THE IMPACTS OF GM FOODS: RESULTS FROM A RANDOMIZED CONTROLLED TRIAL OF BT EGGPLANT IN BANGLADESH

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We implemented a cluster randomized controlled trial to assess the impact of genetically modified eggplant (Bt brinjal) in Bangladesh. Our two primary outcomes were changes in yield and in pesticide costs. Cultivation of Bt brinjal raises yields by 3,564 kg/ha. This statistically significant impact is equivalent to a 51% increase relative to the control group. There is a statistically significant fall in pesticide costs, 7,175 Taka per hectare (85 USD per ha), a 37.5% reduction. Yield increases arise because Bt farmers harvest more eggplant and because fewer fruits are discarded because they are damaged. Bt brinjal farmers sell more eggplant and receive a higher price for the output they sell while incurring lower input costs, resulting in a 128% increase in net revenues. Bt brinjal farmers used smaller quantities of pesticides and sprayed less frequently. Bt brinjal reduced the toxicity of pesticides as much as 76%. Farmers growing Bt brinjal and who had pre-existing chronic conditions consistent with pesticide poisoning were 11.5% points less likely to report a symptom of pesticide poisoning and were less likely to incur cash medical expenses to treat these symptoms. Our results are robust to changes in model specification and adjustment for multiple hypothesis testing. We did not find evidence of heterogeneous effects by farmer age, schooling, or land cultivated. Bt brinjal is a publicly developed genetically modified organism that conveys significant productivity and income benefits while reducing the use of pesticides damaging to human and ecological health.

Key words: Bangladesh, eggplant, GMOs, pesticides, yield.

JEL codes: Q16, Q12, O13.

There exist multiple agronomic, economic, and environmental challenges to ensuring that global food production can meet the nutritional needs of the world's population both today and in the future. As noted by the United Nations Food and Agriculture Organization (FAO), business as usual approaches will not suffice. Instead, FAO argues that there is a need to ensure that food insecure individuals have the resources needed to purchase healthy diets, that consumers are aware of the importance of consuming healthy diets, and that food waste is reduced. Yield increases are necessary, but these must be achieved in an environmentally sustainable fashion (Food and Agriculture Organization 2018).

There are several approaches to sustainably increasing yields, including those that draw on conventional plant breeding strategies, interventions based around agro-ecological farming and sustainable land management practices, and, more controversially, genetically modified crops. Zilberman, Holland, and Trilnick (2018) write that these "can play an important role in strategies towards this goal in agriculture, mainly by increasing yield per unit of output, reducing the use of pesticides and other chemicals, using land more efficiently, and reducing greenhouse gas emissions." Reviews by Adenle et al. (2020); Barrows, Sexton, and Zilberman (2014); Klümper and Qaim (2014); the National Academies

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Amer. J. Agr. Econ. 103(4): 1186–1206; doi:10.1111/ajae.12162
Published online November 13, 2020

of Sciences, Engineering, and Medicine (2016); and Zilberman, Holland, and Trilnick (2018) show that genetically modified crops generally increase yield and reduce the use of pesticides. However, much of the evidence base for the economic, pesticide, and relatedly the health impacts of GMOs relies on observational studies. As Crost et al. (2007) note, observational farm-level studies do not always control for farmer self-selection. If more efficient farmers are more likely to adopt GMOs, estimates of impacts on yields and other outcomes are likely to be biased upwards. Kouser and Qaim (2011) make a similar observation in the context of assessing the impact of Bt cotton on pesticide poisoning in India, noting that given certain assumptions, this can be addressed through the use of panel data estimation techniques.

We seek to advance knowledge of the impact of GMOs in a manner that addresses these potential biases. Specifically, in Bangladesh we implement a farm-level cluster randomized controlled trial of a genetically modified version of eggplant called *Bacillus thuringiensis* (Bt) brinjal. Brinjal, a lucrative cash crop well suited to smallholder agriculture, is grown and consumed widely across South and East Asia but is susceptible to the fruit and shoot borer (FSB) pest, which can affect up to 86% of plants (Ali, Ali, and Rahman 1980). Farmers frequently apply pesticides to combat FSB, from 23 to as many as 140 times per season, but few take protective measures while applying these pesticides (Sabur and Molla 2001; Rashid, Mohiuddin, and Mannan 2008; Dey 2010; Ahsanuzzaman and Zilberman 2018; Raza et al. 2018). To address FSB, an Indian company, Mahyco, developed a genetically modified brinjal, introducing the *cry1Ac* gene (which expresses an insecticidal protein) sourced from the soil bacterium *Bacillus thuringiensis* (Bt) (Mondal and Akter 2018). In 2005, Cornell University facilitated its transfer to the publicly funded Bangladesh Agricultural Research Institute (BARI), who developed four locally adapted, open-pollinated varieties suitable for Bangladesh (Rashid, Hasan, and Matin 2018; Shelton et al. 2018). After eight years of breeding and testing, in 2013 four varieties of Bt brinjal were approved for cultivation (Mondal and Akter 2018).[1] A series of observational studies showed that these reduced FSB infestation, require fewer pesticides, and result in higher yields with lower production costs (Prodhan et al. 2018; Rashid, Hasan, and Matin 2018; Shelton et al. 2018).

To the best of our knowledge, this is the first study to use an RCT design to assess the impact of a GMO crop in a south Asia setting. As is well understood, carefully implemented RCTs are less vulnerable to concerns regarding selection bias and endogenous placement, thus reducing bias in our measurement of impact. The primary outcomes we consider—yield and pesticide cost—are assessed to confirm whether results from observational studies of the impacts of GMOs, conducted in Bangladesh and elsewhere, hold. We then consider several secondary outcomes. Increased yields do not necessarily translate into increased net revenues if: (*a*) farmers are unable to sell their increased output; (*b*) if they receive a lower price than conventional varieties; and/or (*c*) if other input costs rise. Accordingly, we assess impact on marketed production, price received, and net revenues (gross revenues less measured input costs). We examine whether Bt brinjal reduces the toxicity of pesticides that are applied. Evidence on this exists in developed country settings (see Zilberman, Holland, and Trilnick (2018) for a recent summary) but again to the best of our knowledge is limited in developing country settings. Finally, as noted by Barrows, Sexton, and Zilberman (2014) and the National Academies of Sciences, Engineering, and Medicine (2016), there is limited evidence of the impact of GMOs on farmers' health. Even if farmers reduce the application of pesticides used to combat FSB, offsetting behaviors such as using more pesticides to combat other pests or being less careful when handling pesticides could limit the health benefits of Bt brinjal. Building on Krishna and Qaim (2008) and Kouser and Qaim (2011), we examine the impact of Bt brinjal on self-reported health.

Critics of GM crops claim that GMOs convey no economic, health, or environmental benefits while they also "pose a serious threat to farmer sovereignty" (Non-GMO Project 2019). Our results speak directly to these criticisms. We find that Bt brinjal increased yields by 51% and reduced pesticide costs by 37.5%. Bt brinjal farmers marketed more output, sold at a higher price, incurred lower input costs, and, consequently, had higher net revenues (by 128%). Bt brinjal farmers used smaller quantities of pesticides, sprayed less frequently, and reduced the toxicity of pesticides applied by 42 to76%. Farmers growing

[1]Work was undertaken to introduce Bt brinjal in India and the Philippines. In India, Bt brinjal was approved for commercialization but subsequently a moratorium was placed on its use. It has not been approved in the Philippines.

Bt brinjal and who had pre-existing chronic conditions consistent with pesticide poisoning, were 11.5% points less likely to report a symptom of pesticide poisoning and were less likely to incur cash medical expenses to treat these symptoms. All these benefits were derived from an open-pollinated crop provided by a public agency.

We begin with our study design, including our intervention that bundled together training, extension, an input package, and randomized access to Bt brinjal or a control variety. We then describe our data and estimation strategy. Results on primary outcomes—yield and pesticide costs—are then described, followed by analysis of secondary outcomes relating to marketed production, prices, input costs, net revenues, pesticide use and toxicity, and self-reported health outcomes. After noting limitations to our work, we summarize our findings. A supplementary appendix provides additional results.

