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Tomato pests and diseases in Bangladesh and India: farmers' management and potential economic gains from insect resistant varieties and integrated pest management

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ABSTRACT

Tomato is an important crop in Bangladesh and India, contributing to livelihoods and nutrition, but it is heavily affected by pests and diseases. This study analyzes pest and disease damage and farmers' crop protection methods and quantified the potential economic gains of alternatives to chemical pesticides. Data come from a questionnaire survey of 744 tomato-producing farmers in India (Andhra Pradesh and Karnataka) and Bangladesh (Jashore). Farmers reported an average tomato yield loss from pests and diseases of 11.0 t/ha, of which *Phthorimaea absoluta* caused 2.1 t/ha. Farmers relied heavily on chemical pesticides, but also applied other methods. Better knowledge of pesticide health risks and beneficial insects and more use of alternative pest control methods were associated with lower pesticide use. Using an economic surplus model, we estimate *ex-ante* that the promotion of integrated pest management for the control of *P. absoluta* could generate economic gains of USD 264 million in Bangladesh and India over a 20-year period while insect resistant varieties could generate economic gains of more than USD 8.6 billion over this period.

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1. Introduction

Tomato (*Solanum lycopersicum* L.) is the world's fourth most valuable food crop and produced in almost every country (Schreinemachers, Simmons, and Wopereis 2018). India accounts for 11% of global tomato production and is the world's second-largest producer after China (FAO 2020). Unfortunately, the tomato plant is highly susceptible to many insect pests and plant pathogens, hereafter collectively called "pests", and farmers are in a constant struggle to protect their crop. Tomato pests cause substantial economic losses and lead to the excessive use of pesticides. Globally, over 385 million people per year are affected by unintentional acute pesticide poisonings (Boedeker et al. 2020).

In the tropics and subtropics, tomato plants are particularly affected by tomato yellow leaf curl disease caused by whitefly-vectored begomoviruses (Moriones and Navas-Castillo 2000; Hanssen, Lapidot, and Thomma 2010; Kenyon et al. 2014), bacterial wilt caused by *Ralstonia solanacearum* (Mansfield et al. 2012), and late blight caused by *Phytophthora infestans* (Mont.) De Bary (Fry, 2008, Nowicki et al., 2012). More recently, tomato production has been heavily affected by the invasive South American tomato pinworm, *Phthorimaea absoluta*, also known as *Tuta absoluta* (Desneux et al. 2011; Tonnang et al. 2015; Biondi et al. 2018), which in India was first reported in 2014 (Sridhar et al. 2014) and in Bangladesh in 2016 (Hossain, Mian, and Muniappan 2016).

With limited access to knowledge and information, farmers tend to apply large quantities of chemical pesticides to protect their tomato plants. In a study of three Asian countries, including India (Tamil Nadu), researchers showed photos of typical virus symptoms to tomato farmers and asked them what they thought was the cause. Although 72% of Indian farmers had observed virus-like symptoms in their tomato crop, only 49% could tell it was caused by a virus (Schreinemachers et al. 2015). The high use of chemical pesticides reduces farmer profits and jeopardizes the health of farm workers, consumers, and the environment (Mancini et al. 2005; Stehle and Schulz 2015; Kariathi, Kassim, and Kimanya 2016).

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Resistant varieties are often considered the most cost-effective solution given the challenges of pest management at the farm level (Buragohain et al. 2021). Tomato varieties with resistance to plant diseases are widely adopted in Asia, including resistance to bacterial wilt, late blight, begomovirus, and tomato mosaic virus (TMV) (Schreinemachers and Lin 2022). Resistance to tomato yellow leaf curl, the main type of begomovirus affecting tomato, has been associated with increased income and reduced pesticide use (Colvin et al. 2012). Tomato varieties with broad resistance to insect pests and virus vectors could make tomato yields more predictable and reduce the need for hazardous pesticides (Hanson et al. 2000; Rakha, Bouba, et al. 2017; Rakha, Hanson, et al. 2017; Rakha, Zekeya, et al. 2017).

