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Impacts of the joint adoption of improved varieties and chemical fertilizers on rice productivity in Bolivia: implications for Global Food Systems

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Rice research and technology development in Latin America has increased yields and offered the opportunity for several countries to contribute to global food security by becoming net exporters of this cereal. In spite of the broad availability of rice technologies in the region, rice yields remain substantially low in countries like Bolivia. This study examines how Bolivian rice growers make simultaneous decisions about adopting improved varieties and chemical fertilizers and how this joint decision influences the productivity of this crop. By exploiting a nationally representative survey of rice producers, we use a multinomial logit model and an optimal instrumental variable approach to study both the correlates of technology adoption and the impacts of this adoption on rice yields. Our findings suggest that partial adoption of rice varieties or fertilizers does not affect yields, but the joint adoption of these technologies can almost double rice productivity. Promoting packages of agricultural technologies—instead of single technologies within efforts to make these technologies available for small farmers—would exploit the complementarities of different technologies and boost rice yields in Bolivia. The implications would not only be to achieve the desired self-sufficiency in rice production but also to follow similar pathways of other countries in the region that have become net exporters of rice and are contributing to Global Food Systems.

KEYWORDS

***Oryza sativa L.*, technology adoption, improved crop varieties, impact assessment, multivalued endogenous treatment effect**

1. Introduction

Productivity growth of rice (*Oryza sativa L.*) in recent decades in Latin America has increased the per capita consumption of this cereal and specifically improved the diets of the poor in the region (Zorrilla et al., 2012; FONTAGRO, 2019). As such, several countries have become net rice exporters, showing major potential for the region to contribute to Global Food Systems. However, this yield enhancement in rice production, showing average rice yields between 8 and 10 t/ha, has not reached all rice-producing countries. In spite of the availability of improved varieties and other agronomic technologies in the region, countries like Bolivia keep an average rice yield of ∼3 t/ha (FAOSTAT, 2023).

Although the technological progress of rice production made in Latin America has been well-documented (Calvert et al., 2006; Zorrilla et al., 2012; Martínez et al., 2014), evidence on the uptake of improved rice technologies and their impact on productivity and development outcomes remains limited. Few studies have documented the level and factors that may explain the adoption of improved varieties, fertilizers, and other inputs in rice production in Latin America (Scobie and Posada, 1978; Strauss et al., 1991; White et al., 2005; Morello et al., 2018; Marín et al., 2021; Martinez et al., 2021). However, understanding how adopting improved rice technologies could translate into productivity and welfare impacts in Latin America remains absent.

In Bolivia, rice production represents one of the main sources of income and food security for rural households (Ortiz and Soliz, 2007; MDRyT, 2012). However, the use of improved rice technologies among small and medium-scale farmers remains constrained (Martinez et al., 2021). This low adoption of rice technologies has restrained the Bolivian rice sector from improving yields, facilitating greater participation in local and regional markets (Lopera et al., 2023), and reducing price volatility for producers (Bauguil, 2003) and consumers in urban areas (Perez et al., 2011). With a large share of agricultural land under rice, an improvement of rice productivity to the average rice yields in Latin America could meet the domestic demand and transform Bolivia into a net exporter of this cereal. Exploring the relationship between the uptake of rice technologies and rice productivity in the Bolivian context may help policymakers in designing better strategies to achieve a significant productivity jump, as experienced by similar countries in Latin America.

The agricultural economics literature has extensively documented the impacts of agricultural technology adoption on other crops (Feder and Umali, 1993; De Janvry and Sadoulet, 2006; Doss, 2006) or for rice in other regions (Yamano et al., 2016; Mishra et al., 2022). Wang et al. (2020) reported positive and significant impacts of stress-tolerant rice varieties on yields and income in Yunan, China. Likewise, while Yamano et al. (2018) highlighted the difficulties in adopting natural resource management rice technologies, Mishra et al. (2022) reported that rice technologies on direct seeding, rodent control, and iron toxicity removal significantly affect economic wellbeing. Finally, Mills et al. (2022) found that salinity-tolerant rice varieties increased yields on fields that are not protected by salinity barriers in the Mekong Delta. Still, lower market prices limit the overall economic benefits of these varieties compared to other varieties.

One limitation of the available evidence on the impacts of rice technologies has been the focus of the analysis on the adoption of single technologies. However, a growing body in the broader agricultural technology literature is undertaking the analysis from the perspective of "technological packages." As such, these studies explore the effects of packages of technologies (e.g., improved varieties, along with sustainable agriculture practices) on several outcomes, incorporating the complementarities that joint adoption of technologies can offer. Teklewold et al. (2013) used a multinomial endogenous switching regression, finding that the combined adoption of improved maize varieties and minimum tillage resulted in higher income among farmers in Malawi. However, it also increased family labor demand, especially for women. Meanwhile, using a similar approach, Martey et al. (2023) found that the joint use of Striga-resistant maize and fertilizers had significant positive effects on yields and food consumption. Likewise, using a similar approach, Kassie et al. (2015) found evidence of improved food security and reduced downside risk when Malawian farmers simultaneously adopted maize varieties and chemical inputs. Despite the use of technological packages in the African context, studies that evaluate these packages are not common for rice technologies and are non-existent in Latin America.