Study and Intervention Design

Study Design

We begin with our statistical power calculations. These are based on the two primary outcomes identified in our registered pre-analysis plan[2]: brinjal yields per hectare and total cost of pesticide use per hectare. Our sample size is designed to provide an 80% chance of correctly rejecting the null hypothesis that no change occurred, with a 0.05 level of significance. Using these parameters and data on mean, standard deviations, and intracluster correlations of brinjal cultivation taken from a nationally representative sample of households residing in rural areas (Ahmed 2013), a minimum total sample size of 180 clusters (villages) and 1,046 farm households was required to detect a statistically significant increase in brinjal yields per hectare of 30% between treatment and control groups, with 523 farm households for the treatment group and 523 households for the control group. For reduction of pesticide cost per hectare, 187 clusters and 1,120 farm households (560 treatment and 560 control households) were needed to detect a minimum of 40% reduction in pesticide cost. Additionally, the sample size must be large enough to assess both impacts and account for the possibility that some households would attrit. Accordingly, we planned on a sample of 200 clusters/villages (100 treatment and 100 control villages). Each cluster would include six farm households, yielding a sample of 1,200 households (600 treatment, 600 control).

Intervention Design

The Bt brinjal varieties released by BARI are best suited to winter cultivation, with sowing of seeds beginning in September/October and seedlings transplanted in November. For this reason, we needed to work in localities where farmers cultivated brinjal during this period. Given interest in assessing Bt brinjal as a cash crop, we also needed to work in areas characterized by good physical infrastructure and well-functioning markets for brinjal. Accordingly, in consultation with officials from BARI and the Department of Agricultural Extension (DAE), we purposively selected four districts in the northwest that satisfied these criteria: Bogura, Gaibandha, Naogaon, and Rangpur. Within these four districts, DAE officials provided us with lists, by upazilas (subdistricts), of villages where brinjal is cultivated predominantly in the winter season and with the number of brinjal farmers in each village. We purposively selected ten upazilas with a high concentration of villages with a substantial number of brinjal farmers.[i3] For each upazila, we generated a list of the villages that had at least fifteen brinjal farmers. We gave this list to the firm collecting our quantitative data, Data Analysis and Technical Assistance Ltd (DATA), who randomly assigned 100 villages to the treatment group and 100 villages to the control group.[4] This approach meant that randomization was undertaken independently of both the program implementers and the evaluators.

Next, we conducted a census in all 200 villages, generating a list of all farmers in these villages who had grown brinjal in the

[2]Our pre-analysis plan is available at: http://ridie.3ieimpact.org/index.php?r=search/detailView&id=682

[3]These were: Shahjahanpur, Gaibandha Sadar, Gobindoganj, Palashbari, Dhamoirhat, Manda, Gongachara, Mithapukur, Pirgacha, and Pirganj.

[4]Specifically, DATA: (*a*) used a random number generator to generate a number for each village; (*b*) ordered villages from smallest to largest number; and (*c*) allocated the first 100 villages to the control group and the remaining 100 villages to the treatment group.

preceding twenty-four months. We identified farmers willing to grow either conventional or Bt brinjal on 10-decimal plots (equivalent to 0.10 acres or 0.04 hectares) during the season beginning in November 2017. From these lists, DATA randomly selected 10 farmers from each village, of whom six farmers belong to the study group and four farmers belong the reserve group.[5] Baseline quantitative data were collected from November 25 to December 13, 2017. The endline survey was conducted from July 4 to 17, 2018, after harvesting was complete. A short qualitative survey (focus group discussions and key informant interviews with implementers, farmers, and traders buying and selling brinjal) was also conducted in July 2017.

We received letters of authorization to conduct the survey from the Ministry of Agriculture and Government of Bangladesh, and our study protocol was approved by the Institutional Review Board of the International Food Policy Research Institute.

Intervention Design

The intervention bundled together the following components: training; extension; an input package; and seedlings. A sub-assistant agricultural officer (SAAO), trained in the cultivation of both conventional and GM brinjal varieties, was assigned to each village. Using a curriculum developed for brinjal cultivation by DAE, SAAOs trained all treatment and control farmers on agronomic practices relating to brinjal cultivation over a ten-day period before the start of the winter planting season. This included information on when to plant, the size of plot (0.04 ha), when to apply fertilizer and irrigation, addressing weed infestation, and when to harvest. Particular attention was paid to the safe handling of pesticides and integrated pest management (IPM). Both treatment and control farmers received information on how to manage pests including FSB, leaf hoppers/jassids, beetles, and red spiders. Treatment farmers received additional training on the importance of planting a refuge border around Bt brinjal plots and the need to follow BARI's biosafety rules and guidelines. Farmers also received visits from SAAOs throughout the growing season. All farmers received an input package worth approximately 25 USD. The package included fertilizer, netting (to prevent birds from eating the brinjal), and support posts for plants. This package did not include pesticides. Brinjal seedlings were provided to all farmers in a similar manner. SAAOs distributed Bt brinjal seeds (Bt brinjal-4) to one "lead" farmer in each treatment village and conventional (ISD-006) brinjal seeds to one "lead" farmer in each control village who then raised seedlings. Note that BARI scientists had used ISD-006 when developing the variety of Bt brinjal (Bt brinjal-4) grown by our treatment farmers. Bt brinjal-4 and ISD-006 are genetically identical except that the former contains the gene *cry1Ac*.

Once the seedlings were mature, the lead farmers, with the assistance of SAAOs, distributed them to the other treatment and control farmers to transplant on their respective 0.04 ha plots. (Note that farmers could have declined to use these seedlings, but in practice, virtually no one did so; this was not surprising as during the village census, as noted above, we identified farmers willing to grow either Bt brinjal or conventional varieties). Per BARI's instructions, treatment farmers included a four-sided non-Bt brinjal refuge or boundary, planted with ISD-006, to slow the development of Bt resistance; the existence of these boundaries was confirmed during field visits.

We note that out of 200 treatment and control villages (100 treatment and 100 control) only 6% had distances less than 1 kilometer between treatment and control villages. This, together with the fact that during training of SAAOs, the importance of preventing spillovers of seed distribution or information means that during the intervention spillover effects were unlikely.

Data and Model Estimation

Primary Outcomes

As specified in our pre-analysis plan, we have two primary outcomes: brinjal yield (kg per ha) and cost of pesticides used (Tk per ha). These correspond to the goals of the Bt brinjal breeding program, namely to increase yields while reducing pesticide use.

At endline, farmers were asked to identify the months during which they harvested

[5]Farmers' willingness to participate was reconfirmed in September and November 2017. Out of 1,200 farmers in the original study group, 16 farmers declined to participate, so they were replaced by farmers in the reserve group.

brinjal. For each month, they then indicated how much they had harvested (including fruit that they harvested, but on inspection had to discard because of pest infestation or disease); retained for home consumption; paid out to owners of leased plots; paid to hired labor; gave away as a gift; discarded for any reason, including damage due to pests or diseases; and how much they had sold. Monthly recall was used to aid farmers in remembering all production not just that harvested prior to interview, and farmers were given diaries to record this production as it took place to further minimize recall error. All quantities were recorded in kilograms. Nearly all harvesting took place between January and June 2018.[6] We measured plot size using GPS to ensure that acreage was accurately measured. Using these data, we calculated net yields per hectare (quantity harvested in kilograms minus fruit discarded for any reason, including damage due to pests or diseases). The same set of questions were asked at baseline, but a longer recall period (twelve months) was used and aggregate quantities (rather than quantities by month) were recorded. At baseline, average yields were 30,288 kg per hectare for all sample farmers with the control group reporting higher yields than the treatment group (table 1).

At endline, for the period November 2017 to June 2018, farmers were asked, by month, about the quantity and type of pesticide they had used, how many sprays were applied, and the purchase cost of the pesticide. These detailed questions were administered to aid recall and reduce measurement error. Using these data, we calculated our second primary outcome variable as pesticide cost (in Taka) per hectare (ha) of brinjal cultivated. The same approach was used at baseline but with a twelve-month recall period. Table 1 shows that at baseline, pesticide costs per ha were 30,081 Taka or 372 USD per ha.[7] There was no statistically significant difference in baseline pesticide costs between treatment and control households.