Broad-spectrum insect resistance has been identified in tomato wild relatives and is associated with plant metabolites (Vosman et al. 2018) and trichome types (Rakha, Hanson, et al. 2017; Rakha, Zekeya, et al. 2017). It includes resistance to whiteflies (*Trialeurodes vaporariorum* and *Bemisia tabaci* Genn.), thrips (*Frankliniella occidentalis*), aphids (*Myzus persicae*), caterpillars (*Spodoptera exigua*), spider mites (*Tetranychus urticae* Koch), and pinworm (*Phthorimaea absoluta*) (Rakha, Hanson, et al. 2017; Rakha, Zekeya, et al. 2017; Vosman et al. 2018). Insect resistance also reduces the spread of plant viruses by controlling vector populations. However, it has been challenging to incorporate broad-spectrum insect resistance into cultivated tomato varieties and its effectiveness is not known. Knowing its potential economic benefit is important to justify research investment as the trait is costly to develop.

Effective control strategies based on principles of integrated pest management (IPM) have also been developed to deal with the threat of *P. absoluta* (e.g. Ndereyimana et al. 2020). Such a strategy has been developed and validated for South India, using pheromone traps, sequential applications of different biopesticides and use of the pesticide chlorantraniliprole in combination with systematic monitoring (Buragohain et al. 2021). Using insect resistant varieties in combination with IPM could be a formidable strategy to deal with tomato pests. A sound understanding of farmers' current management of harmful insects and diseases is important to inform such intervention. It also allows for an evaluation of the importance of investments into the new technologies based on real world data. Despite the great economic importance of tomato in South Asia, farmers' practices have not been documented accurately.

Against this backdrop, the study has three objectives. First, to describe farmers' management of insect pests and diseases affecting tomato production in Bangladesh and India, including the cost of pesticides to farmers' health and correlates of pesticide use; second, to quantify farmers' perceived pest damage; and third, to estimate the economic benefits of insect resistant tomato cultivars and IPM methods to control *P. absoluta*. We focus on the major tomato producing areas in India and Bangladesh, where we collected farm household data and quantified economic benefits using an economic surplus model.

2. Data and methods

2.1. Farm survey data

Selected study locations in Bangladesh and India represent areas with intensive, year-round tomato production. Local experts helped us to select two states in India and one district in Bangladesh. In Bangladesh, Jashore District of Khulna Division is the country's main tomato producing area. We selected Madanapalle Mandal in Andhra Pradesh (AP) and Kadur Taluk in Karnataka as major tomato-producing areas in India.

The required sample size was estimated using power calculations. We assumed 80% power and 99% confidence and an effect size sufficient to record a 25% reduction in pest damages, based on a previous study for Tamil Nadu, India (Schreinemachers et al. 2015). Assuming an intracluster correlation of 0.3, we estimated that statistical power would be optimized using 19 villages per study location and nine households per village. Accounting for uncertainty, we aimed for 25 villages and 250 households per location.

Local experts in Bangladesh identified Jashore Sadar and Bagherpara Upazila as the two most important tomato-growing sub-districts (*upazilas*). From a list of tomato-growing villages for nine administrative areas (unions), we randomized selected villages and randomly selected up to ten tomato-producing households per village until we had interviewed 250 households. The total sample included 33 villages in Bangladesh. Using the same approach in India, we selected 25 villages in Kadur and 21 villages in Madanapalle. The total sample covers 79 villages and 750 households, which to our knowledge is the largest survey of tomato farmers in Bangladesh and India.

The questionnaire was developed in English, translated into the local languages, and programmed in Survey Solutions. Data were collected using tablet computers during October 2018 in India and during February and March 2019 in Bangladesh. Six observations were dropped because of missing data, leaving an analytical sample of 744 households.

The primary respondent was the household member in charge of tomato production. Some questions were also asked to the respondent's spouse as previous studies found clear gender differences in the pest management of vegetable farms (Atreya 2007; Schreinemachers et al. 2017a). Respondents were informed about the aim of the study, about the anonymity of the data and their ability to decline or stop the interview at any time without repercussions. Respondents gave their consent verbally. The Institutional Biosafety and Research Ethics Commission of the World Vegetable Center approved the study.

