the effect on technical efficiency at the plot level (Panel B of Table 5), we observe a greater effect. Indeed, we found that ARICA 6 helped the treated farmers significantly increase their efficiency by an average of 12%. This means that ARICA 6 improved the efficiency of rice producers at the plot level.

Effect on cultivation practices and investments in inputs

We turn now to the estimation of the effect of the new variety (ARICA 6) on the adoption of improved cultivation practices and investments in modern inputs. The estimations are presented for four cultivation practices (use of certified seed of a variety, transplantation method, lowland use and planted area) and four input costs (NPK fertilizer, urea fertilizer, seed, and labor). Table 6 presents the ITT estimates for the adoption of cultivation practices. The effect on transplantation methods is positive and significant. The new variety led to more use of the transplantation method for sowing rice. According to the kernel estimates, the new variety increased the percentage of farmers using the transplantation method by 35% (Panel C of Table 6). The treatment effect on certified seed (ARICA 6 or other varieties) use by farmers is significant. This is straightforward because the ARICA 6 seeds provided to treated farmers are certified, while 95% of control farmers used noncertified seeds (see Appendix Table 12). However, the new variety crowded in neither additional area nor lowland use. The treatment effects on planted area and lowland use were not significant. Farmers were used to lowland rice cultivation in our study area, and they did not change this practice due to the new variety.

Table 7 presents the ITT estimates for input costs. New variety has a positive effect on seed cost. According to the kernel estimates, the effect on seed cost is US$ 5.3 per hectare. This confirms the above finding that the high production cost of the treated group is related to the cost of ARICA 6 seeds. Regarding other modern inputs, the new variety has a positive effect only on urea cost. From the kernel estimates, the effect on urea cost is small (US$ 0.7 per hectare). In addition, the treatment effects of the ARICA 6 seeds on NPK and labor costs were not significant. Taking these results together, the use of ARICA 6, a rice variety with an iron-toxicity tolerance, does not crowd in investment in modern inputs, with the exception of urea. To explore the mechanisms that could explain the low crowd-in of investments in modern inputs, a heterogeneity analysis was performed by adding interaction variables to the ITT regressions (equation 2). Table 8 presents the results of the difference-in-differences estimation with two interaction variables: the treatment dummy interacted with credit access and the treatment dummy interacted with irrigation access. Our results show that the new variety may crowd in significant investments when the constraint of unpredictable rainfall is relaxed through irrigation systems (Table 8). Access to irrigation increases the investment in total fertilizers by US$ 99 per hectare. However, the heterogeneity effect of credit access was not significant.

Discussion and policy implications

This paper presents a randomized controlled experiment to assess the effect of an iron toxicity-tolerant variety of rice at both the farmer and plot levels under farmers' actual conditions. We found evidence that ARICA 6 seeds had a significant and positive impact on yield, net income and technical efficiency. This result is important in the current situation of declining productivity and production in the lowlands because of iron toxicity. Our finding of increases in yield due to the use of ARICA 6 seeds is consistent with previous findings. Indeed, similar results were obtained for

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Table 6. Farmer-level effect on cultivation practices

	MD	MDX	DD	DDX	KD	KDX
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Treatment effect on planted area	−0.086	−0.092	0.018	0.018	−0.013	−0.013
	(0.073)	(0.073)	(0.074)	(0.074)	(0.087)	(0.091)
Mean of the dependent variable in the control farmers	1.265					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	520	520	1040	1040	1040	1040
R-squared	0.048	0.094	0.038	0.068	0.005	0.008
Panel B: Treatment effect on lowland use	0.011	0.010	0.011	0.011	0.004	0.003
	(0.008)	(0.007)	(0.010)	(0.010)	(0.007)	(0.008)
Mean of the dependent variable in the control farmers	0.987					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	No	No	No	No
Observations	520	520	1040	1040	1040	1040
R-squared	0.025	0.032	0.026	0.035	0.004	0.004
Panel C: Treatment effect on transplantation method	0.396***	0.392***	0.369***	0.369***	0.353***	0.346***
	(0.104)	(0.100)	(0.060)	(0.060)	(0.063)	(0.064)
Mean of the dependent variable in the control farmers	0.266					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	No	No	No	No

(*Continued*)

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Table 6. (*Continued*)