Secondary Outcomes

As described in our pre-analysis plan, we assessed a number of additional outcomes relating to production. We disaggregated our yield results into amount harvested and amounts discarded post-harvest because of damage due to pests and other reasons. We also ascertained how much was given to hired labor, retained for home consumption, and sold. Based on sales data provided by respondents, we calculated the price received per kg sold and based on data on input costs[8] (seedlings, pesticides, fertilizer, irrigation, hired labor, costs of using animals, tools and machinery), we calculated net revenues as gross revenues (quantity sold $\times$ price) minus measured input costs.

We undertook additional analysis of pesticide use. We assessed whether cultivation of Bt brinjal reduced the frequency of pesticide application and whether it reduced the quantity applied per hectare. Because the farmers in our study provided the trade names of the pesticides that they applied to brinjal, we can assess the impact of Bt brinjal on pesticide toxicity. We did so in two ways.

First, the trade names of these pesticides were matched with a list of registered pesticides that contained their active chemical ingredients (Department of Agricultural Extension of Ministry of Agriculture, Government of the People's Republic of Bangladesh 2016). For eight pesticides used by 43% of farmers (treatment and control) at baseline to combat FSB, we matched their ingredients to the database found in Kovach et al. (1992) to construct Environmental Impact Quotient (EIQ) scores (Kovach et al. 1992; Kniss and Coburn 2015). There are three components to the EIQ score: farm worker risk, consumer, and ecological. Each component receives equal weight. To account for different formulations of the same active ingredient in various pesticides, and differences in rate of application, we used

[6] A similar method was used to collect baseline data. Although this approach is consistent with what we described in our pre-analysis plan, it introduced an unexpected complication. For baseline, this recall period (November to June) captures not only brinjal planted in October but also brinjal planted earlier in the year. As a result, for some baseline farmers, their baseline data captures two harvests on the same plot of land rather than one. This is seen, most notably, in the number of farmers reporting harvesting in November, December, and January. At baseline, 494, 597, and 689 households respectively reported harvesting in these months. At endline (remembering that transplanting of seedlings took place largely in November), the number of farmers harvesting were 7, 29, and 340 in November, December, and January, respectively.

[7] For baseline data, we use the exchange prevailing in mid-2017, 80.7 Taka to one USD.

[8] Note that items provided in the input package are included in these cost calculations.

Table 1. Baseline Household Characteristics by Treatment Status

	All		Treatment		Control		
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	t-test
Primary outcomes							
Brinjal yield in baseline (kg per ha)	30,288	25,166	27,472	24,811	33,105	25,223	3.89***
Cost of pesticides used in baseline (Tk per ha)	30,081	31,488	28,636	29,123	31,526	33,650	1.59
Control variables							
Years of education of the brinjal grower	5.58	4.64	5.84	4.60	5.32	4.66	1.92*
Age of brinjal grower	46.12	12.50	46.03	12.66	46.21	12.35	0.25
Years of working as a farmer	26.68	12.50	26.82	12.56	26.54	12.45	0.39
Size of operated land (acres)	1.49	1.38	1.58	1.56	1.40	1.17	2.19**
Wealth Index	0.00	2.02	0.04	2.09	–0.04	1.94	0.76

Notes: Sample sizes are 598 for Treatment and 598 for Control. Null hypothesis for t test is equality of means between Treatment and Controls. *** significant at the 1% level; ** significant at the 5% level; * significant at the 10% level. Source: 2017 baseline survey.

the adjustment outlined by Kniss and Coburn (2015) to calculate the EIQ Field Use Rating (EIQ-FUR). A higher EIQ-FUR implies greater potential adverse impacts on people and the environment. Supplementary Appendix S1 provides additional details on how we constructed these EIQ-FUR values.

Our EIQ analysis focused on pesticides used for FSB. We complemented this with a second approach in which we matched the pesticides (and their chemicals) used by farmers in our study to the *Globally Harmonized System (GHS) Acute Toxicity Hazard Categories* database constructed by the World Health Organization (United Nations 2011). The GHS ranks the chemicals in these pesticides on a scale from one to five where category 1 is fatal if swallowed, inhaled, or contacts the skin, and category 5 is potentially harmful. We constructed a toxicity score, the Pesticide Use Toxicity Score (PUTS) based on the GHS Oral Hazard category and the frequency of their use. In the GHS Hazard Classification scale, lower levels correspond to more severe levels of toxicity; we invert this to make PUTS more easily interpretable. PUTS is the inverse GHS hazard classification multiplied by the number of times the pesticide was applied. Supplementary Appendix S1 provides additional details on how we constructed PUTS.

Last, we considered whether cultivation of Bt brinjal was associated with improved self-reported health outcomes. Our unit of observation is the individual. Following an approach found in Kouser and Qaim (2011), individuals who reported undertaking work on any field crops were asked if during the last agricultural season they had experienced eye irritation, headaches, dizziness, nausea or vomiting, diarrhea, fever, convulsions, shortness of breath, wheezing, coughing, skin disease, or joint pain (stiffness, swelling). We also asked how long (in days) these symptoms persisted, the number of days during the agricultural season that these symptoms prevented the individual from working, and the amount of cash medical expenses associated with treating these symptoms.

Sample Characteristics and Control Variables

Ahmed et al. (2019) provide details on the sampled population. In brief, farming is the main occupation for most surveyed households (84.1%), followed by business and trade. Around 48% of treatment farmers and control farmers cultivate their own land. It is common for our sampled farmers to augment their landholdings through rental arrangements. Nearly one-half of surveyed farmers sharecrop (46.7% of treatment farmers and 44.1% of control farmers), a smaller fraction also obtain land through cash leases (10% and 13.1% of treatment and control farmers, respectively). Virtually all farmers cultivate rice. At baseline, brinjal occupied only 10% of total cropped area for surveyed farmers (9.5% and

10.7% for treatment and control farmers, respectively). Nearly all households, 95%, are male headed. Most surveyed farmers (81.6%) have access to electricity, and mobile phone ownership is nearly universal (98.1%).

Table 1 lists farmer and household characteristics that we include as controls in our impact estimators. These are variables that we believed a priori to be associated with our primary outcomes (Bruhn and McKenzie 2009) and were specified in our pre-analysis plan: age of household head; education of household head; wealth status (based on a principal components analysis of ownership of consumer durables and housing quality); land operated during the prior twelve months (November 2016 to October 2017), and number of years working as a farmer.[9] Treatment households operated slightly larger farms (0.18 acres more) and had slightly more schooling (0.5 grades); other characteristics did not differ between treatments and controls.

Balance

Bruhn and McKenzie (2009) note that there are both beneficial and problematic aspects associated with testing for randomization. In our case, randomization was undertaken by an independent third party (DATA) trained by us in how to implement randomized selection. Further, this was a straightforward randomization exercise, involving neither multiple phases nor stratification. Given all this, we follow McKenzie (2015) by undertaking an omnibus test of joint orthogonality. We include in our linear probability model the control variables that appear in our impact estimators as well as two primary outcomes: brinjal yields (kg/ha) and pesticide costs (Tk/ha).

Table 2 shows no association between any baseline characteristic and treatment status except that, at baseline, yields were higher in control households. However, a Wald test does not reject the null hypothesis that the regressors are jointly equal to zero, implying that imbalance between treatment and control households in baseline characteristics is not a concern for this study.