The questionnaire collected data on farm household characteristics and tomato production (e.g. inputs, output, and technologies used). Respondents estimated the loss of harvest due to all pests combined and estimated the quantity that they thought they would have harvested had the crop not been affected. For each tomato harvest, farmers were asked to estimate the quantity of damaged and undamaged tomatoes, the quantity sorted out and the farm gate price of damaged and undamaged fruits. Pesticide use was recorded in number of sprays and the quantity of undiluted product applied. As the recall period is long, farmers could not provide detailed information on the products they had used. Pesticide quantities were expressed in kilograms of undiluted product assuming 1 g/ml to convert liquids.

Questions concerning insect pests and management methods were asked to the person most involved in this task. A photo tool was used to identify the three most harmful pests. The assignment of damages to specific pests was based on farmers' assessment. This was done for each production cycle, after the perceived total damage was estimated. Pests were categorized in six groups in the data analysis (bacterial, fungal, and viral diseases, insect vectors, other insects, and other causes of fruit damage).

Respondents were asked about their experience of 13 symptoms of acute pesticide poisoning (following Krishna and Qaim (2008); Kouser and Qaim (2011); Schreinemachers et al. (2017a)), while recognizing that self-reported symptoms might be biased and might not capture long-term health effects. We recorded the cost incurred by farmers for medical treatment, medication, and lost working days resulting from pesticide poisoning. Lost working days were valued using the average wage of hired labor.

2.2. Knowledge, attitudes, and practices

An assessment of knowledge, attitudes, and practices (KAP) was included to understand what farmers know about insect pests, what damage they perceive, and what control methods they apply. The tool is described in Schreinemachers et al. (2017a) and focuses on insect pests only. Knowledge was assessed using 14 photos of arthropods and respondents were asked to sort them into two groups of harmful and beneficial arthropods. We also assessed farmers' knowledge of *P. absoluta* by showing four photos of arthropod pests (tomato leaf and fruit damaged by *P. absoluta*, leaf damaged by serpentine leaf miner, tobacco cutworm eating into a tomato fruit) and asking which two photos showed *P. absoluta*.

Attitudes were measured using a set of questions on health concerns associated with pesticide spraying and another set of questions about the perceived necessity and effectiveness of pesticides following Schreinemachers et al. (2017a). We measured farmers' risk attitude, an important driver of pesticide use, using a staircase task (Falk et al. 2016). In this task, farmers were given a hypothetical choice between a relatively low guaranteed payout and a higher payout with a 50% chance of winning. The choice was repeated five times with different payouts.

Finally, practices referred to the type and quantity of pesticides applied, the number of sprays, and the adoption of 14 practices that experts considered to be part of tomato IPM in the local context (regular scouting, buying healthy seedlings, using resistant varieties, rotating with non-host crops, planting barrier crops, planting trap crops, picking and destroying insects by hand, using sticky traps, using pheromone traps, applying biopesticides, release or promotion of natural enemies, using a smartphone app to identify pests, growing tomato under insect nets, and the raising of seedlings).

2.3. Correlates of pesticide use

Knowledge, attitudes, and IPM practices were used as independent variables in a regression model to explain variations in pesticide use, expressed as chemical pesticide use in kg of market formulation per hectare per month. We controlled for seasons and regions. Pesticide use and all other non-binary variables were expressed in logarithms to reduce the influence of positive outliers. Zero values were replaced with half of the observed minimum value before taking logarithms.

Pest incidence in farmers' fields could be an important driver of pesticide use, but it is difficult to measure in a questionnaire survey. We assumed that the pest pressure on a particular farm is related to the pest pressure on all other farms in the same region. Therefore, we included a spatial lag of the observed damages of other farms in the same region into the model. To this end, pests were grouped into viruses and their vectors, fungal diseases, bacterial diseases, and diseases that cannot be effectively controlled with pesticides. Following Kondo (2016), we assumed that for each category each farmer *i* experiences a pest pressure equal to the sum of damages experienced by each other farmer *j* planting in the same month, weighted by

$$w_{ij} = \begin{cases} \dfrac{d_{ij}^{-\delta}}{\sum_{j=1}^{n} d_{ij}^{-\delta}}, if\ d_{ij} < d, i \neq j, \delta > 0, \\ 0, otherwise, \end{cases}$$

where *d* is the threshold distance and δ is the distance decay parameter. GPS coordinates of the farmer's house were used to calculate distances. The spatial lags were created for each planting and summarized at the household level, according to the planted area. The threshold distance was chosen to include all households per location. The decay parameter was chosen to minimize the Akaike information criterion in an OLS regression of the lagged variable on the experienced damages, controlling for the region and season and using a log-log link.