This article aims to fill in the gaps as well as provide evidence on whether the joint adoption of modern improved rice varieties (MIV) and chemical fertilizers could lead to a significant rice yield increase in Bolivia. Given that the increase in rice acreage is not feasible in Bolivia, increasing rice yields eventually will support the aspiration of the country to achieve rice production self-sufficiency and become a net exporter of this cereal. We take advantage of a comprehensive household and plot survey on a nationally representative sample of Bolivian rice producers and use an instrumental variable approach to control for potential selection bias in the estimation procedure.

We found that the adoption of rice technologies is positively correlated with farm size, being a member of a farmer organization and having access to agricultural credit. Conversely, we found evidence that the adoption of these technologies is discouraged by having other sources of farm income. On the other hand, once we accounted for the potential endogeneity of the decision to adopt rice technologies, we found that individual use of either improved rice varieties or chemical fertilizers does not influence rice yields. However, when both technologies are jointly adopted, rice yields are almost doubled (+1.67 t/ha).

2. Rice production and access to improved technologies in Bolivia

Although soybeans and other industrial crops in Bolivia have become the main source of country revenue and forex, rice and other cereals remain the main source of income and food security for small and medium farmers (Ortiz and Soliz, 2007). There are over 180,000 ha of rice in Bolivia (90% cultivated under rainfed conditions), managed by approximately 45,000 farmers (Lopera et al., 2023). Approximately 95% of rice production is concentrated in the Santa Cruz, Beni, and Cochabamba regions.

Between the 1960s and 1980s, average rice yields in Bolivia (2.1 t/ha) were not different from the average yields in Latin America and were slightly higher than that in Brazil, the leading producer and consumer of rice in the region (Table 1). By the early 1980s, the strengthening of several rice improvement programs in the region made various improved varieties available that adapted to different local conditions. Likewise, other countries started promoting improved agronomy in rice production (Zorrilla et al., 2012). It did not take long to observe different countries in the region progressively increasing rice productivity, bringing the current average yield in Latin America to 4.49 t/ha (Table 1). This productivity transformation has made countries like Brazil, Paraguay, Uruguay, and Argentina become net rice exporters

TABLE 1 Average rice yields (t/ha) evolution in a selected group of Latin-American countries.

Period	Latin-America	Bolivia	Brazil	Argentina	Colombia	Nicaragua	Paraguay	Peru	Uruguay
1961–1980	1.58	1.57	1.50	3.57	3.20	2.68	2.17	4.13	3.67
1981–1990	2.00	1.67	1.76	3.87	4.48	3.33	2.29	4.80	4.90
1991–2000	2.63	1.96	2.57	4.87	4.35	3.37	3.86	5.75	5.60
2001–2010	3.39	2.30	3.66	6.09	4.70	3.68	3.85	6.88	6.95
2011–2021	4.49	2.86	5.75	6.72	5.11	5.72	6.29	7.79	8.32

and contributors to Global Food Systems (FAOSTAT, 2023). Conversely, this productivity boom has not reached Bolivia, with its average rice yield remaining at only 2.86 t/ha. This low productivity has made Bolivia heavily dependent on rice imports, which reached 72,000 tons in 2014 (FAOSTAT, 2023).

Rice is not native to Latin America, and Bolivia heavily depends on improved varieties or advanced breeding lines introduced from neighboring countries (Taboada et al., 2000). Initially, the Bolivian Rice Improvement Program introduced materials from Brazil, the USA, and Southeast Asia. However, in 1997 with the establishment of the Centro de Investigación Agricola Tropical (CIAT-Santa Cruz) and its collaboration with the Latin-American Fund for Irrigated Rice (FLAR), the breeding program started a phase of population improvement through recurrent selection (Taboada et al., 2005). This brought a variety of modern improved varieties (MIV) to Bolivian rice farmers. The new varieties' traits included high yielding, higher micronutrient content (Viruez and Taboada, 2013), and water-use efficiency (Grenier et al., 2010). Between 2004 and 2014, 12 MIVs were released in Bolivia and are the focus of this article. Some of the MIVs have been planted consistently in between 45 and 60% of the rice acreage since 2013 (Martinez et al., 2021) without significant changes over time (Taboada and Viruez, personal communication, March 2023).

The other 40–55% of the rice areas have also been under improved rice varieties, despite being old varieties and not bred specifically to address the production conditions in Bolivia. However, the use of these old improved varieties may be explained by the limited capacity of the country to produce certified seeds (Martinez et al., 2021). Until the late 1990s, there were no consistent efforts to produce large quantities of certified rice seed (Ortiz and Soliz, 2007). However, between 2000 and 2005, a center for certified seed production was established in San Juan de Yapacani Cooperative, with financial support from the Japanese Cooperation (OPMAC Consulting, 2009). This cooperative, integrated by Japanese descendants cultivating rice since 1951 and engaged with the technical backing from the CIAT-Bolivia, produced enough certified seed to cover 23% of the total rice area in the country (Vargas, 2014). Unfortunately, the end of the initiative discouraged many of the cooperative seed producers to continue producing certified rice seed and, therefore, the supply was reduced (OPMAC Consulting, 2009).