Attrition

Our actual baseline survey consisted of 1,196 households (598 treatment households and 598 control households). We successfully traced and re-interviewed 1,176 households, 593 treatment households, and 583 control households, losing only twenty households (five treatment and fifteen controls), an attrition rate of 1.7%.[10] In our pre-analysis plan, we specified that if an omnibus test of joint orthogonality rejects the null hypothesis that these baseline values are uncorrelated with attrition status, and if attrition exceeds 10%, we would assess the robustness of our findings to the use of inverse-probability-of-attrition weights (Fitzgerald, Gottschalk, and Moffitt 1998). Accordingly, we estimated a linear probability model where the outcome variable equals one if the household was lost to follow-up for any reason, zero otherwise. Our regressors include treatment status, the control variables we include in all extended model specifications (age of household head; education of household head; wealth status; land operated during the previous twelve months, and number of years working as a farmer), and our two primary outcomes, namely brinjal yield at baseline and cost of pesticides.[11] Standard errors account for clustering at the level of randomization, the village. A Wald test does not reject the null hypothesis that the regressors are jointly equal to zero (table 2). Households randomized into Bt brinjal cultivation were less likely to attrit, but although this coefficient is statistically significant, the magnitude is small (1.8% points). Given these results and given the very low level of attrition, we do not implement the weighting methodology proposed by Fitzgerald, Gottschalk, and Moffitt (1998). Attrition is not a concern for this study.

Estimation Strategy

We use our randomized design to estimate an intent-to-treat (ITT) analysis using the ANCOVA specification described in McKenzie (2012). Define:

[9]As more than 95% of households are male headed, we did not include this characteristic in our extended specification. As a robustness check, we included it as an additional control; doing so does not change our results.

[10]Seven control and two treatment households decided not to continue growing brinjal, four control households switched to another non-GM variety, two households migrated, and five could not be traced.

[11]The official exchange rate for the Taka, the currency of Bangladesh, was 84.13 Taka per 1.00 USD on March 31, 2019.

Table 2. Balance and Attrition: Linear Probability Estimates

	(1)		(2)	
	Dependent variable: treatment status		Dependent variable: household lost to follow up	
Baseline characteristics	Coefficient	SE	Coefficient	SE
Treatment status is Bt brinjal	—	—	−0.018**	0.009
Years of education of the brinjal grower	0.006	0.004	0.001	0.0008
Age of brinjal grower	−0.001	0.002	0.0001	0.0005
Years of working as a farmer	0.002	0.002	−0.0004	0.0004
Size of operated land (in acres)	0.020	0.016	−0.009***	0.003
Wealth Index	−0.004	0.010	0.0007	0.002
Brinjal yield in baseline (kg/ha)	-2.05×10^{-6} **	9.87×10^{-7}	-5.06×10^{-7}***	1.68×10^{-7}
Cost of pesticides used in baseline (Tk/ha)	-2.22×10^{-7}	6.98×10^{-7}	7.90×10^{-8}	1.05×10^{-7}
Constant	0.500***	0.096	0.050**	0.022
Joint test of orthogonality (F test)	1.69		1.67	
p-value	0.11		0.11	
Sample size	1196		1196	

Note: Estimates are based on linear probability models. Column (1): Dependent variable equals one if household was in a treatment village at baseline, zero otherwise. Column (2): Dependent variable equals one if the household was lost to follow up, zero otherwise. Standard errors clustered at the village level. *** significant at the 1% level; ** significant at the 5% level; * significant at the 10% level. Source: 2017 baseline and 2018 endline surveys.

Y_{i1} Baseline value of outcome variable for household i

Y_{i2} Endline value of outcome variable for household i

T_i Treatment status, =1 if household in village randomized to receive Bt brinjal

$\mathbf{X}_{i1}$ Vector of control variables (age of household head; education of household head; wealth status (based on a principal components analysis of ownership of consumer durables and housing quality); land operated during the winter cropping season, 2016–17 and number of years working as a farmer).[12]

β Parameters to be estimated

ε_I Disturbance term

We estimate a basic and extended ANCOVA treatment effect equation.

The basic model is:

$$(1) \quad Y_{i2} = \beta \bullet Y_{i1} + \beta \bullet T_i + \varepsilon_I$$

The extended model is:

$$(2) \quad Y_{i2} = \beta \bullet Y_{i1} + \beta \bullet T_i + \beta \bullet \mathbf{X}_{i1} + \varepsilon_I$$

[12]As more than 95% of households are male headed, we did not include this characteristic in our extended specification. As a robustness check, we included it as an additional control; doing so does not change our results.

Continuous outcomes are estimated using ordinary least squares and dichotomous outcomes are estimated using linear probability models. Standard errors are adjusted for clustering at the unit of randomization, the village (Abadie et al. 2017). We assess the robustness of our findings by comparing results from the basic model and the extended model and, where appropriate, winsorizing our outcome variables (setting the values of the bottom two percentiles equal to the second percentile and by setting the values of the top two percentiles equal to the ninety-eighth percentile to assess robustness to outliers) and, where appropriate, taking the log of the dependent variable. When the dependent variable is in log form, we use the formula found in Kennedy (1981) to convert parameter estimates to percentage point changes. Some observations have zero values at endline and so, as a further check on our findings, we apply the inverse hyperbolic sine transformation described in Bellemare and Wichman (2020) to our dependent variables as a further robustness check. In cases where we need to account for multiple hypothesis testing, we use the method proposed by Romano and Wolf (2005).

We explore whether there are differential effects by subgroups based on farmer characteristics: age, schooling, and land cultivated.

Note that because of the criteria for inclusion in the study meant that the sample was relatively homogeneous, there may be limited scope for heterogeneous effects.

Results

Primary Outcomes: Yields and Pesticide Costs

Table 3 reports the results of estimating equations (1) and (2) for our primary outcomes. Cultivation of Bt brinjal, relative to the control crop, increase yields by 3,564 kg/ha (column 1). This impact is significant at the 1% level. This estimate is robust to adding control variables (column 2), winsorizing net yields (column 3), expressing yields in logs (column 4) or constructing the IHS transformation (column 5). Applying the Kennedy (1981) formula to the log net yield results found in column (4), we find that Bt brinjal increases net yields by 51%. We also examined the distribution of yields across Bt brinjal and control households by plotting the density functions of log net yields for treatment and control farmers. Appendix Figure S2.1 shows that, relative to control households, the distribution of (log) net Bt brinjal yields per hectare is shifted to the right. This suggests that mean differences between treatment and control groups are not being driven by a small number of households but rather that Bt brinjal yields are generally higher than those from conventional varieties. A Kolmogorov–Smirnov test rejects the null hypothesis that the two distributions are equal at the 1%level.

Column 6 shows that Bt brinjal cultivation reduces pesticide costs by 7,175 Taka per hectare or (using the June 2018 exchange rate of 84.3 Taka per dollar), 85 USD per ha, significant at the 1% level. Again, results are robust to add control variables, winsorizing, and using log or IHS transformation (columns 7–10). Using the Kennedy (1981) formula, Bt brinjal cultivation reduces the per ha cost of using pesticides by 37.5%.

In our pre-analysis plan, we noted that we had two domains of primary outcomes: pesticide use and yields. Within each domain, we defined a single outcome; accordingly, for our primary outcomes we had not intended to adjust for multiple hypothesis testing. That said, doing so, using the method proposed by Romano and Wolf (2005) does not change these findings. For example, the p-values for our results for pesticide use and yields using the extended specification (columns 2 and 6) are 0.0038 and 0.0000, respectively. Romano-Wolf p-values for these models are 0.005 and 0.001.

We explored whether there are differential effects by subgroups based on farmer characteristics: age, schooling, and land cultivated (note that we did not disaggregate by sex of head as female headed households account for only 5% of the sample). We did not find evidence of differences in impacts in these subgroups, possibly because the sample is relatively homogeneous, and thus there may be limited scope for heterogeneous effects. Results are available on request.

Secondary Outcomes: Output, Revenues, and Costs

Columns (1), (2) and 5 of table 4 explain why net yields rise. Results from our extended specification show that Bt brinjal farmers produced 113.3 kg more brinjal (column 1) per farmer. (Endline mean production by control farmers was 487 kg). After harvesting, they discarded 43 kg less than control farmers (column 2). Also noteworthy is the fact that Bt brinjal farmers retained more brinjal (6.5 kg) for home consumption than control farmers (column 4); more Bt brinjal farmers gave more brinjal to workers than control farmers. Impacts on production, loss, and own consumption are statistically significant, and they remain so even after using the Romano and Wolf (2005) correction for multiple hypothesis testing (see Supplementary Appendix Table S2.1). We obtain near identical results if we use the base model instead, if we winsorize or if we estimate using logs (results available on request). We considered whether this increased production reflected a larger area devoted to brinjal. aLTHOUGH column (5) shows that Bt brinjal farmers cultivated a slightly larger area, this difference arises because of the requirement for Bt brinjal farmers to construct a non-Bt brinjal boundary; brinjal from this boundary is excluded from our production estimates.

