IFPRI Discussion Paper 01910

February 2020

Adoption and Impact of Hybrid Rice in India

Evidence from a Large-Scale Field Survey

Digvijay S. Negi

Anjani Kumar

Pratap S. Birthal

Gaurav Tripathi

South Asia Regional Office

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

The International Food Policy Research Institute (IFPRI), established in 1975, provides research-based policy solutions to sustainably reduce poverty and end hunger and malnutrition. IFPRI's strategic research aims to foster a climate-resilient and sustainable food supply; promote healthy diets and nutrition for all; build inclusive and efficient markets, trade systems, and food industries; transform agricultural and rural economies; and strengthen institutions and governance. Gender is integrated in all the Institute's work. Partnerships, communications, capacity strengthening, and data and knowledge management are essential components to translate IFPRI's research from action to impact. The Institute's regional and country programs play a critical role in responding to demand for food policy research and in delivering holistic support for country-led development. IFPRI collaborates with partners around the world.

AUTHORS

Digvijay S. Negi (digvijay@igidr.ac.in) is an assistant professor in the Indira Gandhi Institute of Development Research, Mumbai, Maharashtra, India.

Anjani Kumar (anjani.kumar@cgiar.org) is a research fellow in the South Asia Regional Office of the International Food Policy Research Institute (IFPRI), New Delhi, India.

Pratap S. Birthal (ps.birthal@icar.gov.in) is Indian Council of Agricultural Research (ICAR) national professor in the ICAR–National Institute of Agricultural Economics and Policy Research, New Delhi, India.

Gaurav Tripathi (g.tripathi@cgiar.org) is a senior research analyst in the South Asia Regional Office of IFPRI, New Delhi, India.

Notices

Abstract

India's rice production has come under pressure from a number of biotic and abiotic stresses, resulting in a significant deceleration in its productivity growth in recent years. Hybrid rice technology is considered a sustainable option for boosting productivity growth. The adoption rate of hybrid rice technology, however, has remained sluggish. This paper, using data from a large-scale, nationally representative survey of farm households, identifies causes of low adoption of hybrid rice technology and subsequently assesses the impact of low adoption on crop yield. Our findings demonstrate that in India, hybrid rice is often grown on relatively poor soils, resulting in greater costs for irrigation as well as for other inputs, such as fertilizers, essential for growth. Although hybrid rice technology appears to be scale neutral, farmers' poor access to information on its biochemical traits and agronomic practices, as well as poor access to financial resources, hampers scaling up its adoption. More important, our findings reveal that the relative yield advantage of hybrids over open-pollinated modern varieties is not large enough to incentivize rapid adoption of hybrid rice technology.

JEL codes: Q1, Q16, Q18
Keywords: Hybrid rice, adoption, impact, India

Acknowledgments

We are grateful to the Indian Council of Agricultural Research (ICAR) for extending financial support to conduct this study.

This study was undertaken as a part of the CGIAR Research Program on Policies, Institutions, and Markets (PIM) led by the International Food Policy Research Institute (IFPRI), and as part of ICAR-IFPRI workplan.

1. Introduction

In India, rice is one of the most important staple food crops, in terms of both consumption and production. Fueled by technological change (that is, the arrival of high-yielding seeds, chemical fertilizers, and agrochemicals) and backed by investments in irrigation, infrastructure, and institutions (credit and extension services) as well as sustained policy support (procurement of output by the central government at pre-fixed prices and provision of input subsidies), India's rice production increased tremendously in the past five decades, from 31 million tons[1] in 1966/1967 to 110 million tons in 2016/2017 (India, MoAFW 2018). Nonetheless, the need to produce more rice remains as urgent as ever to meet the nation's growing demand (Kumar and Joshi 2016).

Rice is grown in diverse agroecologies in India, and most of these have been confronting biotic and abiotic pressures, such as quantitative and qualitative deterioration of natural resources (that is, land and water), increasing frequency of extreme climatic events (for example, droughts and floods), rising input costs, declining profits, and shrinking farm sizes. India's land frontier appears to have reached its extensive margin of exploitation—for the past three decades the net sown area has been stagnating at around 142 million hectares (India, MoAFW 2018). So has the acreage under rice, at around 43 million hectares. Thus, prospects for growth through area expansion are not optimistic. Growing water scarcity is another key constraint to production of rice (a water-guzzling crop). More than half of India's land is water-stressed (Shiao et al. 2015). Of the utilizable water, over 86 percent is used for irrigation and almost two-thirds comes from underground resources. In fact, over time, Indian agriculture's reliance on groundwater has increased considerably, leading to overexploitation of groundwater beyond its sustainable limits in several parts of the country. Climate change has also become a real threat to sustainable development of agriculture and agriculture-based livelihoods. The frequency of extreme climatic events such as droughts, floods, and heat waves has increased in the recent past and is predicted to rise in the plausible future climate scenario (IPCC 2018), the food security and livelihood consequences of which are more serious than those of mean changes in the climate (Birthal et al. 2015).

More important, the technological gains realized from the adoption of short-duration, fertilizer-responsive, semi-dwarf, high-yielding varieties have started slowing down. Yield growth of rice, after attaining a peak of 3.6 percent per year during the 1980s, has decelerated to 1.6 percent per year in the decade ending 2016/2017 despite the increasing use of modern seeds, chemical fertilizers, and other inputs. Arresting deceleration in yield growth is therefore vital to maintaining self-sufficiency in rice supply and, thus, to improving the livelihoods of the millions of smallholder farmers who dominate Indian agriculture. Hybrid rice technology has the potential to reverse the deceleration in yield growth and to improve the profitability of smallholder rice production systems. Hybrids are claimed to have a yield advantage of 15–30 percent over conventionally bred open-pollinated varieties (Janaiah and Xie 2010; Prakash et al. 2017; Spielman, Kolady, and Ward 2013).

Fascinated by the impressive performance of hybrid rice technology in China during the 1970s and 1980s, the Indian Council of Agricultural Research (ICAR) initiated a systematic research program for development of hybrid rice toward the late 1980s and released the first hybrid for commercial cultivation in 1994 (cited in Janaiah and Xie 2010). Subsequently, concerted research efforts of both the public and private sectors led to the development and release of a number of rice hybrids.[2]

[1] *Tons* refers to metric tons throughout.
[2] By 2018, the number of hybrids had reached to 105.

Despite the claim of higher yield over the inbred varieties, hybrid rice may have occupied barely 10 percent of the total rice-cropped area in India by 2017/2018.[3] This discrepancy compels one to look into the question of why the adoption of hybrid rice technology has remained so low. There could be several reasons—technological, economic, ecological, institutional, and social—for the poor adoption of hybrid rice technology, pointing to the need for an in-depth probe. From the technological perspective, hybrid vigor[4] is the basis of yield gain over conventionally bred open-pollinated varieties; however, these yield gains decline drastically after the first-generation (F1) hybrid seeds. This characteristic compels farmers to purchase fresh seeds every season to sustain the yield gains, in contrast to the open-pollinated or inbred varieties, the grains of which can be stored and used as seeds for sowing in the subsequent season, resulting in no yield penalty. Another often-cited reason for the low adoption of hybrid rice technology is its substantially higher cost of acquisition—that is, the price of seeds. In India, the hybrid seed business, including production and marketing, is controlled by a few private companies. In 2018, of the total hybrid varieties released for commercial cultivation, more than two-thirds came from the private sector. Hybrid rice seed is 6–10 times higher in price than the seeds of the open-pollinated varieties developed, produced, and marketed by public-sector agencies (Spielman, Kolady, and Ward 2013). Resource-poor smallholder farmers, therefore, cannot afford frequent or regular purchases of hybrid seeds.