2.4. Economic surplus model

A partial equilibrium economic surplus model was used to estimate the economic benefits of adopting insect resistant tomato varieties and IPM methods for the control of *P. absoluta*. The ex-ante impact model to estimate research benefits is described in Alston, Norton, and Pardey (1995) and is one of the most commonly used methods to evaluate returns to agricultural research investments (e.g. Ameriana (2009), Mamaril (2009) and Schreinemachers et al. (2017b) applied it to tomato varieties and Rakshit et al. (1970) to sweet gourd IPM). The model assumes a simplified market, in which factors like market power or climate change play no role. It also assumes that the technology will be successfully developed and introduced. The model does not provide a forecast but is used to explore possible economic effects of interventions under alternative scenarios.

We used the closed economy version of the model because there is little international trade in tomato and tomato products in India and Bangladesh (FAO 2020). Demand and supply functions were assumed as linear, which is common in studies of this kind that lack data on the relationship between price and supply/demand. The method assumes that technological change will lead to a parallel downward shift in the supply curve, driven by an increase in crop yield or a decrease in input costs. Adoption is assumed to follow an S-shaped curve, starting slow and taking up speed before fading out. Following Alston, Norton, and Pardey (1995), the change in consumer surplus (CS), producer surplus (PS), and total surplus (TS) in year *t* are estimated as:

$$\Delta \mathrm{CSt} = \mathrm{Pt} \cdot \mathrm{Qt} \cdot \mathrm{Zt} \cdot \left(1 + 0.5 Zt \cdot \eta\right) \quad (1)$$

$$\Delta \mathrm{PSt} = \mathrm{Pt} \cdot \mathrm{Qt} \cdot \left(Kt - Zt\right) \cdot \left(1 + 0.5 Zt \cdot \eta\right) \quad (2)$$

$$\Delta \mathrm{TSt} = \Delta \mathrm{CSt} + \Delta \mathrm{PSt} \quad (3)$$

where P_t is the average wholesale price (USD/ton), Q_t is total production (tons) and η is the absolute value of price elasticity of demand. K_t is the per-unit and per-period cost reduction from technology adoption and estimated as:

$$K_t = A_t \cdot \left[\frac{\left(\frac{\Delta \mathrm{Y}}{\mathrm{Y_t}}\right)}{(\varepsilon)} - \left(\frac{\Delta \mathrm{C}}{\left(\mathrm{Y_t} \cdot \mathrm{P_t}\right)}\right) \right] \quad (4)$$

where A_t is the total area planted under the new technology, *ΔY* is the change in yield (t/ha), *ΔC* is the change in production cost (USD/ha), Y_t is the average national yield (t/ha), and ε is the price elasticity of supply. Z_t, is the market price effect, calculated as:

$$\mathrm{Z^t} = \mathrm{K^t} \cdot \left(\frac{\varepsilon}{(\eta + \varepsilon)}\right) \quad (5)$$

The area planted under the new technology was calculated by assuming a bell-shaped adoption profile, using logistic regressions after transforming $A_t = \frac{U\max}{\left(1 + e\left(\text{-a-b} \cdot t\right)\right)}$ to the logarithmic form $ln\left[\frac{At}{\left(U\max - At\right)}\right] = a + b \cdot t$, where U_{max} is the upper bound on adoption, *b* is the slope coefficient related to the rate of adoption, and a is the intercept related to the time when adoption begins.

Future economic gains were converted to current dollar values using a social discount rate of 5.2% as estimated for agricultural projects in India by Kula (2004) and used in economic surplus models by Krishna and Qaim (2008) and Ramasundaram et al. (2014). Hence, the model accounts for the opportunity cost of research investments and enables comparison to these other studies.