Although Bt brinjal farmers retained more brinjal for home consumption, because they both produced more and discarded less post-harvest, it is not surprising that table 5 column (1) shows that they sold 143.6 kg more brinjal, an impact significant at the 5% level. However, these increased sale quantities do not

Table 3. Impact of Bt Brinjal on Net Yields and Pesticide Costs

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Net yield per ha					Cost of pesticides used (Tk per ha)				
			Winsorized	Ln yield	IHS			Winsorized	Ln cost	IHS
Treatment: Bt brinjal	3,564***	3,553***	3,313***	0.42***	0.36*	−7175***	−7196***	−6852***	−0.47***	−0.28**
	(1,221)	(1,212)	(1,110)	(0.12)	(0.19)	(1213)	(1211)	(998.67)	(0.06)	(0.11)
Baseline: Net yield	0.03*	0.03*								
	(0.02)	(0.02)								
Baseline: Net yield winsorized			0.05***							
			(0.02)							
Baseline: Ln net yield				0.17***						
				(0.05)						
Baseline: IHS net yield					0.06					
					(0.05)					
Baseline: Pesticide cost						0.06***	0.05***			
						(0.01)	(0.01)			
Baseline: Pesticide cost winsorized								0.06***		
								(0.01)		
Baseline: Ln pesticide cost									0.11***	
									(0.03)	
Baseline: IHS pesticide cost										0.19**
										(0.08)
Grower: Education		−139.28	−103.96	−0.00	−0.02		−8.51	−7.82	−0.00	−0.03***
		(99.06)	(81.46)	(0.01)	(0.02)		(102.0)	(86.78)	(0.01)	(0.01)
Grower: Age		−100.16*	−92.16*	−0.00	−0.00		−139.59**	−95.97**	−0.01*	−0.01*
		(57.19)	(53.54)	(0.01)	(0.01)		(66.69)	(48.70)	(0.00)	(0.00)
Grower: Years as farmer		70.64	59.14	0.00	−0.00		81.97	49.79	0.00	0.00
		(52.24)	(48.47)	(0.01)	(0.01)		(55.56)	(43.82)	(0.00)	(0.00)
Household wealth		351.56	195.49	0.02	0.06		−403.30	−215.97	−0.02	0.03
		(405.68)	(327.62)	(0.04)	(0.05)		(361.36)	(310.25)	(0.02)	(0.03)
Land operated by household		133.08	7.50	−0.02	−0.03		−54.92	−21.94	0.01	0.01
		(347.70)	(288.74)	(0.04)	(0.05)		(309.01)	(258.24)	(0.02)	(0.03)
Constant	9,357***	12,671***	11,880***	6.91***	8.52***	20170***	24615***	22538***	8.82***	8.77***
	(892)	(2,301)	(2,133)	(0.55)	(0.65)	(1016)	(2682)	(2113)	(0.31)	(0.93)

Note: IHS is inverse hyperbolic sine transformation. Standard errors clustered at the village level. *** significant at the 1% level; ** significant at the 5% level; * significant at the 10% level. Sample sizes are 1,166 (columns 1,2,3,5,6,7,8,10), 1,114 (column 4) and 1,137 (column 9).

Table 4. Impact of Bt Brinjal on Production

	(1)	(2)	(3) Amount (kg)	(4)	(5)
	Harvested	Discarded	Paid to labor	Retained for home consumption	Land allocated to brinjal cultivation (ha)
Treatment: Bt brinjal	113.32** (53.96)	−42.97*** (10.25)	5.61 (4.96)	6.45*** (2.08)	0.0023** (0.0009)
Baseline: Harvested	0.01 (0.01)				
Baseline: Discarded		−0.02 (0.01)			
Baseline: Paid out			0.00 (0.00)		
Baseline: Retained				−0.01 (0.01)	
Baseline: Brinjal area cultivated					0.0515*** (0.0097)
Grower: Education	−1.59 (4.45)	1.13 (0.70)	−0.34 (0.48)	0.23 (0.24)	0.0001 (0.0001)
Grower: Age	−3.11 (2.21)	−0.00 (0.37)	−0.37 (0.36)	0.03 (0.14)	0.0000 (0.0000)
Grower: Years working as farmer	2.99 (2.19)	0.22 (0.35)	0.27 (0.36)	0.06 (0.10)	−0.0001 (0.0000)
Household wealth	−0.11 (18.18)	−7.33** (3.23)	−1.18 (2.19)	0.10 (0.67)	−0.0003 (0.0003)
Land operated by household	21.09 (17.09)	12.94* (7.12)	0.19 (1.10)	1.46* (0.76)	0.0001 (0.0003)
Constant	505.29*** (86.56)	44.73*** (14.17)	43.10*** (11.40)	16.51*** (5.93)	0.0366*** (0.0021)

Note: Standard errors clustered at the village level. *** significant at the 1% level; ** significant at the 5% level; * significant at the 10% level. Sample size is 1,166. Source: 2017 baseline and 2018 endline surveys.

necessarily imply higher profits. For example, if Bt brinjal sells for a lower price than conventional varieties or if there are higher non-pesticide costs associated with Bt brinjal production, then net profits would not be higher. Our extended ANCOVA, model shows that, conditional on selling any brinjal, the sale price for Bt brinjal was 0.96 Tk/kg higher than for conventional varieties (column 2), statistically significant at the 5% level. The mean sale price for control households was 7.6 Tk/kg (0.083 USD/kg), and so this corresponds to a 12.6% increase. This does not appear to reflect differences in marketing channels. Table S2.2 in the Supplementary Appendix shows no differences in the identity of buyers of Bt brinjal or the conventional variety grown by the control group, the reasons for using a particular buyer, or the location of these sales. We note that traders purchasing Bt brinjal knew that it was a GM crop, and, to the best of our knowledge, consumers knew that they were purchasing a GMO food. A consequence of reduced pesticide application was that Bt brinjal looked better and had no marks of infestation or holes, the skin of the brinjal was much softer, making the food easier to prepare and, according to the respondents in our qualitative fieldwork, tastier. The following quotation from a market trader illustrates these points in a manner consistent with our impact estimates on price.

> At the beginning, I could not sell this brinjal in this market; I forced them to take it, especially those who are known to me to come every day. I told them no problem if you do not pay money. Then, when they took the brinjal home and ate it, they told me to give them more brinjal. Since then, demand is getting higher. In fact, it was not sold for two or three days at the beginning. After that, I enticed all of them to buy this. Since then, I did not have any problems.

The third column of table 5 shows the impact on revenue of Bt brinjal cultivation, controlling for baseline characteristics. Given that Bt brinjal increases the amount of brinjal sold in the market (column 1), the price received (column 2), and given that a larger fraction of Bt brinjal farmers made any sale of brinjal, it is not surprising that Bt brinjal increased revenues by 1,325 Taka (15.77 USD), statistically significant at the 5% level and a 27% increase relative to the control group mean of 4,895 Taka (58.27 USD).[13]

Next, we consider cost. At endline, on a per hectare basis, the cash costs of production of Bt brinjal are lower than conventional varieties (72,109 Taka for treatment vs. 81,902 Taka for control farmers) largely because Bt brinjal farmers incurred a considerably lower cost for pesticides compared with control farmers (see Supplementary Appendix Table S2.3). Note that we exclude a valuation of family labor used for brinjal cultivation given the challenges associated with valuing this labor. That said, as shown in Supplementary Appendix Table S2.4, Bt brinjal farmers report using 250 days of family labor, compared to 278 days of family labor for control households (see columns 5 and 8), a difference driven largely because Bt brinjal farmers used less family labor for pesticide application, 23.4 days compared to 35.9 days for control households. Table 5, column (4) shows that Bt brinjal reduces the cost of brinjal production 319 Taka (3.77 USD), statistically significant at the 5% level and an 8.8% reduction relative to the control group mean of 3,620 Taka.