	MD	MDX	DD	DDX	KD	KDX
	(1)	(2)	(3)	(4)	(5)	(6)
Observations	520	520	1040	1040	1040	1040
R-squared	0.212	0.238	0.170	0.193	0.085	0.095
Panel D: Treatment effect on use of certified seeds of a variety	0.941***	0.938***	0.970***	0.970***	0.973***	0.966***
	(0.019)	(0.021)	(0.025)	(0.025)	(0.021)	(0.022)
Mean of the dependent variable in the control farmers	0.056					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	No	No	No	No
Observations	520	520	1040	1040	1040	1040
R-squared	0.882	0.884	0.793	0.799	0.818	0.804

Note: The odd and even columns show the regressions without and with covariates, respectively. Columns 1–2 present the simple mean-difference estimates (ρ^{MD} and ρ^{MDX}), columns 3–4 present the DD estimates (ρ^{DD} and ρ^{DDX}), and columns 5–6 present the kernel propensity-score matching DD estimates (ρ^{KD} and ρ^{KDX}). Values in brackets are clustered village-level robust standard errors. For simplicity, the coefficients on the household covariates are not included in the table, but the full results can be obtained from the author. *** $p < 0.01$. FE stands for fixed effect.

Table 7. Farmer-level effect on input costs

	MD	MDX	DD	DDX	KD	KDX
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Treatment effect on seed cost (US$/ha)	6.747*	6.358*	7.237	7.237	4.817	5.306*
	(3.874)	(3.385)	(4.499)	(4.514)	(3.163)	(3.138)
Mean of the dependent variable in the control farmers	24.929					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	520	520	1040	1040	1040	1040
R-squared	0.029	0.060	0.036	0.053	0.008	0.008
Panel B: Treatment effect on labor cost (US$/ha)	3.268	2.043	4.612	4.612	1.255	1.313
	(14.400)	(13.636)	(9.241)	(9.273)	(11.315)	(11.698)
Mean of the dependent variable in the control farmers	137.953					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	520	520	1040	1040	1040	1040
R-squared	0.032	0.099	0.028	0.073	0.000	0.000
Panel C: Treatment effect on urea fertilizer cost (US$/ha)	1.667*	1.403**	0.634**	0.634**	0.658**	0.720**
	(0.844)	(0.635)	(0.271)	(0.272)	(0.313)	(0.340)
Mean of the dependent variable in the control farmers	0.331					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes

(*Continued*)

Table 7. (*Continued*)

	MD (1)	MDX (2)	DD (3)	DDX (4)	KD (5)	KDX (6)
Observations	520	520	1040	1040	1040	1040
R-squared	0.028	0.066	0.021	0.065	0.005	0.005
Panel D: Treatment effect on NPK fertilizer cost (US$/ha)	2.248*	1.789*	0.199	0.199	0.373	0.352
	(1.241)	(0.934)	(1.299)	(0.980)	(1.074)	(1.060)
Mean of the dependent variable in the control farmers	0.753					
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	No	Yes	No	Yes	No	Yes
Year FE	No	No	Yes	Yes	Yes	Yes
Observations	520	520	1040	1040	1040	1040
R-squared	0.021	0.061	0.021	0.064	0.006	0.007

Note: The odd and even columns show the regressions without and with covariates, respectively. Columns 1–2 present the simple mean-difference estimates (ρ^{MD} and ρ^{MDX}), columns 3–4 present the DD estimates (ρ^{DD} and ρ^{DDX}), and columns 5–6 present the kernel propensity-score matching DD estimates (ρ^{KD} and ρ^{KDX}). Values in brackets are clustered village-level robust standard errors. For simplicity, the coefficients on the household covariates are not included in the table, but the full results can be obtained from the author. ** $p < 0.05$, * $p < 0.10$. FE stands for fixed effect.

Table 8. Farmer-level effect on input costs with interaction variables

	Urea cost		NPK cost		Total fertilizer cost	
	DDX	DDXI	DDX	DDXI	DDX	DDXI
	(1)	(2)	(3)	(4)	(5)	(6)
Treatment	0.634**	0.094	0.199	−0.643	0.833	−0.549
	(0.272)	(0.435)	(0.474)	(0.795)	(0.672)	(1.189)
Treatment * Irrigation		38.906***		60.557***		99.463***
		(5.034)		(8.044)		(13.077)
Treatment * Credit		1.660		2.437		4.097
		(1.730)		(2.639)		(4.367)
Mean of the dependent variable in the control farmers	0.331		0.753		1.084	
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Household covariates	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	520	520	520	520	520	520
R-squared	0.065	0.308	0.064	0.324	0.066	0.324