Some studies, based on evidence from small-scale farm surveys, have reported poor yield gains, inferior grain quality, greater susceptibility to insect pests and diseases, and low output price as important factors discouraging farmers from adopting hybrid rice technology (Janaiah 2000, 2002; Janaiah and Xie 2010; Praksah et al. 2017). Lack of information on hybrid rice technology and its agronomic practices, poor-quality seeds, and higher seed price are also important reported reasons for the poor adoption of hybrid rice technology (Spielman, Kolady, and Ward 2013; FAO 2014). From a large-scale survey in Bangladesh, Mottaleb, Mohanty, and Nelson (2014) identified lack of irrigation and poor access to institutional credit as important constraints on the adoption of hybrid rice technology.

The quality of natural endowments, or the agroecological conditions of a region, are important for realization of the potential benefits of a technology. Based on a field survey in a few Indian states, Janaiah and Xie (2010) reported that hybrids have a 25–30 percent yield/profit advantage over open-pollinated varieties in rainfed regions, whereas their performance in irrigated regions is found to be pretty much the same as that of open-pollinated varieties. Thus, in irrigated regions, the small or negligible yield gains, coupled with higher seed prices, point toward the possibility that the marginal cost of production of hybrid rice is higher than its marginal benefits.

Most of these studies, the exception being Mottaleb, Mohanty, and Nelson (2014), are based on small samples and often overlook the critical role of factors such as topography, soil type, rainfall, irrigation, infrastructure, information, and institutions, which all matter in exploiting the potential gains of hybrid rice technology. In India, rice is grown in diverse agroecological conditions; hence, the empirical evidence from small-scale surveys is of limited use for policy actions.

This paper, using data from a large-scale farm survey, examines the role of socioeconomic, institutional, and agroecological factors in the adoption of hybrid rice technology, and

[3] This estimate is based on the volume of sales of first-generation seeds.
[4] Hybrid seed is the first-generation seed developed by crossing two distantly related varieties, one of which is male and sterile.

subsequently assesses the technology's impact on crop yield, controlling for several observed and unobserved farm and farm household characteristics.

The rest of the paper is organized as follows. Section 2 describes the sampling procedure and data, followed by Section 3, on descriptive statistics. The empirical strategy for quantifying the impact of hybrids on yield is outlined in Section 4. Section 5 discusses results, and concluding remarks are made in the last section.

2. Data

The data used in this paper have been extracted from a nationally representative, large-scale survey of farm households conducted by the International Food Policy Research Institute (IFPRI) in 2017/2018. The main aim of this survey was to understand the diffusion patterns of modern varieties of important crops in major Indian states and the socioeconomic factors underlying any differences in these patterns.

The survey was conducted following a multistage sampling procedure, with the respondent's state as the first stage and the household as the ultimate unit of sampling. Initially, all states were considered in the sampling design. However, taking into consideration the contiguity of states, the relative sizes of their agricultural sectors, and similarities or dissimilarities in agroclimatic and socioeconomic conditions, the sampling design was modified to merge smaller states and bifurcate larger states (Table A1 in the appendix). Accordingly, except for Assam, all the states in the northeastern region (that is, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, and Sikkim), because of their contiguity, small agricultural sector, and fairly similar agroecological and socioeconomic conditions, were considered a single unit for the first-stage sampling. On the other hand, Uttar Pradesh, one of the largest states of India, because of considerable spatial heterogeneity in its agroclimatic and socioeconomic conditions, was bifurcated into eastern Uttar Pradesh and western Uttar Pradesh. Uttarakhand, once a part of Uttar Pradesh, was merged with that state's western region. Likewise, Telangana was given back to its parent state, Andhra Pradesh.

For sampling of the units below the state, we compiled a list of districts in each state, of blocks in each district, and of villages in each block from the 2011 census of India. In each state, the districts were ranked in ascending order of their combined share of five major crops in the total cropped area in the state, and accordingly, 13 districts, representing different agroclimatic conditions, were selected for further sampling of blocks, villages, and households. From each district three blocks, and from each block two villages were randomly selected. Finally, from each village a sample of around 20 farm households was drawn at random.

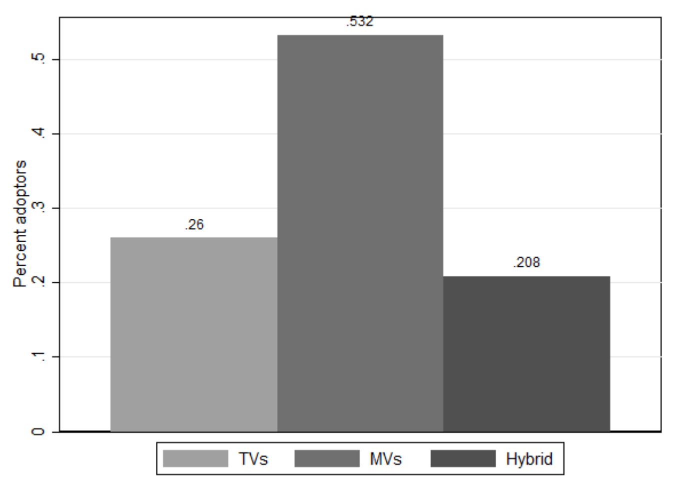
From the selected households, information was collected on several farm and household characteristics, such as landholding size, soil type, irrigation source(s), acreage allocations to crops and their varieties, sources of seeds, crop yields, access to information and institutional credit, and sociodemographic characteristics such as family size, religion, caste, age, and education.

The survey canvassed 30,540 farm households. However, for our purposes, we retained only the households that had grown rice in the year of the survey. Rajasthan and Madhya Pradesh possess miniscule area under rice cultivation; hence the observations from these states are not included in the analysis. Table A1 in the appendix provides the sample size of rice-growing households from each state.

3. Descriptive Statistics

Based on their year of release for commercial cultivation, the open-pollinated varieties were classified as "traditional" or "modern." The varieties that were less than 15 years of age at the time of the survey are classified as modern varieties (MVs), and those more than 15 years old are considered traditional varieties (TVs).[5]

Figure 1. Adoption rates of traditional varieties, modern varieties, and hybrids, India, 2017/2018



Source: Authors' calculations using data from International Food Policy Research Institute - Indian Council of Agricultural Research national farm household survey, India, 2017/2018.
Note: MV = modern variety; TV = traditional variety.

Table 1 shows the distribution of farm households growing TVs, MVs, and hybrids, their shares in the total rice-cropped area, and their yields. Figure 1, in bar plots, shows the adoption of TVs, MVs, and hybrids. Approximately 79 percent of the farm households in our sample cultivated open-pollinated varieties—53 percent MVs and 26 percent TVs. Hybrid rice was grown by about one-fifth of the households. Their area shares also follow a similar pattern, with MVs occupying 61 percent of the total rice-cropped area, followed by TVs (21 percent) and hybrids (18 percent).