Although San Juan de Yapacani was also used to disseminate recommendations for better agronomic management of rice production, there was no equivalent program to the certified seed that could make other agricultural inputs broadly available, including chemical fertilizers (Viruez and Taboada, 2013). The use of chemical fertilizers has been traditionally low in Bolivian agriculture, with an average of 5.3 kg/ha compared with the 107.4 kg/ha applied on average in Latin America (Vargas, 2014). In the rice sector, only farmers with access to irrigation have been able to use the recommended quantity of chemical fertilizers, but this group only represents 10% of the total area under rice production (Ortiz and Soliz, 2007). In general, the low use of fertilizers in Bolivia is associated with the high cost and the lack of domestic production in Bolivia (Killeen et al., 2008).

In the 1980s and 1990s, there were some attempts to promote kits or packages of agricultural inputs in the country but, in general, farmers were splitting the kits and adopting the agricultural inputs independently (Godoy et al., 1998). Only more recently, and with the explicit policy of the government to achieve greater competitiveness in agriculture to improve access to domestic and international markets, the promotion of packages of rice technologies has started to be implemented (Killeen et al., 2008; World Bank, 2018). However, the recommended usage of chemical fertilizers in these packages has not been based on farm-level soil testing, which is required for the optimal use of this input (Murphy et al., 2020). Recently, some agricultural development projects led by the National Institute for Agricultural and Forestry Innovation (INIAF) and the World Bank have promoted the joint use of certified seeds and agronomic practices, reporting yield increases of up to 100% (World Bank, 2018). Nevertheless, this yield increase estimation was not done using a counterfactual framework and focused on selected farmer groups, not representing the potential effect at the national level. This fact may not allow drawing definite recommendations for a broader scaling-up of these initiatives.

3. Materials and methods

3.1. Theoretical framework and econometric approach

Over the years, agricultural land and labor markets in Bolivia—and Latin America, more broadly—have presented pronounced failures that have restricted different production factors from being allocated efficiently (Bauguil, 2003; World Bank, 2018). To model farmers' decision to adopt improved rice technologies, we follow an agricultural household model framework that allows farmers' production decisions to be non-separable from meeting household consumption objectives (Bardhan and Udry, 1999; De Janvry and Sadoulet, 2006). In our case, factors beyond rice and inputs prices, namely, households' consumption preferences and attributes, play a role in determining choices on technology adoption. Ultimately, a representative household makes a decision on the technologies used for rice production to maximize its expected utility.

Let there be J possible (mutually exclusive) packages of technologies available to produce rice, such that the indirect utility derived by the implementation can be defined as follows:

$$V_j = \mathrm{x}\theta_j + e_j, \quad for\ j = 1, ..., J \tag{1}$$

where x is a $1 \times K$ vector of attributes of the household, θ_j is a $K \times 1$ vector of unknown parameters, and e_j is an error independently and identically Gumbell (0,1) distributed. While V_j is unobservable, we observe whether the technological package j is adopted in the farm. Under a maximization process, the household chooses package g if and only if $V_g \geq V_j$, for all $g \neq j$, for $g, j \in \{1, ...J\}$. Let $d_j \in \{0, 1\}$ be defined as $d_j = 1\left[adopts\ package\ j\right]$, which implies $\sum_{j=1}^{J} d_j = 1$ from mutual exclusion. Under this setting, the probability of adopting a technological package j follows from a multinomial logit (MNL) model (McFadden, 1973) such that:

$$\begin{aligned}\Pr\left(\text{Adopting package j} \mid \mathrm{x}\right) &= \Pr\left(\mathrm{d_j} = 1 \mid \mathrm{x}\right) \\ &= \frac{\exp\left(\mathrm{x}\theta_\mathrm{j}\right)}{\sum_{\mathrm{t}=1}^{\mathrm{J}} \exp\left(\mathrm{x}\theta_\mathrm{t}\right)},\end{aligned} \tag{2}$$

and the partial effects follow:

$$\begin{aligned}\frac{\partial \Pr\left(d_j = 1 \mid \mathrm{x}\right)}{\partial x_k} &= Pr\left(d_j = 1 \mid \mathrm{x}\right) \\ &\times \left\{\theta_{jk} - \frac{\sum_{t=1}^{J} \theta_{tk} \exp\left(\mathrm{x}\theta_t\right)}{\sum_{t=1}^{J} \exp\left(\mathrm{x}\theta_t\right)}\right\};\end{aligned} \tag{3}$$

hence, the sign of coefficient estimates, $\hat{\theta}_{jk}$, does not necessarily provide a direction of the partial effects (Cameron and Trivedi, 2005; Wooldridge, 2010).

In our case, we focus on the two most spread technologies available for rice production in the Bolivian context, namely, modern improved varieties and chemical fertilizers (Rodriguez, 2009), which have long been the main production-enhancement strategies promoted by the Bolivian agricultural authorities (MDRyT, 2012). Hence, there are four feasible mutually exclusive technological packages ($J = 4$) that the rice-farming households can choose from, namely, no adoption of either technology, only MIV, only chemical fertilizers, or joint adoption of both MIV and fertilizers.

3.1.1. Impacts of technology adoption: average treatment effects

Our main target is measuring the impacts associated with the adoption of MIV and chemical fertilizers. Most previous studies on the impacts of joint technology adoption in agriculture have followed a multinomial endogenous switching regression approach (e.g., Teklewold et al., 2013; Kassie et al., 2015; Khonje et al., 2018; Shafiwu et al., 2022) focusing on estimating the average treatment effects on the treated (ATT). However, we are interested in measuring the potential impacts at the scale of the adoption of these technologies. We, therefore, should also consider those farmers who would not be "treated" in the *status quo*. Our analysis then focuses on estimating the average treatment effects (ATE) of technology adoption on rice production via optimal instrumental variable methods and exploiting an MNL model.