We used expert assessments to estimate the slope and intercept of the adoption curve for four future years, while assuming zero adoption for the current year, as the technology is not yet available. The experts were team members of the project "Resist Detect Protect: wide spectrum insect resistance and sound management strategies to sustainably manage insect pests on Solanaceous vegetables in South Asia". They included tomato breeders and IPM experts from the public and private sector, plant biologists, and agricultural economists. Most team members had good knowledge of tomato production in South Asia. We applied the Delphi method (Dalkey and Helmer 1963) to obtain a consensus estimate. We first asked for initial estimates using an online survey and received answers from eight persons. We then discussed the estimates in three smaller groups during an in-person meeting with 27 experts in December 2019. Each group arrived at a consensus estimate and the results were averaged across the groups.

We fitted an ordinary least squares (OLS) model with a log-linear transformation through these points to derive parameters a and b in the adoption function. We assumed a 3-year lag between investment and time of release for the IPM method and a 6-year lag for the improved varieties. The adoption ceiling for the IPM method was set to the current adoption of biopesticides in our survey. The adoption ceiling for the (hypothetical) insect resistant varieties was set based on the expert assessment. Economic gains were calculated for each year from 2020 to 2040.

We used government data on tomato area, yield, and wholesale prices. Future area and production for 2020–2040 were estimated using a linear trend based on 1980–2018 data. Wholesale prices for 2013–2017 did not show a trend and their mean was therefore taken as the future price. The price elasticity of demand was set to 0.35, based on the average of three studies of vegetables in Bangladesh (Murshid et al. 2008; Anwarul Hu and Arshad 2010; Rakshit et al. 1970), and to 0.28, as based on four studies in India (Srinivasan 1987; Kumar, Kumar, and Mittal 2004; Krishna and Qaim 2008; Pons 2011). The price elasticity of supply was set to 0.34 based on the average of three studies in Bangladesh (Rahman and Yunus 1993; Mostofa, Karim, and Miah 2010; Rakshit et al. 1970). No data on the elasticity of supply was available for India and we assumed it to be 1.0 as suggested by Alston, Norton, and Pardey (1995).

The potential yield loss reduction from insect resistant varieties and IPM methods was estimated through expert consultation for lack of field trial data. Experts estimated that cultivars with broad-spectrum insect-resistance would reduce insecticide use by half, which is conservative as insect resistance could eliminate the need for insecticides altogether. This estimate translated to a 4.25% reduction in variable input costs, considering that insecticides account for about half (54%) of all pesticides and pesticides accounted for 17% of variable input costs. For the IPM package, we also assumed that it could reduce insecticide use by 50% and total variable input costs by 4.25%, which, again, is conservative as Buragohain et al. (2021) estimated it could eliminate insecticides. We did not measure health or other benefits (e.g. on biodiversity) from reduced pesticide use.

3. Results

3.1. Characteristics of farm households

Agriculture was the primary income source of farm households in our sample (Table 1), contributing 83% of the mean household income. In Jashore, where the average farm size was much smaller (0.47 ha) than in the two Indian states (1.84 ha), the average household derived 60% of its income from agriculture, whereas this was 98% in Karnataka.

A male household member was in charge of tomato production in 98% of the households (Table 1). In India, women participated in the decision-making on

Table 1. Characteristics of the sample of tomato producers in Bangladesh and India; sample means, 2017–18.

	Andhra Pradesh, India	Karnataka, India	Jashore, Bangladesh	Total
	($n=252$)	($n=248$)	($n=244$)	($n=744$)
Household size (persons)	4.60 (1.69)	4.39 (1.29)	4.28 (1.38)	4.42 (1.47)
Household income (1000 USD/year)[a]	2.89 (2.40)	3.27 (1.95)	2.07 (1.74)	2.74 (2.11)
Household income from agriculture (1000 USD/ year)[a]	2.59 (2.29)	3.20 (1.96)	1.18 (1.17)	2.33 (2.05)
Farm size (ha)	1.34 (0.95)	2.34 (1.69)	0.47 (0.43)	1.39 (1.38)
Number of different crops cultivated	2.17 (0.64)	4.48 (1.01)	3.15 (1.30)	3.26 (1.39)
Person in charge of tomato production is a man (proportion)	1.00	0.95	1.00	0.98
Age of person in charge of tomato (years)	46.54 (10.32)	48.17 (13.43)	44.53 (11.99)	46.42 (12.05)
Formal education of person in charge of tomato (years)	6.35 (4.91)	6.66 (4.50)	5.61 (4.03)	6.21 (4.52)

[a]Includes investment in livestock but excludes other capital investments. Standard deviations are presented in parentheses.