Hybrids and MVs possess a considerable yield advantage over TVs (Table 1 and Figure 2). The average yield of hybrid paddy is estimated to be 5.4 tons per hectare, about 21.2 percent higher than the average yield of TVs. The yield advantage of MVs, however, is relatively smaller (14.8 percent higher than the yield of TVs). Putting it differently, the difference between the mean yield of hybrids and that of MVs is not large enough to induce farmers to switch—hybrids have a yield advantage of only 5.6 percent over MVs.

[5] The government often does not include varieties that are more than 15 years of age in its seed supply chain.

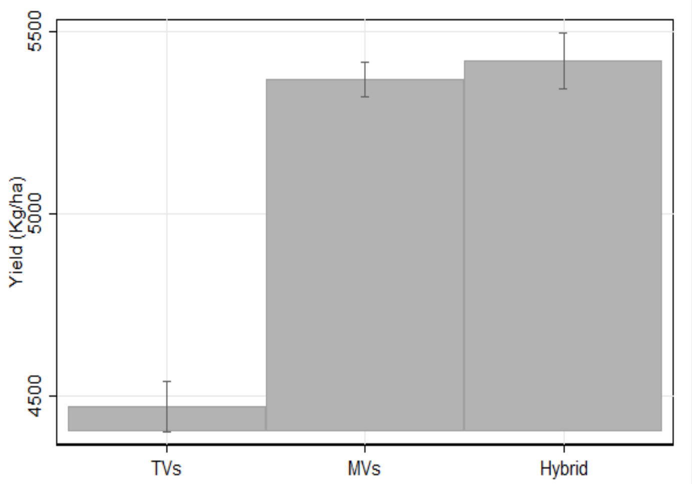
Table 1. Distribution of traditional varieties, modern varieties, and hybrids

Variable	TVs	MVs	Hybrids	Total
Percentage of households	26.0	53.2	20.8	100.0
Percentage of area	20.6	61.5	17.9	100.0
Paddy yield (kg/hectare)	4,470	5,130	5,419	5,011
Observations	4,963	8,883	3,990	17,836

Source: Authors' calculations using data from International Food Policy Research Institute - Indian Council of Agricultural Research national farm household survey, India, 2017/2018.
Note: MV = modern variety; TV = traditional variety.

Besides the varietal traits (that is, yield gain, grain quality, and stress tolerance), several other factors may also influence the adoption of hybrid rice technology. These include agroecological conditions (for example, soil type, precipitation, and irrigation), farmers' awareness of the technology, availability of seeds, endowment of resources (for example, land, labor, and capital), and so on.

Figure 2. Realized yields from traditional varieties, modern varieties, and hybrids



Source: Authors' calculations using data from International Food Policy Research Institute - Indian Council of Agricultural Research national farm household survey, India, 2017/2018.
Note: MV = modern variety; TV = traditional variety. Shaded region denotes 95 percent confidence interval.

A widely held belief is that resource-poor farmers cannot afford frequent purchases of hybrid seeds because of their significantly higher prices, compared with the seeds of open-pollinated varieties. To know whether this belief is true or not, we specifically investigated households' sources of seeds for hybrid versus conventionally bred varieties (Table 2). As expected, about 90 percent of the hybrid rice farmers procured their required seed from private seed companies. About 8 percent of them used grains saved from their previous harvest. The presence of the public sector in the hybrid seed business is extremely limited; only 2.2 percent of households said they procured seeds from government agencies.

Table 2. Farmers' source of seeds of varieties and hybrids

Source	TVs	MVs	Hybrids	Total
Private seed companies	25.05	22.38	89.62	38.16
	(1,243)	(1,988)	(3,576)	(6,807)
Government agencies	2.22	60.71	1.95	31.29
	(110)	(5,393)	(78)	(5,581)
Farm saved/exchanged	72.74	16.91	8.42	30.54
	(3,610)	(1,502)	(336)	(5,448)
Total	100	100	100	100
	(4,963)	(8,883)	(3,990)	(17,836)

Source: Authors' calculations using data from International Food Policy Research Institute - Indian Council of Agricultural Research national farm household survey, India, 2017/2018.
Note: MV = modern variety; TV = traditional variety. Number of observations in parentheses.

A majority of the households growing MVs relied on purchased seeds procured from public-sector agencies. Over 61 percent of the surveyed households procured seeds of MVs from public-sector agencies, including research and extension institutions. Private seed companies were the next-most-important source (22 percent) of such seeds. The use of farm-saved seeds was limited to 17 percent of the growers. On the other hand, more than 72 percent of the households cultivating TVs used seeds saved from the previous harvest or acquired from fellow farmers. Private seed companies are the second-largest source of seeds for TVs. The supply of seeds for TVs from government agencies is extremely limited.

Many other factors could also differentiate farm households in their choice of open-pollinated varieties versus hybrids. Table 3 presents the means of some important characteristics of the farm households growing TVs, MVs, and hybrids. There is no significant difference between adopters and nonadopters of hybrids in resource endowments and demographic characteristics (age, education, and gender of household head). Similarly, the landholding size of adopters and nonadopters of hybrid rice is pretty much similar. Likewise, the household size (a proxy for household labor endowment) also does not differ much between adopters and nonadopters of hybrid rice.

Irrigation, however, appears to differentiate households in their choice of seeds. Adoption of hybrids and MVs is higher among the households who have a reliable source of irrigation, that is, tube wells. Among adopters of hybrid rice, over 43 percent have tube wells on their farms, as compared with 33 percent and 18 percent of the growers of MVs and TVs, respectively. In fact, the cultivation of TVs is more prominent among those who rely on rainfall and canal irrigation. Hybrid rice is also grown under rainfed conditions, but only on a limited scale.

Soil type may also differentiate farm households in their choice of seeds. Generally, loam, sandy loam, and clayey soils are preferred for rice cultivation because of their better water-holding capacity. Our findings, however, show that hybrid rice, although grown on all types of soils, is grown more often on black and red soils, which are relatively less fertile and have lower water-holding capacity than the other soil types.

Households' access to information and financial resources is critical to their adoption of new technologies such as hybrid rice. From Table 3 we notice that farm households, in general, do not have much access to institutional finance, but growers of hybrids and MVs have relatively better access to it. Information sources are also different for adopters and nonadopters of modern seeds—the growers of hybrids and MVs rely largely on the public extension system for their information needs. For growers of TVs, the public extension system and progressive farmers are equally important sources of information.