Following Kekec (2021), we assume that a household chooses a single technological package $j \in \{1, 2, 3, 4\}$ of agricultural inputs, let the outcome of yields under technology package j be given as follows:

$$y_j = \alpha_j + \mathrm{m}\delta_j + u_j, \tag{4}$$

where m is another $1 \times M$ vector of household attributes, δ_j is another $M \times 1$ vector of unknown parameters, and u_j is a random error. Now, let $j = 1$ be the base group for comparison of technology packages, namely, no implementation of either improved rice varieties or fertilization. Hence, the average treatment effect from using a package j to no use of enhancing practices is given as follows:

$$\begin{aligned}ATE_{j,1} &= E\left(y_j - y_1\right) \\ &= \left(\alpha_j - \alpha_1\right) + E\left(\mathrm{m}\right)\left(\delta_j - \delta_1\right).\end{aligned} \tag{5}$$

Hence, a proper estimator of the *ATE* would plug in consistent estimators derived from a sample of n individuals, namely, $\hat{\alpha}_j$ and $\hat{\delta}_j$, for $j = 1, ..., J$, and $\bar{\mathrm{m}} = \frac{1}{n}\sum_{i=1}^{n} \mathrm{m}_i$. That is, we can simply set up an estimator of the form:

$$A\hat{T}E_{j,1} = \left(\hat{\alpha}_j - \hat{\alpha}_1\right) + \left(\bar{\mathrm{m}}\right)\left(\hat{\delta}_j - \hat{\delta}_1\right), \tag{6}$$

which can be further reduced to $A\hat{T}E_{j,1} = \left(\hat{\alpha}_j - \hat{\alpha}_1\right)$ whenever $\bar{\mathrm{m}} = \mathbf{0}$ or no heterogeneity is added to the yield outcome.

As noted in Kekec (2021), we only observe the outcome under technology j (Equation 4) for those who effectively adopted technology package j within the sample. That is, the empirically observed yield outcome follows:

$$\begin{aligned}y &= d_1 y_1 + d_2 y_2 + d_3 y_3 + d_4 y_4 \\ &= \sum_{j=1}^{4} d_j \alpha_j + \sum_{j=1}^{4} d_j \mathrm{m}\delta_j + \zeta\end{aligned} \tag{7}$$

where $\zeta = d_1 u_1 + ... + d_4 u_4$. Since every d_j is in ζ, estimating (7) by ordinary least squares (OLS) will provide inconsistent estimators of α_j and δ_j, for all j. Standard instrumental variable methods would fail to account for the endogeneity in all d_j since they are also in ζ, hence failing the exclusion restriction. Nevertheless, Kekec (2021) noted that we can obtain consistent estimators by following an alternative approach in two steps[1]:

1. From a multinomial logit model of technology adoption, retrieve the predicted probabilities: $\hat{\Lambda}_{ij} = \exp\left(\mathrm{x}_i\hat{\theta}_j\right) / \sum_{t=1}^{4} \exp\left(\mathrm{x}_i\hat{\theta}_t\right)$, and then
2. Estimate Equation (7) by two-stage least squares (TSLS) using instruments $\left(\hat{\Lambda}_{ij}, \hat{\Lambda}_{ij}\mathrm{m}_i\right)$ for $\left(d_{ij}, d_{ij}\mathrm{m}_i\right)$, hence achieving consistent estimates of α_j and δ_j, for $j = 1, 2, 3, 4$.

This approach differs from traditional instrumental variables in that it uses optimal instruments and achieves asymptotic variance minimization. In addition, an important feature of this approach

1 If all elements of m are in x, identification requires that $\dim(\mathrm{x}) > \dim(\mathrm{m})$.

is that such optimality and consistency hold regardless of whether the multinomial logit is the correct underlying model of technology adoption. This reveals a clear drawback of endogenous switching regression or control function methods, which entirely rely on having the correct model for achieving consistency by including proper additional variables in the regression of interest. Finally, we can retrieve our desired measure of treatment effects by plugging in the TSLS estimates into Equation (6). Furthermore, we can obtain correct standard errors by bootstrapping (Wooldridge, 2010). Our analysis focuses on a case with no additional heterogeneity in yields (i.e., we set $\delta = \mathbf{0}$), as such addition only brings precision at the cost of requiring further instruments, which, on average, increases the odds of weak instrumentation. Our main assumption for identification is to consider membership to a farmer' association, extension services, and access to credit for agricultural inputs as variables that affect yields only through their effect on the adoption of improved varieties and fertilization.

While our approach would have also been suitable for estimating the impacts of the adoption of rice technologies on rice income, limitations on the available data made it difficult to include this outcome variable in the analysis. However, as our theoretical framework assumes that technology adoption is welfare-enhancing given that farmers make choices that maximize utility, we perform a statistical analysis to compare the Poverty Probability Index (PPI) (IPA, 2017) and the Household Dietary Diversity Score (HDDS) (FAO, 2010) across the different adoption groups.