Note: The odd and even columns show the regressions without and with covariates, respectively. Values in brackets are clustered village-level robust standard errors. For simplicity, the coefficients on the household covariates are not included in the table, but the full results can be obtained from the author. *** $p < 0.01$, ** $p < 0.05$. DDXI means Difference-in-Difference with covariates and interaction variables. FE stands for fixed effect.

stress-tolerant rice varieties. Sahrawat (2010) showed that the integrated use of tolerant genotypes can reduce the effects of iron toxicity and is practical for sustaining increased rice productivity, especially under high and persistent iron toxicity stress. Dar et al. (2017) and Emerick et al. (2016) also found that Swarna-Sub1, a submergence-tolerant rice variety, has a significant positive effect on rice yield when fields are submerged for 7 to 14 days and has no yield penalty under non-flooded conditions. In contrast, Yamano et al. (2017) found using an RCT that adopters of an improved drought-tolerant variety, i.e., Sahbhagi Dhan, obtained 1.3 t/ha less than the non-adopters in India. However, most literature is related to drought and flood tolerance. This paper provides evidence on the effect of an improved variety with iron-toxicity tolerance. It is worth noting that the effect may not be driven solely by the iron-toxicity tolerance of ARICA 6. Improved varieties have usually high-yielding trait. In addition, the yield of ARICA 6 under farmers' actual conditions is far below the agronomic potential of the variety. This can be explained partially by the low quantity of modern inputs used by farmers. In fact, the median farmer in our study area uses no fertilizer. This shows the importance of random experiment of new varieties under farmers' conditions, which are different from breeding and agronomic trials' conditions.

Economically, the results showed that the use of ARICA 6 seeds increased the net income of rice producers in lowlands prone to iron toxicity. This is consistent with other findings (Arouna et al., 2017; Dibba et al., 2012) on high-yielding rice varieties. The effect of ARICA 6 on income is explained by the fact that the adoption of ARICA 6 significantly improved yield while inducing only a slight additional cost due to the cost of certified seeds. However, additional investments related to a new technology may negatively affect its adoption at scale (Suri, 2011). Indeed, smallholder farmers are resource-poor and may not be capable to invest in costly innovations. A small increase in the cost of seeds could be a major investment for a risk-averse farmer. In addition, farmers facing constraints related to credit access, market access and production technologies may choose to invest less (Karlan et al., 2014). For smallholder farmers to adopt a new technology, the technology should not be costly in terms of investment (Croppenstedt et al., 2003). This means that ARICA 6 may have a high potential to be adopted by smallholder farmers not only through the wide dissemination but also through the reduction in seed costs.

We found that there is a significant difference between the farmer-level and plot-level effects of the treatment. This may be partially explained by the fact that treated farmers cultivated both ARICA 6 and traditional varieties. Therefore, the plot effect is expected to be larger than the farmer effect. However, the difference between the plot and farmer effects may hide the effect of unobserved effort made by the treated farmers (Chassang et al., 2012). Indeed, treated farmers may have chosen their best plots for the new variety or may allocate more time and resources to the ARICA 6 plots. In a standard RCT, it is difficult to disentangle the effect of such unobservable data. To check for potential bias due to unobserved effort by the treated farmers, we analyzed the treatment effect on labor cost. The treatment effect of the ARICA 6 seeds on labor costs was not significant. This implies that, it is unlikely that in this study, treated farmers have made unobservable effort decisions. However, future research on improved variety testing under farmers' conditions might consider, if resources permit, using extended RCTs such as selection trials (Chassang et al., 2012) to account for unobservable effort and the beliefs of the treated farmers.

We also found that ARICA 6 seeds do not crowd in investments in modern inputs, with the exception of urea. The ARICA 6 variety does not induce farmers to make large investments in modern inputs for agricultural transformation. However, when the additional constraint of unpredictable rainfall is relaxed, improved seeds led to more investments in modern inputs. The reduction in production constraints related to water management and the adoption of improved varieties may encourage farmers to invest more because the technical complementarities between the new variety, fertilizer and water are likely to be high. This finding extends the results of Emerick et al., (2014) showing that new varieties are effective in crowding in additional investments in modern inputs but only if farmers do not face other major constraints. Our finding is like the results of Carter et al. (2016). Indeed, Carter et al. (2016) showed that standalone insurance contracts have minimal effects on the adoption of new technologies, whereas insurance interlinked with credit access is much more effective at crowding in technological change. Therefore, the adoption of improved seed varieties is not enough to crowd in large investments in modern inputs if farmers face additional constraints such as erratic rainfall due to a lack of irrigation systems. Policy measures to increase water management through supplemented rain-fed systems and public irrigation schemes may contribute to the use of high levels of modern inputs and the adoption of improved agricultural practices for agricultural transformation and increased food security.