Table 3. Summary statistics

Specification	(1)	(2)	(3)	(4)	(5)
Variable	Mean traditional varieties	Mean modern varieties	Difference = (1) - (2)	Mean hybrid	Difference = (1) - (4)
Land size (hectares)	1.03	1.55	-0.52***	1.05	-0.02
Household size (number)	6.08	6.42	-0.34***	6.22	-0.14**
Age of family head (years)	46.61	45.67	0.94***	47.88	-1.27***
Male household head (dummy)	0.88	0.94	-0.06***	0.90	-0.02**
Tenurial status (1 = own land, 0 otherwise)	0.88	0.91	-0.03***	0.90	-0.02***
Access to institutional credit (= 1 if yes, 0 otherwise)	0.05	0.17	-0.12***	0.09	-0.04***
Educational level of the household head (dummy)					
Not literate (= 1 if yes, 0 otherwise)	0.25	0.23	0.02***	0.29	-0.04***
Up to primary (= 1 if yes, 0 otherwise)	0.26	0.25	0.01*	0.23	0.03***
Middle (= 1 if yes, 0 otherwise)	0.16	0.19	-0.02***	0.17	-0.01
Secondary (= 1 if yes, 0 otherwise)	0.19	0.20	-0.01	0.18	0.01
Higher secondary & above (= 1 if yes, 0 otherwise)	0.14	0.14	0.00	0.14	0.01
Religion (dummy)					
Hindu (= 1 if yes, 0 otherwise)	0.61	0.75	-0.14***	0.84	-0.23***
Muslim (= 1 if yes, 0 otherwise)	0.17	0.12	0.05***	0.08	0.09***
Christian (= 1 if yes, 0 otherwise)	0.18	0.02	0.16***	0.08	0.10***
Other (= 1 if yes, 0 otherwise)	0.05	0.11	-0.06***	0.01	0.04***
Social group (dummy)					
Scheduled caste (= 1 if yes, 0 otherwise)	0.10	0.12	-0.02***	0.16	-0.06***
Scheduled tribe (= 1 if yes, 0 otherwise)	0.28	0.13	0.15***	0.14	0.14***
Other backward caste (= 1 if yes, 0 otherwise)	0.30	0.40	-0.10***	0.51	-0.21***
Other caste (= 1 if yes, 0 otherwise)	0.32	0.35	-0.03***	0.19	0.13***
Soil type (dummy)					
Clay (= 1 if yes, 0 otherwise)	0.24	0.26	-0.03***	0.14	0.09***
Sandy (= 1 if yes, 0 otherwise)	0.12	0.16	-0.04***	0.10	0.03***
Loam & sandy loam (= 1 if yes, 0 otherwise)	0.45	0.49	-0.03***	0.37	0.08***
Black soil (= 1 if yes, 0 otherwise)	0.13	0.07	0.06***	0.32	-0.19***
Red soil (= 1 if yes, 0 otherwise)	0.06	0.02	0.04***	0.07	-0.01
Irrigation source (dummy)					
Rainfed (= 1 if yes, 0 otherwise)	0.45	0.42	0.03***	0.23	0.22***
Surface irrigation (= 1 if yes, 0 otherwise)	0.38	0.19	0.19***	0.34	0.04***
Tube well or bore well (= 1 if yes, 0 otherwise)	0.18	0.39	-0.21***	0.43	-0.26***
Information sources on new varieties (dummy)					
Public extension system (= 1 if yes, 0 otherwise)	0.32	0.60	-0.28***	0.58	-0.26***
Progressive farmer (= 1 if yes, 0 otherwise)	0.34	0.14	0.19***	0.22	0.11***
Mass media (= 1 if yes, 0 otherwise)	0.23	0.08	0.15***	0.18	0.05***
Input dealer (= 1 if yes, 0 otherwise)	0.04	0.02	0.02***	0.08	-0.03***
No. of observations	4,963	8,883	n.a.	3,990	n.a.

Source: Authors' calculations using data from International Food Policy Research Institute - Indian Council of Agricultural Research national farm household survey, India, 2017/2018.
Note: n.a. = not applicable. ***, **, and * indicate statistical significance at the 1 percent, 5 percent, and 10 percent levels, respectively.

Indian society is fragmented along the lines of caste and religion, and some studies have shown that the early adopters of innovations generally belong to economically and socially upper strata of the society (Ali 2012; Birthal et al. 2014). The distribution of rice farmers by religion shows a higher adoption of hybrids and MVs among Hindus. Likewise, among caste groups, adoption of hybrids is relatively higher among the so-called other backward castes (OBCs).[6]

4. Empirical Strategy

The simplest econometric model to assess the impact of adoption of modern seeds on crop yield can be specified as

$$Y_i = \theta^j \delta T_i^j + \beta X_i + \lambda v_i + \epsilon_i \,, \tag{1}$$

where Y is the rice yield on farm i. T^j denotes farmers' observed choice of a rice variety (TV or MV or hybrid). X is a vector of farm-specific control variables, and v_i is a vector of unobserved household-specific latent variables. If farm households were to be randomly assigned to choose a variety, then $\mathrm{Corr}(T_i^j, v_i) = 0$, and the coefficients θ^j provide the true effect of adoption of hybrids or MVs. This is, however, not the case. The choice of a variety is essentially a self-selection process driven by several observable and unobservable farm and farm household characteristics. For example, a latent variable, say the skills or innate ability of farmers, could be correlated with the decision to adopt a specific rice variety or hybrid. More-skilled farmers might choose an MV or hybrid, and less-skilled farmers a TV. This relationship can be represented by a selection equation:

$$T_i^j = \gamma Z_i + \rho v_i + \varepsilon_i. \tag{2}$$

In Equation (2), the choice of variety T_i^j by farm household i is contingent upon the observable variables in Z and the unobservable latent variables in v_i. Considering the choice of rice variety (TV or MV or hybrid) as a multinomial treatment, and following Deb and Trivedi (2006), we write the joint distribution of treatment and outcome variables, conditional on the common latent variables, as follows:

$$Pr(Y_i, T_i^j | X_i, Z_i, v_i) = f(\theta^j \delta T_i^j + \beta X_i + \lambda v_i) g(\gamma Z_i + \rho v_i). \tag{3}$$

Because the outcome and treatment are conditionally independent, their joint probability density can be written as the product of their marginal probability densities. Equation (3) has an advantage in that it explicitly models the endogenous selection process through which households are matched with available varieties/hybrids in our dataset. Yet the challenge in estimating Equation (3) is that the latent variables are unobservable. Under the assumption that variables in v_i are independently and identically distributed with a standard normal distribution, these can be integrated out of the joint density using the procedure described in Deb and Trivedi (2006).

Therefore, to assess the true effect of adoption of hybrids or MVs, there is a need for an instrumental variable that satisfies two conditions: (1) The instrument should be relevant; that

[6] From top to bottom, there are four distinct groups on the caste hierarchy in India: (1) upper castes, (2) OBCs, (3) scheduled castes, and (4) scheduled tribes.

is, it should be correlated with the choice of seeds. (2) It should be exogenous; that is, it should not be correlated with the outcome variable (yield) except through its effect on the choice of seeds. The natural endowment of a region can predict suitability for cultivation of a crop and its varieties; hence we consider the natural endowment of a region as a valid instrument in our model. Specifically, our dataset contains information on soil types that can serve as exogenous variables for predicting farmers' choice of rice seeds. Hence, the vector Z in Equation (2) will contain all the variables of vector X in Equation (1), along with the dummies for soil type as instruments.

Of the farm households in our sample, 26 percent have multiple plots. Therefore, as a robustness check, we estimate a plot-level regression, controlling for the household fixed effects. The plot-level variant of Equation (1) can be written as

$$Y_{pi} = v_i + \theta^j \delta T_{pi}^j + \epsilon_{pi} , \qquad (4)$$

where Y_{pi} is the plot-level rice yield for household i. v_i can now be differenced with the household fixed effects. Because households are nested within a district, the district fixed effects become redundant. In Equation (4), we do not include controls due to lack of information on different plots. Nevertheless, the estimates of Equation (4) may serve as a good test of robustness, although these may not be strictly comparable to those estimated from Equation (3), for two reasons: First, Equation (4) is estimated for a subsample, so the possibility of selection bias cannot be ruled out. Second, even when controlling for the household fixed effects, the estimated coefficients may not capture the true effect of hybrids or MVs if farmers choose more fertile plots for cultivation of MVs or hybrids and less fertile plots for cultivation of TVs.