3.2. Data

We used cross-sectional information on rice farmers in Bolivia, where producing households reported information on the main production season of 2013. This dataset, initially explored by Martinez et al. (2021), is nationally representative of the adoption of modern improved rice varieties.[2] The survey also collected information about the adoption of other agricultural practices and household socioeconomic characteristics. Sampling followed a multistage strategy, where the primary sampling units (clusters) were communities with an optimal size of roughly 14 households per community. A total of 775 households were considered in the analysis.[3] Table 2 summarizes the averages of relevant variables to our modeling strategy disaggregated by the defined technological packages. Noticeably, the largest share of farmers in our sample (45.3%) did not use either modern improved varieties (MIV) or chemical fertilizers, which is our base comparison category. Meanwhile, the adoption of only MIV reached 28.9%, while adopters of only fertilizers corresponded to 8.5% of the sample. Finally, rice-farming households using MIV and chemical fertilizers represented 17.3% of the sampled households. Due to infrequent bookkeeping among Bolivian rice farmers, it was neither possible to include the fertilization rate in the analysis nor was it possible to estimate the rice income. As expected, the lowest average yield was found among non-adopters at 1.89 t/ha, although this was not too different from the average yields of farmers adopting only chemical fertilizers (1.93 t/ha). On the other hand, adopters of only MIV had an average yield of 2.19 t/ha, and adopters of the combination of MIV and fertilizers reported an average yield of 2.79 t/ha.

Of note, 40% of total crop production in our sample was devoted to rice, and the average rice acreage fell into the small/medium-scale farm definition (97.4% of the sample). The descriptive statistics in Table 2 also show that while non-adopters had the lowest average farm size (32 ha), farmers adopting both MIV and chemical fertilizers had, on average, 94 ha. Adopters of only one technology (MIV or fertilizers) were more around the mid-size farms of the sample.

There was a higher percentage of being a member of a farmer organization, having received extension services, and receiving credit for purchasing agricultural inputs among the adopters of rice technologies. The percentage of farmers receiving extension and using credit services was larger among the fertilizers-only adopters (27.3 and 21.1%, respectively) than among MIV-only adopters (21 and 13.8%); however, we observed the opposite trend among those who were part of a farmers' association (15.2% *vis-à-vis* 21.4%). Likewise, adopters of the MIV and fertilizers were located farther from San Juan the Yapacaní, the main center of diffusion of rice technologies in Bolivia. On average, adopters of MIV-only, fertilization-only, or dual-adopters were, respectively, 8, 49, and 59% closer to the diffusion center than the in-sample average. In contrast, non-adopters were ∼36% farther away than the average farmer.

We also included in the analysis off-farm income and revenues from animal and by-product sales as covariates, as these sources of income may show a transition out of agricultural production (Larochelle and Alwang, 2015). Our sample showed that dual-adopters had the highest off-farm income on average. Conversely, revenues from animal and by-product sales were reported only by between 27 and 32% of the different types of adopters of rice technologies. Finally, schooling levels were higher among single or dual adopters than among non-adopters.

While the analysis of this 10-year-old dataset may raise questions about the relevance of the results and their policy implications, the rice production, consumption, and marketing conditions remain similar to the situation described in 2013

2 The total sample used in Martinez et al. (2021) was of 802 observations, and was nationally representative, following a two-stage random procedure (First selected primary sample units (PSU) and then households in each PSU). To estimate the minimum sample required, we first estimated a simple random sample expecting to estimate up to 60% of adoption of MIV, a 95% level of confidence and a 3.5% level of precision. Then, to account for the two-stage procedure, we included a conservative intra-class correlation of 0.05 and estimated a design effect of 1.55. Thus, the simple random sample grew from 497 households randomly distributed among major rice producing areas to 770 households selected in at least 65 PSU. We ended up interviewing 845 households in 98 farm communities but had a valid sample of 802 households. The current study uses 775, which is a reduction of 27 observations. This was due to the lack of reliable yield data on these 27 observations, but the sample remains nationally representative. We have added a footnote to explain in detail the sampling procedure.

3 The full sample used in Martinez et al. (2021) consisted of 802 observations, but for this paper analysis, complete information on rice yields and main covariates was only available for 775 households due to limited bookkeeping.

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TABLE 2 Descriptive statistics of the sample.

	Sample		No adoption		Improved varieties (MIV)		Fertilization		MIV + fertilization	
Share of sample	–		45.3%		28.9%		8.5%		17.3%	
Variables	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Farm size (ha)	51.60	106.8	31.68	45.0	58.11	91.4	47.81	64.1	94.74	205.0
Paddy rice yield (t/ha)	2.13	1.4	1.89	1.27	2.19	1.4	1.93	1.53	2.79	1.48
Share of rice within the farm (%)	42.84	37.7	40.21	40.8	44.69	35.9	48.20	38.6	43.98	30.8
Member of a farmer association (1 = yes) (%)	15.9		7.1		21.4		15.2		29.9	
Received extension services (1 = yes) (%)	18.5		11.1		21.0		27.3		29.1	
Received credit for purchasing agricultural inputs (1 = yes) (%)	13.0		4.8		13.8		21.2		29.1	
Distance to San Juan de Yapacaní (log scale)	4.00	1.4	4.36	1.3	3.92	1.3	3.51	0.9	3.41	1.6
Schooling of the head of the household (years)	6.08	4.3	5.25	3.8	6.73	4.4	5.58	4.2	7.43	5.0
Age of the head of the household (years)	45.95	12.5	46.65	12.9	45.73	12.8	47.06	12.3	43.92	11.1
Off-farm income in the household (1 = yes) (%)	48.1		45.9		48.7		47.0		53.7	
Income from animal sales and by-products (1 = yes) (%)	31.9		35.3		27.7		31.8		29.9	
Beni (%)	29.4		42.5		26.3		9.1		10.4	
Cochabamba (%)	10.3		8.3		17.0		9.1		5.2	
Observations	775		351		224		66		134	

Source: elaborated by the authors.