Finally, we look at net revenue (revenue less measured costs). Table 5, column (5) shows that Bt brinjal increases net revenues by 1,635 (19.39 USD), statistically significant at the 1% level and a 128% increase relative to the control group mean of 1,275 Taka.

Note that the impacts of Bt brinjal on output, prices, revenues, costs, and net revenues are similar if we use the base specification, if we winsorize or if we use a log specification for these outcomes. They do not differ when we disaggregate by farmer age, education, or landholdings. These results are available on request. All impacts remain statistically significant when we apply the Romano and Wolf (2005) correction for multiple hypothesis testing (see Supplementary Appendix Table S2.5).

Secondary Outcomes: Pesticide Use

The first two columns of table 6 address additional aspects of pesticide use. Column

[13]To put this number in context, monthly income in rural Bangladesh was 13,353 Taka or 16.62 USD in 2016 (Bangladesh Bureau of Statistics 2017).

Table 5. Impact of Bt Brinjal on Sales, Revenues, and Costs

	(1) Quantity sold Kg	(2) Unit price Taka per kg	(3) Revenue Taka	(4) Measured input costs Taka	(5) Net revenue (revenue less measured input costs) Taka
Treatment: Bt brinjal	143.60*** (49.29)	0.96** (0.42)	1325.87** (647.13)	−318.54** (147.70)	1635.94*** (585.57)
Baseline: Quantity sold	0.01 (0.01)				
Baseline: Unit price		0.07** (0.03)			
Baseline: Revenue			0.05*** (0.01)		
Baseline: Measured input costs				0.12*** (0.02)	
Baseline: Net revenue					0.04*** (0.01)
Grower: Education	−2.73 (4.12)	0.07 (0.03)	−38.24 (71.77)	−15.41 (12.92)	−22.05 (66.47)
Grower: Age	−2.72 (2.02)	0.05 (0.02)	−36.03 (27.47)	−3.94 (7.01)	−31.23 (24.81)
Grower: Years working as farmer	2.39 (2.01)	−0.02 (0.02)	28.80 (33.29)	−6.63 (7.69)	35.55 (31.48)
Household wealth	8.66 (16.15)	−0.14 (0.13)	205.34 (258.25)	−2.12 (44.00)	193.22 (245.40)
Land operated by household	6.62 (14.31)	0.18 (0.16)	201.15 (244.29)	39.38 (36.86)	174.32 (237.37)
Constant	406.87 (79.42)	4.16 (0.87)	3968.78*** (1221.37)	3241.46*** (328.00)	544.92 (1051.17)

Notes: See table 4.

(1) shows that, controlling for baseline outcome levels and household characteristics, the cultivation of Bt brinjal reduced the number of pesticide applications by 7.4 (statistically significant at the 1% level), a 33.6% reduction relative to the control group mean of 21.8 sprays.

Column (2) shows that the quantity of pesticide used also fell, by 28.2% when we compare the magnitude of the impact (a drop of 4622 m/ha) to the endline control group mean, 16,415 mL/ha. Disaggregating by median farmer age, education, and total landholdings showed no evidence of differential impacts related to pesticide application. Results are robust to expressing these outcomes in logs, winsorizing, using our base specification, or using the IHS transformation.

How did this reduced use of pesticide affect pest infestation? At baseline, treatment farmers reported that 98.4% of their brinjal plots were infested by the FSB pest, and on these plots 35.5% of plants were affected. Thus, 34.9% ($0.984 \times 0.355 = 0.349$) of all brinjal plants grown by treatment farmers in the previous season were infested by FSB. For the control group, at baseline 98.9% of all plots were infested by FSB, and 36.4% of the plants were infested in those plots; thus 36.0% ($0.989 \times 0.364 = 0.360$) of their brinjal plants were infested by FSB. At endline, plot-level infestation of FSB for the treatment group fell to 10.6%. The percentage of plants affected by FSB in those infested plots was 17.2%; thus, only 1.8% ($0.106 \times 0.172 = 0.018$) of all Bt brinjal plants grown by the treatment farmers were infested by FSB. By contrast, 90.3% of all plots of the control group and 37.5% of the plants in those plots were infested by FSB; thus, 33.9% ($0.903 \times 0.375 = 0.339$) of all ISD-006 brinjal plants grown by the control farmers were infested by FSB. Additionally, as discussed in Ahmed et al. (2019), plant-level infestation by secondary pests—leaf-eating beetles, thrips, white flies, jassids, aphids, mites, leaf bugs, and leaf rollers—fell for both treatment and control farmers. This suggests that the training that farmers received in IPM had some effect on reducing some types of pest infestations but not FSB.[14]

[14] Temperatures during the endline winter season were lower than the baseline winter season, which may have also contributed to lower pest infestation.

We now consider impacts on the toxicity of pesticides that brinjal farmers apply, using the Environmental Impact Quotient (EIQ) scores and the Pesticide Use Toxicity Score (PUTS). This is shown in columns (3) through (7) of table 6. For all measures, Bt brinjal reduces the toxicity of pesticides used and, in all cases, the impacts are statistically significant at the 1% level. Comparing these impact estimates to the endline mean of the control group, these reductions correspond to a 64.5% reduction in the EIQ Field Use Rating (control group mean is 7.15); a 76.1% reduction in the Consumer EIQ (control group mean is 0.92); a 71.5% reduction in the Farm Worker EIQ (control group mean is 1.65); and a 63.5% reduction in the Ecological EIQ (control group mean is 18.9). These results are robust to transforming the dependent variable into logs, using the IHS transform, winsoring the data, or, because some of these measures have zero values, estimating a tobit. The final column of table 6 shows that Bt brinjal reduces to PUTS score by 7.2 points, a 42% decline relative to the endline mean of 16.9 for the control group. Last, we note that all impacts remain statistically significant when we apply the Romano and Wolf (2005) correction for multiple hypothesis testing (see Supplementary Appendix Table S2.6).

Secondary Outcomes: Health

We have shown that cultivation of Bt brinjal reduces the use of pesticides, including those that are particularly hazardous to human health. Are these changes large enough to improve health outcomes? We address this question using data on 2,531 individuals who engaged in any crop cultivation at both baseline and endline. Their average age was 40. Somewhat more than half of the sample (62%) were male, and 38% were female. Most (69%) report at least one symptom consistent with pesticide poisoning and, on average, respondents report experiencing 1.8 such symptoms. A third (34%) reported that they missed a day's work because of these symptoms; days missed averaged 1.8 days. Just under half (42%) reported that they sought medical attention to address these symptoms, and 58% stated that they had incurred cash expenses to deal with these. On average, individuals spent 675 Taka on fees, tests, transport, and medicines when treating these symptoms. Note that the variation in these expenses (standard deviation is 3,457) is high relative to the mean. Supplementary Appendix Table S2.7 provides full descriptive statistics.

We use an ANCOVA specification and the same household controls used to assess outcomes in other domains. Because illness is reported at an individual level, we control for individual characteristics (age, sex, relationship to household head). We use linear probability models when the outcome is dichotomous and OLS estimators for continuous variables. As some of these continuous variables are count data and some are truncated at zero, we also assess robustness using Poisson and Tobit estimators.

Table 7a tells us that individuals engaged in crop cultivation that included Bt brinjal were 6.2% points less likely to report symptoms consistent with pesticide poisoning, significant at the 5% level. Individuals in households growing Bt brinjal were 6.2% points less likely to report that they needed to seek medical care for these symptoms, but this is only marginally significant. We do not find statistically significant impacts on number of symptoms, work days lost, or whether the household incurred cash expenses associated with treating symptoms.[15] Further, if we adjust for multiple hypothesis testing, none of these impacts remain statistically significant at the 10% level (see Supplementary Appendix Table S2.8a). As eggplant accounts for only a small amount of farm area, these reported health symptoms could also arise from spraying in other crops. This would explain why the treatment effects of Bt eggplant are relatively small. Also, although at baseline a majority of farmers reported symptoms consistent with pesticide exposure (69%, see Supplementary Appendix Table S2.7), the number of reported work days lost because of these symptoms was small (1.89 days), and so there was limited scope for improving some of these outcomes.