5. Results and Discussion

5.1. Factors influencing adoption

Table 4 presents estimates of the multinomial treatment effects model for the choice of hybrids and MVs over TVs. We begin with examining whether the agroecological conditions have a say in the adoption of rice hybrids. The coefficients of soil type, the instrumental variables, indicate that the cultivation of hybrids is more prominent in black and red soils, whereas clayey soil, which is relatively more fertile and has a better water-holding capacity, is preferred for cultivation of MVs.

Table 4. Multinomial logit model for factors influencing adoption, with traditional varieties as base category

Variable	Modern varieties	Hybrids
Ln(Operated area)	0.118**	-0.00132
	(0.0465)	(0.0412)
Ln(Family size)	-0.0645	0.0440
	(0.0842)	(0.0800)
Ln(Age of family head)	-0.0621	-0.190*
	(0.108)	(0.110)
Gender of the farmer	0.182	0.00390
	(0.133)	(0.108)
Education: Up to primary (base category illiterate)	0.0771	-0.0898
	(0.0832)	(0.0874)
Education: Middle (base category illiterate)	0.193*	0.0105
	(0.1000)	(0.0960)
Education: Secondary (base category illiterate)	0.0407	-0.0220
	(0.0980)	(0.107)
Education: Higher secondary & above (base category illiterate)	-0.0187	-0.0318
	(0.126)	(0.122)
Religion: Muslim (base category Hindu)	-0.258	-0.413**
	(0.187)	(0.190)
Religion: Christian (base category Hindu)	-1.219***	-0.394*
	(0.199)	(0.226)
Religion: Other (base category Hindu)	0.667	-1.173***
	(0.438)	(0.372)
Social group: Scheduled caste (base category other caste)	0.102	0.380***
	(0.128)	(0.140)
Social group: Scheduled tribe (base category other caste)	-0.331*	-0.00331
	(0.175)	(0.194)
Social group: Other backward caste (base category other caste)	0.0986	0.407***
	(0.130)	(0.136)
Soil type: Sandy (base category clay soil)	-0.212	-0.137
	(0.174)	(0.153)
Soil type: Loam & sandy loam (base category clay soil)	-0.289*	-0.259*
	(0.158)	(0.133)
Soil type: Black soil (base category clay soil)	-0.555**	1.251***
	(0.274)	(0.281)
Soil type: Red soil (base category clay soil)	-0.827**	0.605**
	(0.345)	(0.298)
Irrigation: Surface (base category rainfed)	0.00270	0.547***
	(0.170)	(0.166)
Irrigation: Tube well or bore well (base category rainfed)	0.547***	1.165***
	(0.164)	(0.143)
Institutional loans dummy	0.403***	0.117***
	(0.142)	(0.022)
Technical advice: Extension agent	0.668***	0.985***
	(0.166)	(0.152)
Technical advice: Progressive farmer	-0.184	-0.338**
	(0.143)	(0.150)
Technical advice: Radio/television/newspaper/Internet	-0.628***	-0.439***
	(0.183)	(0.159)
Technical advice: Private agents/input dealers	-0.0651	0.518***
	(0.168)	(0.152)
Tenurial status	0.263**	0.133
	(0.128)	(0.125)
Constant	0.463	-0.739
	(0.546)	(0.456)
Number of observations	17,836	

Source: Authors' calculations using data from International Food Policy Research Institute - Indian Council of Agricultural Research national farm household survey, India, 2017/2018.

Note: Figures in parentheses are standard errors robust to intradistrict correlation of residuals. ***, **, and * indicate statistical significance at the 1 percent, 5 percent, and 10 percent levels, respectively.

Rice is a water-guzzling crop; therefore, assured irrigation is a critical factor in farmers' decision to adopt MVs or hybrids. MVs or hybrids, however, may differ in their water requirements and also in their tolerance to water stress. Our results indicate a higher probability of adoption of hybrids as well as MVs under irrigated conditions, but even higher with an assured supply of water, as suggested by the positive and significant coefficient on the ownership of tube wells. On the other hand, cultivation of TVs is more prominent under rainfed and canal-irrigated conditions. This could be a rational choice because some of the TVs can better withstand water stress, as compared with the MVs and hybrids.

Land size has a differential effect on adoption of hybrids and MVs. The regression coefficient of land size is positive and significant in the case of MVs, but it does not have any significant influence on the adoption of hybrids. This result points to the scale neutrality of hybrid rice technology. It is in contrast to the results of Mottaleb, Mohanty, and Nelson (2014), who showed a positive association between land size and adoption of hybrids. There could be several explanations for this discrepancy. It is argued that smallholder farmers cannot afford frequent purchases of costly hybrid seeds. Therefore, the probability of using hybrid seeds is likely to increase when the capital constraint is relaxed. The regression coefficient of farmers' access to institutional credit is positive and significant, confirming this observation. Note that India's agricultural credit system has recently undergone significant transformation in terms of flexibility in the supply of farm credit, collateral requirements, interest rates, and modes of disbursement. In 1998 India introduced a credit card for farmers (known as the Kisan Credit Card) that enables them to withdraw funds multiple times for purchase of seeds and other inputs within the sanctioned credit limit. Interest rates on short-term loans have also been reduced considerably, now ranging from 4 percent to 7 percent. By 2018, a total of 23.5 million farm households had been issued Kisan Credit Cards.

Studies also implicate a lack of diffusion of information on hybrid rice technology and associated management practices as an important deterrent to its adoption. In our model we include dummies for farmers' access to information from various sources: government extension agents, progressive farmers, input dealers, and mass media. The results indicate a differential influence of information sources on the adoption of hybrid rice technology. The probability of using hybrid seeds is higher for those who rely more on information from government sources and input dealers. Mass media and progressive farmers, on the other hand, have a negative influence on the adoption of hybrid rice technology. The probable reason for this contrast could be the way the information is transferred from different sources. Less educated farmers may not fully comprehend the information provided by mass media and fellow farmers, which are indirect channels of information transfer, resulting in a loss of information. On the other hand, with government extension workers, the farmers have a direct interface for their information needs. The positive influence of input dealers on the adoption of hybrids is expected. Hybrid seeds are costlier than conventional seeds, and smallholder farmers, due to their liquidity constraints, purchase seeds (along with other inputs) from input dealers on credit against their commitment of repayment after harvest. Babu and colleagues (2011) reported such an arrangement to be a common phenomenon in the Indian state of Tamil Nadu.

Adoption of hybrids and also of MVs is not influenced much by demographic characteristics such as family size or the gender and education of the household head. Their adoption, however, seems to be associated with the age of the household head, younger farmers being more likely to adopt. Further, we find that choice of seeds is differentiated by social factors, such as the religion and caste of the farm households. The probability of adopting hybrids and MVs is higher among Hindu households, especially those belonging to OBCs.

5.2. Impact on crop yield

Following the arguments of Altonji, Elder, and Taber (2005) and Oster (2019), we estimate different specifications of Equation (1), either including or not including control variables. We begin with a parsimonious specification (1) in which crop yield is regressed on dummies for households growing MVs and hybrids, and then proceed to include household-level controls and higher-order fixed effects—that is, state fixed effects, district fixed effects, and village fixed effects—so as to account for the influence of unobserved spatial characteristics.