TABLE 3 Coefficient estimates for multinomial logit (MNL) model of technology adoption.

Variables	(1) Improved varieties (MIV)	(2) Fertilization	(3) MIV + fertilization
Farm size (log scale)	0.334** (0.136)	0.420*** (0.162)	0.818*** (0.150)
Share of rice within the farm (%)	0.015*** (0.005)	0.020*** (0.006)	0.020*** (0.006)
Member of a farmer association (1 = yes)	0.734* (0.409)	0.227 (0.485)	1.015*** (0.334)
Received extension services (1 = yes)	0.169 (0.330)	0.583* (0.317)	0.363 (0.319)
Received credit for purchasing agricultural inputs (1 = yes)	0.641* (0.389)	0.908** (0.435)	1.043*** (0.375)
Distance to San Juan de Yapacaní (log scale)	−0.014 (0.098)	0.026 (0.133)	0.031 (0.142)
Schooling of the head of the household (years)	0.061** (0.028)	−0.004 (0.044)	0.042 (0.032)
Age of the head of the household (years)	0.007 (0.009)	0.007 (0.014)	−0.011 (0.011)
Off-farm income in the household (1 = yes)	−0.063 (0.200)	0.013 (0.286)	0.220 (0.239)
Income from animal sales and by-products (1 = yes)	−0.363 (0.222)	−0.403 (0.333)	−0.404* (0.244)
Constant	−2.746*** (0.846)	−3.966*** (1.202)	−4.540*** (0.971)
Observations	775	775	775
Department controls	Yes	Yes	Yes

Clustered standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.
Source: elaborated by the authors.

(Taboada and Viruez, personal communication, March 2023). Furthermore, current agricultural policies to support the increased productivity and competitiveness of Bolivian agriculture and to mitigate the effects of the COVID-19 pandemic are calling for enhancing the access to improved crop technologies that could lead to Bolivia's self-sufficiency and export orientation (MDRyT, 2017, 2021).

4. Results and discussion

For our identification strategy, we required that the instruments have sufficient explanatory power within the multinomial logit (MNL) model of technology adoption. We report the estimates of the covariates in the MNL specification and their marginal effects in Tables 3, 4, respectively. Our findings showed a positive and significant effect of receiving credit for production inputs across all possible adoption of rice technologies scenarios (Table 3). Farm size and being a member of a farmers' association also had positive effects, although among MIV-only or dual adoption. On the other hand, extension services only significantly affected the adoption of chemical fertilizers. We did not find a significant effect on the adoption of any rice technology due to the distance to the main rice technological center in Bolivia, which differs from an earlier analysis (Martinez et al., 2021). However, both results are not directly comparable. While Martinez et al. (2021) explored the joint determinants of adoption unconditional to other technologies, our estimation specifically conditions whether other inputs are accounted for in the production system.

Focusing on marginal effects estimation, we found that most covariates clearly reduced the odds of being a non-adopter (Table 4). On the other hand, we found that the magnitude of the increase in the probability of adopting a specific technological package varied across the three adoption scenarios. A 1% increase in farm size increased the odds of becoming a full adopter by 0.07% points, while it decreased the odds of being a non-adopter by 0.09% points. In addition, being a member of a farmers' association reduced the odds of opting out of technology by 14.1% points. In comparison, it increased the odds of becoming a dual adopter by 7.9% points. That being said, receiving credit for rice production was correlated with an increase of 7.4% points in the likelihood of using both technologies. On average, an additional year of schooling increased the odds of adopting MIV by 1% point, while at the same time, it reduced the probability of being a non-adopter. Having animal sales as a source of income seemed to discourage technology adoption, making farmers 7.4% points less likely to use either chemical fertilizers or MIV, on average. Finally, we found no significant marginal effects of accessing extension services, the distance to the main rice technological center, or off-farm income on the adoption decisions.

Table 5 reports the estimated average treatment effects (ATE) of adopting different rice technologies on rice paddy yields, comparing OLS and TSLS estimates. Columns 1 and 3 compare the results in levels, whereas columns 2 and 4 take the comparison to logarithmic scales (percentage increases). Under the assumption of strict exogeneity of the decision to adopt rice technologies, the adoption of MIV alone would have significantly increased (at 10%) rice yields by 0.3 t/ha (16.6%). Likewise, the joint adoption of MIV and chemical fertilizers would have significantly increased (at 1%) rice yields by 0.91 t/ha (48.5% increase) in comparison with the non-adopters' group. Adopting only chemical fertilizers would not have had a significant effect on rice yields.