Our pre-analysis plan specified that we would assess whether these impacts differed

[15]We run three checks on model specification: (*a*) for our core results, the reduction in reported symptoms and the seeking of medical care, we re-estimate using a probit and calculate marginal effects. This produces near identical results to those generated by the linear probability model; (*b*) we winsorize the number of days lost because of these symptoms and the cash costs associated with treatment. Re-estimating with the winsorized data does not produce statistically significant impacts; and (*c*) for days lost and cash costs, we run Powell's (1984) censored least absolute deviations estimator (CLAD); this does not produce statistically significant impacts either.

Table 6. Impact of Bt Brinjal on Pesticides: Additional Results

	(1) Number of pesticide applications	(2) Quantity of pesticides used (ml per ha)	(3) EIQ-FUR	(4) EIQ-Consumer	(5) EIQ-Farm worker	(6) EIQ-Ecological	(7) PUTS
Treatment: Bt brinjal	−7.37*** (1.22)	−4,621.77*** (1,095.05)	−4.61*** (1.62)	−0.70*** (0.13)	−1.18*** (0.25)	−12.01*** (4.53)	−7.16*** (1.56)
Baseline: Number applications	0.07*** (0.02)						
Baseline: Quantity used		0.04** (0.02)					
Baseline: EIQ-FUR			0.03 (0.03)				
Baseline: EIQ-Consumer				0.06** (0.03)			
Baseline: EIQ-Worker					0.05* (0.03)		
Baseline: EIQ-Ecological						0.03 (0.03)	
Baseline: PUTS							0.09*** (0.02)
Grower: Education	−0.10 (0.09)	−123.69 (93.31)	−0.07 (0.13)	−0.02 (0.02)	−0.02 (0.03)	−0.16 (0.37)	−0.25* (0.15)
Grower: Age	−0.10 (0.06)	−148.42*** (52.32)	−0.05 (0.06)	−0.00 (0.01)	−0.01 (0.01)	−0.15 (0.16)	−0.12 (0.09)
Grower: Years working as farmer	0.05 (0.05)	75.68* (41.21)	−0.01 (0.05)	−0.00 (0.00)	−0.00 (0.01)	−0.02 (0.15)	0.02 (0.08)
Household wealth	0.10 (0.42)	223.61 (360.30)	−0.41 (0.26)	−0.02 (0.03)	−0.05 (0.05)	−1.14 (0.73)	0.99* (0.56)
Land operated by household	0.31 (0.36)	−312.20 (256.06)	0.02 (0.39)	−0.00 (0.03)	−0.02 (0.06)	0.07 (1.11)	0.02 (0.47)
Constant	22.55*** (2.51)	21,496.73*** (2,441.01)	9.79*** (2.83)	1.18*** (0.37)	2.11*** (0.60)	26.26*** (7.71)	20.89*** (4.08)

Notes: See table 4. EIQ refers to Environmental Impact Quotient scores. PUTS is the Pesticide Use Toxicity Score.

by age, sex, and relationship to the household head. These disaggregations (available on request) do not show any evidence of differential impact. However, many individuals in our sample have worked as farmers for decades, have been exposed to pesticides for a long period of time, and consequently may have developed chronic conditions consistent with pesticide poisoning. We wondered if the presence of pre-existing chronic conditions might affect our results. At baseline, approximately 20% of our sample (522/2,531) reported suffering from either persistent respiratory problems or from persistent skin disease.

In table 7b, we report the impact of bt brinjal on self-reported illness, conditional on pre-existing chronic condition relating to pesticide exposure. Individuals who had such pre-existing conditions and who lived in villages randomly selected to grow Bt brinjal were 11.5% points less likely to report a symptom of pesticide poisoning, reported 0.37 fewer such symptoms, were 12% points less likely to seek medical care for these symptoms, and were 11% points less likely to incur cash medical expenses to treat these symptoms. All impacts are statistically significant at the 5% level. These results are robust to using our base specification and in the case of number of symptoms, using either a Poisson or Tobit regressor. Also, they remain statistically significant at or just above the 5% level after adjusting for multiple hypothesis testing (see Supplementary Appendix Table S2.8b).

We note that both treatment and control households received training on the safe handling of pesticides. If treatment households were more likely to adopt these practices, then the differences in self-reported illness could reflect this training, not the cultivation of Bt brinjal. To assess this possibility, at baseline and endline, we asked farmers cultivating brinjal to describe how they handled pesticides. The following patterns emerge (full results are reported in supplementary appendix 4). There are some correct practices that virtually all farmers, irrespective of treatment status, undertook at both baseline and endline: washing after spraying; changing clothes; wearing long-sleeved clothing; and wearing trousers. There were some practices that more farmers undertook at endline compared to baseline: reading and following instructions; not using bare hands when mixing pesticides; and checking for wind direction before spraying. These improvements were observed in both treatment and control households. Finally, there were some practices that few farmers undertook at baseline and that showed little change at endline: mixing pesticides with a stick and wearing gloves; and wearing eye protection, gloves, or sandals/shoes while spraying. We see little evidence of change in either treatment or control households. Crucially, looking across these practices, we see that they are similar across treatment and control households at baseline. Where we observe changes, we observe them for both groups. This suggests that differences in pesticide handling practices does not account for the reduction in the self-reported symptoms described above.

Limitations. We note three limitations associated with our analysis. First, our intervention consisted of a package of activities (most notably, training and a stipend) as well as the provision of seedlings, the latter randomized to be either Bt brinjal or the control variety, ISD-006. Specifically, we note that farmers growing Bt brinjal received extensive training and support; the increase in yield relative to the control group might have been smaller in the absence of this support. That said, both the treatment and control groups received training on IPM; absent that training, the control group might have experienced even greater production losses due to pest infestations and might have spent even more money on pesticides. If this the case, our results underestimate the impact of Bt brinjal. Second, data on production, sales, and inputs as well as symptoms relating to pesticide poisoning are self-reported. If respondents in the treatment group felt some social desirability bias to exaggerate their production success, or reductions in illness, this would upwardly bias our impact estimates. Third, we do not have direct measures of pesticide residues in soils; such information would provide a useful complement to our findings about the environmental benefits of Bt brinjal.

Summary and Conclusions. In Bangladesh, we implemented a cluster randomized controlled trial to assess the impact of Bt brinjal. Households in both treatment and control villages received a bundle of interventions including training, extension, an input package, and seedlings. Control villages received a conventional variety, ISD-006. Treatment villages received Bt brinjal-4, a variety that was genetically identical to ISD-006 except for the addition of one gene (*cry1Ac*) that conveyed