Table 5 presents the results. In all of the specifications, the treatment effect of MVs and hybrids is positive and significant at less than the 5 percent level. The state fixed effects in specifications (2) and (3), the district fixed effects in specification (4), and the village fixed effects in specification (5) explain significant variation in paddy yield. However, on accounting for the higher-order fixed effects, the size of the coefficients becomes smaller. For example, without including the fixed effects, hybrids have a yield advantage of 30 percent over TVs, but including the village fixed effects reduces the advantage to just about half: 16 percent.

As a robustness check, we estimate Equation (1) using the plot-level data including household fixed effects (specification 6). The regression coefficients of MVs and hybrids are positive and comparable to those obtained from specification (1) for the overall pool of sample households, but larger than those estimated including village fixed effects. The plot-level estimates suggest that our results are robust to household-level, time-invariant, unobservable variables.

Table 5. Ordinary least squares estimates of the impact of modern varieties and hybrids on rice yield, with log paddy yield in kilograms/hectare as dependent variable

Specification	(1)	(2)	(3)	(4)	(5)	(6)
Independent variable						
Modern varieties	0.221**	0.107**	0.0975**	0.0797***	0.0560**	0.108**
	(0.0889)	(0.0476)	(0.0459)	(0.0274)	(0.0254)	(0.0428)
Hybrids	0.306***	0.180***	0.173***	0.200***	0.162***	0.324***
	(0.0755)	(0.0613)	(0.0569)	(0.0414)	(0.0367)	(0.102)
Ln(Operated area)	n.a.	n.a.	0.00990	0.00302	-0.00576	n.a.
			(0.0169)	(0.0134)	(0.0148)	
Ln(Family size)	n.a.	n.a.	0.00225	0.0127	0.00452	n.a.
			(0.0219)	(0.0178)	(0.0193)	
Ln(Age of family head)	n.a.	n.a.	0.0536	0.0408	0.0392	n.a.
			(0.0326)	(0.0346)	(0.0384)	
Gender of the farmer	n.a.	n.a.	0.140**	0.0804**	0.0952**	n.a.
			(0.0577)	(0.0393)	(0.0441)	
Education: Up to primary (base category illiterate)	n.a.	n.a.	0.0636***	0.0604***	0.0607***	n.a.
			(0.0229)	(0.0185)	(0.0186)	
Education: Middle (base category illiterate)	n.a.	n.a.	0.0754***	0.0716***	0.0642***	n.a.
			(0.0216)	(0.0207)	(0.0219)	
Education: Secondary (base category illiterate)	n.a.	n.a.	0.0646**	0.0613***	0.0490**	n.a.
			(0.0251)	(0.0213)	(0.0216)	
Education: Higher secondary & above (base category illiterate)	n.a.	n.a.	0.0537*	0.0656**	0.0454	n.a.
			(0.0307)	(0.0297)	(0.0323)	
Religion: Muslim (base category Hindu)	n.a.	n.a.	0.0660*	0.0361	0.0380	n.a.
			(0.0395)	(0.0306)	(0.0317)	
Religion: Christian (base category Hindu)	n.a.	n.a.	-0.0492	0.00172	-0.0273	n.a.
			(0.0563)	(0.0445)	(0.0450)	
Religion: Other (base category Hindu)	n.a.	n.a.	-0.353**	-0.287	-0.376**	n.a.
			(0.169)	(0.180)	(0.186)	
Social group: Scheduled caste (base category other caste)	n.a.	n.a.	-0.0853*	-0.0639*	-0.0472	n.a.
			(0.0494)	(0.0353)	(0.0321)	
Social group: Scheduled tribe (base category other caste)	n.a.	n.a.	-0.0956	-0.0434	0.0251	n.a.
			(0.0639)	(0.0373)	(0.0334)	
Social group: Other backward caste (base category other caste)	n.a.	n.a.	-0.0390	0.0155	0.0135	n.a.
			(0.0372)	(0.0262)	(0.0209)	
Soil type: Sandy (base category clay)	n.a.	n.a.	-0.113***	-0.0463	-0.0225	n.a.
			(0.0394)	(0.0320)	(0.0298)	
Soil type: Loam & sandy loam (base category clay)	n.a.	n.a.	-0.102***	-0.0301	-0.00646	n.a.
			(0.0345)	(0.0224)	(0.0261)	
Soil type: Black soil (base category clay)	n.a.	n.a.	-0.0428	-0.0107	0.0429	n.a.
			(0.139)	(0.138)	(0.115)	
Soil type: Red soil (base category clay)	n.a.	n.a.	-0.0706	-0.0438	-0.00906	n.a.
			(0.0763)	(0.0730)	(0.0576)	
Irrigation: Surface (base category rainfed)	n.a.	n.a.	0.134***	0.126***	0.144***	n.a.
			(0.0497)	(0.0438)	(0.0472)	
Irrigation: Tube well or bore well (base category rainfed)	n.a.	n.a.	0.162***	0.155***	0.173***	n.a.
			(0.0568)	(0.0483)	(0.0598)	
Institutional loans dummy	n.a.	n.a.	0.0590**	0.0372*	0.0260	n.a.
			(0.0260)	(0.0209)	(0.0240)	
Technical advice: Extension agent	n.a.	n.a.	-0.0595	-0.0578	-0.115	n.a.
			(0.0706)	(0.0843)	(0.0988)	
Technical advice: Progressive farmer	n.a.	n.a.	0.0448	-0.00157	-0.00178	n.a.
			(0.0388)	(0.0248)	(0.0229)	
Technical advice: Radio/television/newspaper/Internet	n.a.	n.a.	0.127**	0.0853	0.0842**	n.a.
			(0.0540)	(0.0549)	(0.0351)	
Technical advice: Private agents/input dealers	n.a.	n.a.	0.0538	-0.0150	0.00620	n.a.
			(0.0578)	(0.0436)	(0.0497)	
Tenurial status	n.a.	n.a.	-0.0266	-0.0344	-0.00850	n.a.
			(0.0276)	(0.0236)	(0.0235)	
Constant	8.156***	8.243***	7.925***	7.960***	7.961***	2.492***
	(0.0765)	(0.0468)	(0.190)	(0.150)	(0.178)	(0.0271)
State dummy	No	Yes	Yes	No	No	No
District dummy	No	No	No	Yes	No	No
Village dummy	No	No	No	No	Yes	No
Household dummy	No	No	No	No	No	Yes
Number of observations	18,933	18,933	18,932	18,930	18,906	5,344
R^2	0.0122	0.215	0.228	0.313	0.408	0.779

Source: Authors' calculations using data from International Food Policy Research Institute - Indian Council of Agricultural Research national farm household survey, India, 2017/2018.

Note: n.a. = not applicable. Figures in parentheses are standard errors robust to intradistrict correlation of residuals. ***, **, and * indicate statistical significance at the 1 percent, 5 percent, and 10 percent levels, respectively.