Although the results showed no evidence that credit access leads to additional investments in modern inputs, modern credit facilities such as contract farming, in-kind credit and group-based credit may be useful. Labor represents the primary cost of rice production in lowlands. Investment credit is required to increase access to small-scale machinery. Although the lowlands provide the appropriate biophysical conditions for expanding rice cultivation and intensifying sustainable rice production, the clay soil makes lowlands difficult to cultivate with manual labor. Adapted equipment is required for large-scale production. Policy options such as subsidies and investment credit facilities could increase the affordability and accessibility of this equipment for large-scale production and food security in Africa.

Conclusion

Lowlands in Africa provide favorable biophysical conditions for the expansion and intensification of sustainable rice production, particularly under conditions of irregular rainfall and climate change. Unfortunately, iron toxicity in these areas remains a crucial problem that limits the production of rice in many lowlands. Reducing the effects of iron toxicity in SSA lowlands through improved and resistant germplasms is one solution to this problem. In this paper, we assessed the impact of adopting an iron toxicity-tolerant rice variety (ARICA 6), using field experiments in Guinea. We presented evidence that the adoption of ARICA 6 has a positive and significant impact on the land productivity (yield), profit and technical efficiency of rice-producing farmers. However, adoption of ARICA 6 variety is not enough to crowd in large investments in modern inputs because farmers are facing other constraints. To achieve the potential of the large-scale adoption of ARICA 6 and sustainable rice intensification in lowlands for food and nutrition security, the large-scale release of this variety may be a policy option to improve rice production and increase food security for rice producers, but additional measures such as reducing the constraints due to unpredictable rainfall through water management may increase the benefits of the improved variety.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/aae.2024.27.

Data availability statement. All data are available from the authors and will be made open access after publication.

Acknowledgements. This study was conducted under the CGIAR Research Program on Rice and the Stress Tolerant Rice for Africa and South Asia (STRASA) project funded by a grant from the Bill & Melinda Gates Foundation [Grants no. OPP1088843] and coordinated by the International Rice Research Institute (IRRI) in partnership with the Africa Rice Center (AfricaRice) and the CGIAR initiative on Transforming Agri-Food Systems in West and Central Africa (TAFS-WCA). Authors thanks Baboucarr Manneh, Nani Drame, Moussa Sie, and Ibnou Dieng for their contributions to the evaluation and data analysis of ARICA 6 before its release. The support of Wilfried Yergo and the NARS partners from Burkina Faso, Guinea, Ghana, and Nigeria who contributed to the breeding of ARICA 6 is also acknowledged.

Author contribution. Conceptualization, A.A., M.L.B., and J.A.Y.; methodology, A.A. and J.A.Y.; formal analysis, A.A.; data curation, A.A. and P.K.; writing – original draft, A.A. and P.K., writing – review and editing, A.A., M.L.B., P.K and J.A.Y.; supervision, J.A.Y.; funding acquisition, A.A.

Financial support. This study was supported by the Bill & Melinda Gates Foundation, Seattle, WA, USA (Grants no. OPP1088843); CGIAR Research Program on Rice (RICE CRP); and Transforming Agri-Food Systems in West and Central Africa Initiative of the CGIAR (TAFS-WCA).

Competing interests. All authors declare none.

Code availability. The code for the data analysis is available from the authors and will be made available after publication.

Declaration Artificial Intelligent AI. We declare that artificial intelligent (AI) was not used in any way in the generation of the manuscript.

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Cite this article: Arouna, A., M.L. Barry, P. Kamano, and J.A. Yabi (2024). "Does Adoption of Improved Variety Encourage Farmers to Invest in Modern Inputs and Use Good Practices? Evidence from Rice Farmers in Guinea." *Journal of Agricultural and Applied Economics* **56**, 597–620. https://doi.org/10.1017/aae.2024.27