Table 7a. Impact of Bt Brinjal on Self-Reported Illness and Its Consequences

	(1)	(2)	(3)	(4)	(5)
	Any symptom of pesticide exposure	# symptoms of pesticide exposure	Lost days of work b/c symptoms of pesticide exposure	Sought medical treatment for any of these symptoms?	Incurred cash expenses associated with treating symptoms?
Treatment: Bt brinjal	–0.062** (0.031)	–0.136 (0.092)	–0.024 (0.025)	–0.062* (0.034)	–0.048 (0.031)
Baseline: Any symptom	0.108*** (0.024)				
Baseline: Number symptoms		0.169*** (0.022)			
Baseline: Lost work			0.065** (0.026)		
Baseline: Sought treatment				0.094*** (0.024)	
Baseline: Incurred cash expenses					0.105*** (0.025)
Age	0.006*** (0.001)	0.014*** (0.004)	0.006*** (0.001)	0.006*** (0.001)	0.006*** (0.001)
Female	0.059 (0.042)	0.152 (0.104)	0.034 (0.035)	0.044 (0.040)	0.057 (0.042)
Spouse of head	–0.048 (0.046)	–0.104 (0.113)	–0.039 (0.040)	–0.020 (0.046)	–0.053 (0.047)
Child, son/daughter-in-law or grandchild of head	–0.132*** (0.046)	–0.382*** (0.119)	–0.045 (0.041)	–0.107** (0.048)	–0.145*** (0.047)
Other relation to head	–0.195*** (0.047)	–0.371*** (0.130)	–0.091* (0.048)	–0.189*** (0.050)	–0.189*** (0.050)
Grower: Education	–0.006** (0.003)	–0.008 (0.009)	–0.005* (0.003)	–0.006** (0.003)	–0.006** (0.003)
Grower: Age	–0.005*** (0.001)	–0.008* (0.004)	–0.004*** (0.001)	–0.004*** (0.002)	–0.004*** (0.001)
Grower: Years working as farmer	0.002 (0.001)	0.006 (0.005)	0.002* (0.001)	0.001 (0.002)	0.001 (0.002)
Household wealth	0.010 (0.009)	–0.021 (0.029)	0.005 (0.009)	0.002 (0.010)	0.006 (0.010)
Land operated by household	–0.028*** (0.009)	–0.048** (0.022)	–0.021*** (0.006)	–0.036*** (0.008)	–0.027*** (0.009)
Constant	0.642*** (0.066)	0.916*** (0.204)	0.263*** (0.065)	0.510*** (0.065)	0.562*** (0.068)

Notes: Sample size is 2,531. Standard errors clustered at the village level. *** significant at the 1% level; ** significant at the 5% level; * significant at the 10% level. Source: 2017 baseline and 2018 endline surveys.

Table 7b. Impact of Bt Brinjal on Self-Reported Illness and Its Consequences, Conditional on Pre-Existing Chronic Condition Relating to Pesticide Exposure

	(1)	(2)	(3)	(4)	(5)
	Any symptom of pesticide exposure	# symptoms of pesticide exposure	Lost days of work b/c symptoms of pesticide exposure	Sought medical treatment for any of these symptoms?	Incurred cash expenses associated with treating symptoms?
Treatment: Bt brinjal	–0.115*** (0.042)	–0.374** (0.166)	–0.046 (0.050)	–0.122** (0.050)	–0.109** (0.044)
Baseline: Any symptom	0.007 (0.056)				
Baseline: Number symptoms		0.143*** (0.041)			
Baseline: Lost work			0.074 (0.050)		
Baseline: Sought treatment				0.041 (0.041)	
Baseline: Incurred cash expenses					–0.001 (0.047)
Age	0.002 (0.003)	0.002 (0.009)	0.006** (0.003)	0.007** (0.003)	0.005* (0.003)
Female	–0.061 (0.117)	–0.439 (0.286)	–0.167* (0.086)	–0.043 (0.107)	–0.086 (0.113)
Spouse of head	0.013 (0.126)	0.292 (0.331)	0.187** (0.094)	0.042 (0.114)	0.052 (0.123)
Child, son/daughter-in-law or grandchild of head	–0.236** (0.106)	–0.832*** (0.309)	–0.036 (0.110)	–0.034 (0.109)	–0.173* (0.102)
Other relation to head	–0.125 (0.127)	–0.432 (0.331)	0.017 (0.152)	–0.232* (0.128)	–0.213* (0.124)
Grower: Education	–0.001 (0.006)	0.026 (0.018)	0.004 (0.006)	–0.002 (0.006)	0.002 (0.006)
Grower: Age	–0.008*** (0.003)	–0.012 (0.011)	–0.007** (0.003)	–0.009*** (0.003)	–0.010*** (0.003)
Grower: Years working as farmer	0.007** (0.003)	0.020* (0.011)	0.006* (0.003)	0.005 (0.003)	0.006** (0.003)
Household wealth	0.013 (0.015)	–0.019 (0.057)	–0.013 (0.018)	0.018 (0.017)	0.008 (0.016)
Land operated by household	–0.036* (0.019)	–0.118** (0.056)	–0.036** (0.017)	–0.078*** (0.017)	–0.052** (0.021)
Constant	0.962*** (0.139)	1.693*** (0.462)	0.293*** (0.128)	0.764*** (0.142)	0.907*** (0.137)

Notes: Sample size is 522. Standard errors clustered at the village level. *** significant at the 1% level; ** significant at the 5% level; * significant at the 10% level. Source: 2017 baseline and 2018 endline surveys.

protection against the fruit and shoot borer pest.

Our two primary outcomes were changes in yield and in pesticide costs. We find that cultivation of Bt brinjal raises yields by 51% relative to the control group while reducing pesticide costs by 37.5%. These results are consistent with observational studies of yield and pesticide use summarized in Klümper and Qaim (2014), Zilberman, Holland, and Trilnick (2018), and other reviews noted in our introduction. Yield increases arise because Bt farmers harvest more eggplant and because less fruit is discarded post harvest. Compared to control farmers, Bt brinjal farmers both sell more eggplant and receive a higher price for the output. They incur lower input costs, resulting in a 128% increase in net revenues. Bt brinjal farmers used smaller quantities of pesticides and sprayed less frequently, and Bt brinjal reduced the toxicity of pesticides that were applied. Farmers growing Bt brinjal and who had pre-existing chronic conditions were 11.5% points less likely to report a symptom of pesticide poisoning. Our results are robust to changes in model specification and adjustment for multiple hypothesis testing. We did not find evidence of heterogeneous effects by farmer age, schooling, or land cultivated.

We note three policy implications that follow from these results. They support the view that GMOs can contribute to the goal of increasing yields while reducing environmental stressors. They provide further justification for releasing Bt brinjal in countries such as India and the Philippines, where these varieties have been developed but not approved for cultivation due to public reservations about GMO foods. They point to the valuable role that public agencies can play in the dissemination of GMOs. The involvement of BARI and the Bangladesh Department of Agriculture in the development and support of Bt brinjal cultivation alleviates concerns raised by anti-GMO activists regarding farmer sovereignty.

We have noted several limitations to our study. The most significant is the fact that Bt brinjal was provided as part of a package. Doing so allows us to better isolate the impact of Bt brinjal but raises concerns regarding external validity. Additional RCTs with a slimmer package would make it possible to assess whether this is a concern. Clinical measures of health and chemical measures of pesticide residues would strengthen our ability to assess impacts on health and the environment. Finally, our finding that consumers are willing to pay more for a GM crop is striking; further work understanding why would be of value. Such future work would further strengthen the results found here—that Bt brinjal, a publicly developed GMO, conveys significant productivity and income benefits to farmers while reducing the use of pesticides damaging to human and ecological health.

Acknowledgments

We thank the Bangladesh Agricultural Research Institute (BARI) and the Department of Agricultural Extension (DAE) for their excellent support in implementing the study, particularly A.S.M. Mahbubur Rahman Khan, Kazi Md. Shaiful Islam, and Masuma Younus. Helpful comments were received from M. Shahidur Rahman Bhuiyan, Lesley Perlman, Tracy Powell, and Paul Tanger. It is a pleasure to acknowledge Anthony M. Shelton for his technical advice during the study design and feedback on this work. Md. Aminul Islam Khandaker coordinated the baseline and endline surveys; Aklima Parvin, S.M. Tahsin Rahaman, Md. Redoy, and Waziha Rahman for conducted qualitative field research; and Salauddin Tauseef and Md. Latiful Haque provided planning support. Data collection was carried out by survey enumerators and staff from Data Analysis and Technical Assistance (DATA). We specially thank Zahidul Hassan, Mohammad Zobair, and Imrul Hassan at DATA. Pamela Stedman-Edwards, Julie Ghostlaw, and Samita Kaiser also assisted with this study.

Financial support

We gratefully acknowledge the United States Agency for International Development (USAID) for funding this study through the Policy Research and Strategy Support Program (PRSSP) in Bangladesh under USAID Grant Number EEM-G-00-04-00013-00; and the CGIAR Research Program on Policies, Institutions, and Markets (PIM). We thank the Ministry of Agriculture, Government of the People's Republic of Bangladesh for providing additional financial support.

Supplementary Material

Supplementary material are available at *American Journal of Agricultural Economics* online.

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