Ordinary least squares estimates are likely to suffer from omitted-variable or selection bias. Table 6 presents results of the outcome equation corrected for selection bias. As earlier, each column estimates a different specification of Equation (3), incorporating higher-order fixed effects and control variables. The regression coefficients of MVs and hybrids are comparable to those obtained from the fixed-effects regressions (Equation 1). The inverse Mills ratio (IMR) is highly significant in the absence of higher-order fixed effects (specification 1). The IMR is also significant in specification (2), which includes state fixed effects. This result suggests the presence of selection bias in varietal adoption. The likelihood ratio test also reinforces the presence of selection bias. However, with the district fixed effects in specification (3) and the village fixed effects in specification (4), IMR turns out insignificant, suggesting that higher-order fixed effects are sufficient to control for selection bias in the varietal adoption decisions of farm households.

When we correct for selection bias in specifications (3) and (4), the regression coefficient of the yield of MVs remains positive but turns out to be statistically insignificant, suggesting that the average yield of MVs is not much different from that of TVs. However, the regression coefficient of the yield of hybrids remains positive, consistent in size, and statistically significant in all of the specifications. When we control for district and village fixed effects, hybrid rice shows a yield advantage of about 20 percent over TVs, but not much difference in yield from that of MVs.

Besides high-yielding seeds, several other factors influence crop yield. Specifications (3) and (4), which control for higher-order fixed effects, show that irrigation, from both surface and groundwater sources, has a significant and positive effect on crop yield. Farmers' access to credit, too, has a positive and significant effect on yield at the 10 percent level. Interestingly, among the different information sources, mass media appear to influence yield positively and significantly.

Among sociodemographic factors, the education and gender of the household head have a positive and significant influence on paddy yield. The regression coefficients of the education levels of household heads are positive and significant. Yield is positively and significantly associated with male-headed households, possibly due to their better skills and education as compared with their female counterparts. Households' labor endowment (proxied by household size), however, does not have any significant impact. Other factors, such as caste and religion, are not found to be correlated with households' yield outcomes.

Table 6. Multinomial treatment effects model corrected for selection bias, using log rice yield in kilograms/hectare as dependent variable

Specification	(1)	(2)	(3)	(4)
Independent variable				
Modern varieties	0.267***	0.169**	0.0904	0.0458
	(0.0917)	(0.0727)	(0.0755)	(0.0565)
Hybrids	0.194***	0.123*	0.216***	0.193***
	(0.0740)	(0.0669)	(0.0566)	(0.0454)
Ln(Operated area)	-0.00468	0.00550	0.00266	-0.00494
	(0.0195)	(0.0169)	(0.0150)	(0.0156)
Ln(Family size)	0.00914	0.00603	0.0128	0.00378
	(0.0310)	(0.0223)	(0.0189)	(0.0197)
Ln(Age of family head)	-0.0193	0.0525	0.0411	0.0400
	(0.0495)	(0.0327)	(0.0352)	(0.0375)
Gender of the farmer	0.118*	0.132**	0.0801**	0.0965**
	(0.0680)	(0.0570)	(0.0384)	(0.0431)
Education: Up to primary (base category illiterate)	0.0461	0.0610***	0.0609***	0.0623***
	(0.0349)	(0.0232)	(0.0188)	(0.0192)
Education: Middle (base category illiterate)	0.0472	0.0739***	0.0719***	0.0655***
	(0.0347)	(0.0233)	(0.0234)	(0.0234)
Education: Secondary (base category illiterate)	0.00522	0.0658***	0.0617***	0.0495**
	(0.0399)	(0.0255)	(0.0217)	(0.0214)
Education: Higher secondary & above (base category illiterate)	-0.0266	0.0564*	0.0663**	0.0461
	(0.0582)	(0.0313)	(0.0300)	(0.0315)
Religion: Muslim (base category Hindu)	0.177***	0.0724*	0.0373	0.0395
	(0.0515)	(0.0392)	(0.0310)	(0.0312)
Religion: Christian (base category Hindu)	0.109	-0.0229	0.00411	-0.0308
	(0.145)	(0.0538)	(0.0458)	(0.0447)
Religion: Other (base category Hindu)	0.279**	-0.376**	-0.287*	-0.368**
	(0.134)	(0.170)	(0.169)	(0.174)
Social group: Scheduled caste (base category other caste)	-0.0925	-0.0793*	-0.0640*	-0.0481
	(0.0797)	(0.0481)	(0.0368)	(0.0312)
Social group: Scheduled tribe (base category other caste)	-0.106	-0.0924	-0.0441	0.0222
	(0.0796)	(0.0659)	(0.0425)	(0.0344)
Social group: Other backward caste (base category other caste)	-0.0866*	-0.0341	0.0150	0.0121
	(0.0507)	(0.0371)	(0.0267)	(0.0201)
Irrigation: Surface (base category rainfed)	0.215***	0.142***	0.124***	0.140***
	(0.0803)	(0.0500)	(0.0413)	(0.0422)
Irrigation: Tube well or bore well (base category rainfed)	0.136*	0.164***	0.151***	0.167***
	(0.0809)	(0.0585)	(0.0474)	(0.0550)
Institutional loans dummy	0.122**	0.0513**	0.0364*	0.0280*
	(0.0576)	(0.0262)	(0.0195)	(0.0116)
Technical advice: Extension agent	0.0941	-0.0507	-0.0616	-0.120
	(0.0606)	(0.0713)	(0.0866)	(0.0970)
Technical advice: Progressive farmer	-0.242**	0.0405	-0.000331	0.000391
	(0.102)	(0.0389)	(0.0261)	(0.0235)
Technical advice: Radio/television/newspaper/Internet	0.118***	0.136***	0.0866*	0.0837**
	(0.0386)	(0.0509)	(0.0509)	(0.0329)
Technical advice: Private agents/input dealers	0.0398	0.0644	-0.0168	0.00186
	(0.0755)	(0.0590)	(0.0418)	(0.0462)
Tenancy status	-0.0938	-0.0353	-0.0361	-0.00845
	(0.0651)	(0.0285)	(0.0235)	(0.0233)
Constant	8.054***	8.307***	7.571***	7.920***
	(0.278)	(0.230)	(0.173)	(0.181)
Ln(Sigma)	-0.0243	-0.115	-0.168	-0.247**
	(0.110)	(0.106)	(0.111)	(0.108)
Lambda(Improved)	-0.156***	-0.0826*	-0.0106	0.0155
	(0.0357)	(0.0490)	(0.0808)	(0.0629)
Lambda(Hybrid)	0.124***	0.0749**	-0.0171	-0.0355
	(0.0396)	(0.0363)	(0.0687)	(0.0392)
State dummies	No	Yes	No	No
District dummies	No	No	Yes	No
Village dummies	No	No	No	Yes
Number of observations	18,932	18,932	18,932	18,932
Likelihood ratio test for exogeneity of the treatments (chi^2)	62.44	2.79	0.10	1.01

Source: Authors' calculations using data from International Food Policy Research Institute - Indian Council of Agricultural Research national farm household survey, India, 2017/2018.

Note: Figures in parentheses are standard errors robust to intra-district correlation of residuals. ***, **, and * indicate statistical significance at the 1 percent, 5 percent, and 10 percent levels, respectively.

Agricultural productivity has been shown to be inversely related to farm size (Chand, Prasanna, and Singh 2011), but this relationship may not be applicable in the same manner to all crops. Birthal and others (2014) found no significant association between farm size and productivity of cereal crops. We find the coefficient of land size insignificant, suggesting that crop yield is neutral to scale.