Table 2. Participation of women in the management of tomato pests in Bangladesh and India; in proportion of households, 2017–18.

	Andhra Pradesh, India	Karnataka, India	Jashore, Bangladesh	Total
	($n=252$)	($n=248$)	($n=244$)	($n=744$)
Decision making on pest control	0.01	0.01	0.32	0.11
Involved in spraying pesticides	0.21	0.01	0.13	0.12
Involved in other pest control (e.g. scouting)	0.61	0.20	0.02	0.28
Worked in the field on the day it was sprayed	0.01	0.27	0.09	0.12

pest management only in five of the 500 households. Yet, in Bangladesh, women contributed to decision-making about pest management in 32% of the households (Table 2). Women also sprayed pesticides in 21% of households in Andhra Pradesh and 13% in Jashore. Women in Karnataka and Jashore were less involved in pesticide spraying than in Andhra Pradesh but were often working in the field during spraying and therefore directly exposed to pesticides.

3.2. Characteristics of tomato production

Farmers in Karnataka and Andhra Pradesh planted tomatoes on about half a hectare on average, while their peers in Bangladesh planted 0.07 ha (Table 3). Farmers in Karnataka planted tomatoes on average 1.5 times per year, while those in Jashore and Andhra Pradesh planted tomatoes usually just once. The average period that tomatoes were in the field was 140 days. The mean tomato yield was 35.0 t/ha in Jashore, 36.7 t/ha in Andhra Pradesh and 44.5 t/ha in Karnataka with pairwise differences being significant ($p<0.01$; Šidák-multiple-comparison test). Tomato selling prices were substantially higher in Bangladesh than in India. As a result, mean revenue and profit per hectare were higher in Bangladesh, despite the higher input cost.

On average, crop protection accounted for 17% of farmers' production costs. While farmers in Karnataka spent on average 24% of their production expenses on crop protection, farmers in Jashore spent 11%. Notably, 31% of the surveyed farmers in Andhra Pradesh reported a financial loss in tomato production in 2017–2018. This loss and the high standard deviation observed in the data reflect local farmers' opinion that tomato production is a lottery that depends on the price at the time of harvest. The share of farmers reporting a loss was 6% in Karnataka and 2% in Jashore.

Table 3. Characteristics of tomato production in India and Bangladesh, mean per farm and per hectare 2017–18.

	Andhra Pradesh, India	Karnataka, India	Jashore, Bangladesh	Total
	($n=252$)	($n=248$)	($n=244$)	($n=744$)
Tomato area planted (ha/farm)	0.52 (0.32)	0.47 (0.22)	0.07 (0.04)	0.36 (0.30)
Length of production period (days)	116.39 (31.45)	164.86 (58.30)	139.38 (37.82)	140.09 (48.24)
Production cycles per year	1.08 (0.29)	1.52 (0.53)	1.02 (0.16)	1.21 (0.42)
Proportion of production cost spent on crop protection	0.17 (0.05)	0.24 (0.08)	0.11 (0.08)	0.17 (0.09)
Marketable yield (t/ha)[a]	36.74 (14.05)	44.51 (9.99)	35.02 (7.25)	40.66 (12.47)
Revenues (1000 USD/ha)	3.10 (1.69)	4.37 (1.63)	13.89 (6.17)	4.32 (3.16)
Input costs (1000 USD/ha)	2.63 (1.11)	2.55 (0.79)	4.34 (2.24)	2.68 (1.13)
Gross margin (1000 USD/ha)[b]	0.47 (1.76)	1.82 (1.60)	9.55 (5.98)	1.64 (2.89)

Notes: [a]Includes undamaged and damaged fruits, the latter sold at lower prices. [b] Excludes land rental cost and depreciation of equipment. Per hectare data are area-weighted averages over production cycles; all other data are averaged over households. For household averages total $N=744$, for averages per hectare $N=905$ from plot cycle specific data of the same households. Standard deviations are presented in parentheses.