Once the potential endogeneity of the adoption of rice technologies is controlled for, the estimates of the impacts on rice yields change. Although we still found a positive effect of adopting only MIV, the effect is no longer statistically different

TABLE 4 Marginal effect estimates for multinomial logit (MNL) model of technology adoption.

Variables	(1) No adoption	(2) Improved varieties (IV)	(3) Fertilization	(4) IV + fertilization
Farm size (Log scale)	−0.091*** (0.021)	0.011 (0.018)	0.007 (0.010)	0.073*** (0.013)
Share of rice within the farm (%)	−0.003*** (0.001)	0.001** (0.001)	0.001** (0.000)	0.001** (0.001)
Member of a farmer association (1 = yes)	−0.141** (0.061)	0.083 (0.071)	−0.021 (0.034)	0.079** (0.032)
Received extension services (1 = yes)	−0.055 (0.050)	−0.001 (0.055)	0.032 (0.027)	0.024 (0.029)
Received credit for purchasing agricultural inputs (1 = yes)	−0.152** (0.068)	0.047 (0.060)	0.031 (0.028)	0.074** (0.031)
Distance to San Juan de Yapacaní (log scale)	−0.001 (0.020)	−0.005 (0.013)	0.002 (0.008)	0.004 (0.013)
Schooling of the head of the household (years)	−0.009* (0.005)	0.010** (0.005)	−0.003 (0.003)	0.002 (0.003)
Age of the head of the household (years)	−0.001 (0.002)	0.002 (0.001)	0.001 (0.001)	−0.002* (0.001)
Off-farm income in the household (1 = yes)	−0.004 (0.035)	−0.024 (0.033)	−0.002 (0.019)	0.029 (0.024)
Income from animal sales and by-products (1 = yes)	0.074** (0.036)	−0.039 (0.038)	−0.013 (0.025)	−0.022 (0.025)
Observations	775	775	775	775
Department controls	Yes	Yes	Yes	Yes

Clustered standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.
Source: elaborated by the authors.

TABLE 5 Estimated impact of different technological adoptions on paddy rice yields.

Treatment	(1) Yield	(2) Yield (log)	(3) Yield	(4) Yield (log)
Modern improved varieties (MIV)	0.300* (0.163)	0.166** (0.084)	0.959 (1.463)	0.631 (0.841)
Fertilization	0.049 (0.229)	−0.117 (0.157)	−1.473 (1.225)	−1.049 (0.790)
MIV + fertilization	0.911*** (0.218)	0.485*** (0.107)	1.815** (0.833)	1.030** (0.448)
Constant	1.889*** (0.096)	0.376*** (0.068)	1.672*** (0.353)	0.227 (0.219)
Observations	775	775	775	775
Method	OLS	OLS	TSLS	TSLS

Robust regression test (endogeneity test suggested by Wooldridge, 1995), $F_{(3,92)} = 2.59627$ ($p = 0.0571$), Kleibergen-Paap rank chi-square statistic: 2.80 (p-value: 0.08).
Bootstrap standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.
Source: elaborated by the authors.

from zero. Likewise, we continued to find a statistically insignificant effect of the adoption of only chemical fertilizers on rice yields. However, the adoption of MIV and chemical fertilizer jointly would increase more than double the expected rice yields, with a potential increase of roughly 1.67 t/ha (103% increase) compared with those without rice technology. As the endogeneity (Robust regression, Wooldridge, 1995) and the under-identification (Kleibergen-Paap rank statistic) tests rejected their null hypothesis, we prefered the results of the TSLS specification.

Our results are consistent with previous findings that the decision to jointly adopt a package of agricultural technologies has a significant and large effect on crop productivity in comparison with the adoption of individual crop technologies or the non-adoption (Teklewold et al., 2013; Kassie et al., 2015; Khonje et al., 2018; Shafiwu et al., 2022). While there is evidence that genetic improvement by itself could bring a variety of productivity and welfare impacts (Arouna et al., 2017; Zeng et al., 2017; Wossen et al., 2019; Sellitti et al., 2020), some studies have reported that the adoption of only improved crop varieties has not yielded some of the expected impacts due to heterogeneous profitability on adopting improved varieties in Kenya (Suri, 2011), unsustainable rainfall to keep the advantage of NERICA rice varieties in Uganda (Kijima et al., 2011), or inability to show their full potential due to absence of major stresses during the evaluation period (Mills et al., 2022).

An increasing number of studies are providing evidence of much larger impacts coming from complementary crop technologies that are made available as packages to small farmers (Emerick et al., 2016; Tabe-Ojong et al., 2023). These findings support efforts to improve agricultural extension and technical assistance for smallholders in different regions aiming at achieving expected impacts (Berhane et al., 2018; Hörner et al., 2022). In Bolivia, there is a group of agricultural development initiatives that are trying to identify the right mix of agronomic practices to support small farmers. Preliminary reports suggest that crop yields could more than double due to these technology packages (World Bank, 2018). However, this needs to be confirmed with a more rigorous evaluation approach.