6. Conclusions

Of late, India's rice production has come under severe pressure from a number of biotic and abiotic stresses, causing significant deceleration in its yield growth despite the widespread use of the modern varieties. Hybrid rice is one of the options to accelerate yield growth, but its adoption has remained slow due to several factors.

Using data from a large-scale survey of farm households, in this paper we have made an attempt to identify the factors influencing the adoption of hybrids and, subsequently, to assess the impact of hybrid adoption on paddy yield. Natural endowments, in terms of soil quality and water availability, are a key to realizing the gains from hybridization. Our findings show that hybrid rice is often grown in India under irrigated conditions but on poor soils. This situation implies a greater cost of irrigation as well as other inputs, such as fertilizers, essential for plant growth. Further, we find that hybrid seed technology is neutral to scale, but farmers' lack of access to information on hybrids' technological traits and the associated agronomic practices, as well as their lack of access to financial resources for frequent purchases of hybrid seeds, which are much costlier than the seeds of inbred varieties, hampers the widespread adoption of hybrid seed technology.

Finally, our findings clearly demonstrate that the relative yield advantage of hybrids over inbred modern varieties is not much, and therefore we cannot rule out the possibility that the marginal cost of adopting hybrids may be higher than their marginal benefit. In other words, the benefits from hybrid rice technology do not seem significant enough to incentivize its widespread adoption in India.

References

Ali, J. 2012. "Factors Affecting the Adoption of Information and Communication Technologies (ICTs) for Farming Decisions." *Journal of Agricultural & Food Information* 13 (1): 78–96.

Altonji, J. G., T. E. Elder, and C. R. Taber. 2005. "Selection on Observed and Unobserved Variables: Assessing the Effectiveness of Catholic Schools." *Journal of Political Economy* 113 (1): 151–184.

Babu, S. C., C. J. Glendenning, K. Asenso-Okyere, and S. K. Govindarajan. 2011. *Farmers' Information Needs and Search Behaviours: Case Study in Tamil Nadu, India*. Discussion Paper 1165. Washington, DC: International Food Policy Research Institute.

Birthal, P. S., P. K. Joshi, D. S. Negi, and S. Agarwal. 2014. *Changing Sources of Growth in Indian Agriculture: Implications for Regional Priorities for Accelerating Agricultural Growth*. Discussion Paper 1325. Washington, DC: International Food Policy Research Institute.

Birthal, P. S., D. S. Negi, M. T. Khan, and S. Agarwal. 2015. "Is Indian Agriculture Becoming Resilient to Droughts?" *Food Policy* 56 (C): 1–12.

Chand, R., P. A. L. Prasanna, and A. Singh. 2011. "Farm Size and Productivity: Understanding the Strengths of Smallholders and Their Livelihoods." *Economic and Political Weekly* 46 (26/27): 5–11.

Deb, P., and P. K. Trivedi. 2006. "Specification and Simulated Likelihood Estimation of a Non-normal Treatment-Outcome Model with Selection: Application to Health Care Utilization." *The Econometrics Journal* 9 (2): 307–331.

FAO (Food and Agriculture Organization of the United Nations). 2014. *A Regional Strategy for Sustainable Hybrid Rice Development in Asia*. Bangkok, Thailand: FAO Regional Office for Asia and the Pacific.

India, MoAFW (Ministry of Agriculture and Farmers' Welfare). 2018. *Agricultural Statistics at a Glance.* New Delhi.

IPCC (Intergovernmental Panel on Climate Change). 2018. "Summary for Policymakers." In *Special Report: Global Warming of 1.5°C*, edited by Working Group I Technical Support Unit, 3–26. Geneva, Switzerland: World Meteorological Organization.

Janaiah, A. 2000. "Economic Impact of Crop Management on Productivity and Profitability of Hybrid and Inbred Rices in India: Evidences from a Farm-Level Study." *Indian Journal of Agricultural Science* 70 (2): 77–84.

Janaiah, A. 2002. "Hybrid Rice for Indian Farmers: Myths and Realities." *Economic and Political Weekly* 37 (42): 4319–4328.

Janaiah, A., and F. Xie. 2010. *Hybrid Rice Adoption in India: Farm-Level Impacts and Challenges*. Technical Bulletin No. 14. Los Baños, Philippines: International Rice Research Institute.

Kumar, P., and P. K. Joshi. 2016. "Food Demand and Supply Projections to 2030: India." In *International Trade and Food Security: The Future of Indian Agriculture*, edited by F. Brower and P. K. Joshi, 29–63. Wallingford, UK: CAB International.

Mottaleb, K. A., S. Mohanty, and A. Nelson. 2014. "Factors Influencing Hybrid Rice Adoption: A Bangladesh Case." *Australian Journal of Agricultural and Resource Economics* 59 (2): 258–274.

Oster, E., 2019. "Unobservable Selection and Coefficient Stability: Theory and Evidence." *Journal of Business & Economic Statistics* 37 (2): 187–204.

Prakash, A., H. N. Singh, R. S. Shekhawat, and S. Sandu. 2017. "Constraints Faced by Farmers in Production of Inbred and Hybrid Rice in Udham Singh Nagar District of Uttarakhand, India." *International Journal of Current Microbiology and Applied Sciences* 6 (12): 2243–2247.

Shiao, T., A. Maddocks, C. Carson, and E. Loizeaux. 2015. "3 Maps Explain India's Growing Water Risks." World Resources Institute. February 26. www.wri.org/blog/2015/02/3-maps-explain-india-s-growing-water-risks.

Spielman, D. J., D. E. Kolady, and P. S. Ward. 2013. "The Prospects for Hybrid Rice in India." *Food Security* 5 (5): 651–665.

Appendix

Table A1. Number and percentage of sampled rice-growing households by state

State	# of households	Percentage of total respondents
Andhra Pradesh, including Telangana	930	4.67
Assam	1,573	7.91
Bihar	1,541	7.75
Chhattisgarh	1,552	7.81
Eastern Uttar Pradesh	1,410	7.09
Gujarat	500	2.52
Haryana	973	4.90
Jammu & Kashmir	794	3.99
Jharkhand	1,542	7.76
Karnataka	336	1.69
Maharashtra	398	2.00
Northeastern states, excluding Assam	1,700	8.55
Odisha	1,541	7.75
Punjab	1,041	5.24
Tamil Nadu	1,509	7.59
West Bengal	1,421	7.15
Western Uttar Pradesh, including Uttarakhand	1,116	5.61
Total	19,877	100.0

Source: Authors' calculations using data from International Food Policy Research Institute - Indian Council of Agricultural Research national farm household survey, India, 2017/2018.

ALL IFPRI DISCUSSION PAPERS

All discussion papers are available **here**.

They can be downloaded free of charge.

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
www.ifpri.org

IFPRI HEADQUARTERS
1201 Eye Street, NW
Washington, DC 20005 USA
Tel.: +1-202-862-5600
Fax: +1-202-862-5606
Email: ifpri@cgiar.org

SOUTH ASIA REGION
Block C, NASC Complex, DPS Marg
Opposite Todapur, Pusa
New Delhi 110012, India
Phone: +91-11-66166565
Fax: +91-11-66781699
Email: ifpri-newdelhi@cgiar.org
https://southasia.ifpri.info/