Although we were unable to estimate the impacts of the adoption of rice technologies on rice income, comparing the PPI and HDDS between adopters of one technology, adopters of both technologies, and non-adopters provides an indication of the effect of technology adoption on welfare indicators (Table 6). The PPI measures the probability that a household falls under the Bolivian poverty line in 2013–2014, while the HDDS is a dietary diversity index that captures the number of food groups consumed by all household members in the same period of time. We found that non-adopters of either chemical fertilizers or MIV are at a disadvantage compared to adopters of these technologies in both indicators. Adopting only chemical fertilizers correlates with an 8.6% point reduction in the probability of falling under the poverty line. Furthermore, adopting only MIV reduces this probability by 13.5% points, and adopting both technologies implies a reduction of 19.8% points. Likewise, farmers adopting one or both technologies simultaneously are better off in terms of dietary diversity than non-adopters.

While our study documented a relatively low joint adoption of improved rice varieties and chemical fertilizers, our findings also revealed the potential benefits for future scaling-up strategies. Although roughly less than a fifth of Bolivian rice producers are joint adopters of MIV and chemical fertilizers, partial adoption of one of these technologies already occurs in 37% of farmers. To boost the adoption of packages of rice technologies, the rice sector could rely on mechanisms for the widespread dissemination of such technologies, like in the case of vouchers for agricultural inputs (Salazar et al., 2015).

Bolivia has enormous potential for significantly boosting rice yields through the promotion of packages of rice technologies. Currently, Bolivia's production conditions with a predominance of rainfed agriculture are similar to Brazil's situation 20 years ago. However, improving the small farmers' access to packages of rice technologies as Brazil did (Fitz-Olivera and Tello-Gamarra, 2022) could significantly increase rice production. This would not only allow Bolivia to achieve the desired self-sufficiency in rice production but, like many other Latin-American countries, also become an important exporter of rice (Fitz-Olivera and Tello-Gamarra, 2022) and contribute to Global Food Systems.

5. Conclusion

In this article, we studied how Bolivian farmers make adoption decisions for complementary rice technologies and then examined the potential impact of this adoption on rice yields. As in most Latin-American countries, different improved rice technologies have been made available to rice farmers in Bolivia. However, the adoption of these technologies remains constrained, and rice yields are among the lowest in the region. We aim to better understand the adoption of improved rice varieties and chemical fertilizers when both technologies are made available simultaneously.

Taking advantage of a nationally representative plot and household survey of 775 rice growers in Bolivia and using a multinomial logit model and optimal instrumental variable approach, we report significant and strong impacts of the joint adoption of improved rice varieties and chemical fertilizers. Once we controled for the potential endogeneity of the decision to

TABLE 6 Comparison of some welfare measures across different adoption packages.

	Poverty probability index	Std. dev.	Difference in means	Std. error	Household dietary diversity score	Std. dev.	Difference in means	Std. error
Overall	48.17	29.05	–	–	10.51	1.34	–	–
No adoption	56.06	27.97	–	–	10.19	1.4	–	–
Modern improved varieties (MIV)	42.48	29.26	−13.58***	3.33	10.57	1.29	0.35**	0.15
Fertilization	47.47	28.38	−8.6**	4.15	11.08	1.11	0.86***	0.17
MIV + fertilization	36.22	25.68	−19.84***	3.70	10.98	1.09	0.76***	0.14

The table reports the average Poverty Probability Index (PPI) and Household Dietary Diversity Score (HDDS) within every group. The PPI reports the probability that a household falls below the national poverty line, while the HDDS is a count variable referring to the number of food groups consumed by the household's members in the 24 h prior to the survey. Difference in means is the OLS coefficients (with associated standard errors) of the regression of either PPI or HDDS on three dummy variables indicating whether the observation is on a specific group (i.e., adopts a single specific practice or both), thus capturing the difference with respect to those who do not adopt any technology ($N = 775$). Standard errors are clustered at the village (community) level. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

adopt rice technologies, we found that adopting only improved rice varieties or adopting only chemical fertilizers does not significantly affect rice yields; nevertheless, by exploiting the complementarities of these two technologies, the joint adoption of MIV and chemical fertilizers, more than double rice the yields.

Although we were unable to estimate the impacts of the adoption of improved rice varieties and chemical fertilizers on rice income, we found that adopting these technologies is correlated with a reduced probability of Bolivian households falling under the poverty line and with a higher dietary diversity index. Adopting both technologies simultaneously has an even stronger positive effect. Future studies should put more emphasis on addressing the limited bookkeeping among Bolivian farmers to collect reliable data on input use and cost. This would allow us to better estimate rice and farm income and the variable cost of using different technologies.

Based on these research findings, we highlight the implications on rice production and the potential contribution to the Global Food System of the joint adoption of rice technologies. Our results support more recent strategies to promote packages of agricultural technologies instead of single technologies within extension services for small farmers. In countries like Bolivia, where the majority of rice production still relies on rainfed cropping systems, exploiting the complementarities for different technologies may not only increase the adoption of these technologies but also boost rice yields to levels that are comparable to other Latin-American countries producing rice under similar conditions. As this has been the rice development pathway observed in these neighboring countries, broader dissemination of rice technologies has the potential to make Bolivia achieve self-sufficiency in rice production and become a net exporter contributing to Global Food Systems. Future studies that collect additional and more complete rounds of data should be able to confirm this article's findings.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

The conception and design of the study were contributed by JM and RL. Material preparation and data collection were done by RL and CG. Analysis and the first draft of the manuscript were written by JM and RL. The manuscript was reviewed by all authors and edited by RL. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

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