Across locations, 95% of farmers staked their tomatoes, and 83% used drip irrigation. Mulching was practiced by around half the farmers in Andhra Pradesh and Jashore, but only 11% of farmers in Karnataka. Farmers in Andhra Pradesh mostly used plastic mulch, while 90% of farmers in Jashore used rice straw. Nearly all farmers in the Indian sample bought tomato seedlings of determinate and semi-determinate varieties from local nurseries. In Jashore, only 4% bought seedlings, plants were mostly of indeterminate growth habit, and varieties originated from the public sector. Many farmers in Jashore targeted the off-season for producing tomatoes, using raised planting beds (92%), polytunnels to protect plants from rain, and hormone sprays (74%). The importance of off-season production confirms the findings of an earlier study (Schreinemachers et al. 2016).

3.3. Pest management practices

Tomato farmers heavily relied on chemical pesticides, compared to alternative pest control methods. Across the three locations, around 95% of the quantity of pesticides applied was chemical insecticides and fungicides. The highest average

Table 4. Tomato pest management practices in India and Bangladesh, average per farm, 2017–18.

	Andhra Pradesh, India	Karnataka, India	Jashore, Bangladesh	Total
	($n = 252$)	($n = 248$)	($n = 244$)	($n = 744$)
Pesticide use[a]:				
– Insecticides (kg/ha/month)	1.14 (0.82)	1.32 (0.87)	1.17 (1.12)	1.24 (0.87)
– Fungicides (kg/ha/month)	1.04 (0.71)	1.31 (0.82)	1.03 (0.97)	1.18 (0.79)
– Frequency of spraying (sprays/month/plot)	1.37 (0.36)	1.25 (0.40)	1.44 (0.61)	1.35 (0.48)
Other control methods (proportion of farmers):				
– Regular scouting	0.99	1.00	0.91	0.97
– Buy healthy seedlings	0.96	0.97	0.01	0.65
– Resistant variety	0.65	0.99	0.45	0.70
– Rotate with non-host crop	0.08	0.60	0.70	0.46
– Barrier crop	0.75	0.33	0.02	0.37
– Trap crop	0.64	0.32	0.02	0.33
– Pick and destroy insects by hand	0.02	0.42	0.38	0.27
– Sticky traps	0.24	0.25	0.07	0.18
– Pheromone traps	0.18	0.00	0.09	0.09
– Biopesticides	0.40	0.00	0.20	0.20
– Release or promote natural enemies	0.00	0.00	0.13	0.04
– Smartphone app to identify pests	0.02	0.00	0.01	0.01
Use of protective gear (proportion of farmers):				
– Facemask	0.96	0.97	0.77	0.90
– Long-sleeved shirt	0.66	0.95	0.97	0.86
– Hat	0.54	0.86	0.65	0.68
– Hand gloves	0.69	0.51	0.09	0.43
– Coverall	0.10	0.02	0.66	0.26
– Long trousers	0.00	0.00	0.71	0.24
– Glasses/goggles	0.00	0.22	0.14	0.12
– Raincoat	0.12	0.00	0.02	0.05
– Rubber boots/gumboots	0.00	0.00	0.10	0.03
– Respirator	0.00	0.09	0.01	0.03

Notes: [a]Quantities are in market formulation and the reference period stretches from land preparation to the end of the last harvest. Standard deviations are presented in parentheses.

quantity was applied by farmers in Karnataka at 1.32 kg/ha per month of insecticides and 1.31 kg/ha per month of fungicides (Table 4). Tomato farmers sprayed their field once every three weeks (1.4 times per month), which is an average over the whole period from land preparation until final harvest.

Apart from pesticides, regular scouting of plants was the most common method and used by 97% of households (Table 4). Respondents also used other methods such as disease resistant varieties (70% of farmers in the whole sample), healthy seedlings (common in Andhra Pradesh and Karnataka, but not in Jashore), and rotation with non-host crops (common in Karnataka and Jashore, but less in Andhra Pradesh).

Across locations, the adoption of IPM methods like sticky traps, biopesticides, pheromone traps, and the release or promotion of natural enemies did not surpass 20% but there was much variation across locations. Overall, biopesticides made up less than 1% of the quantity of pesticides applied, although 20% of the farmers said to use them. The reported biopesticides were mostly azadirachtin/neem seed oil and Spinosad.

The use of personal protective equipment did not follow usual recommendations. Most farmers reported using facemasks during spraying, but enumerators noted that this was often just a towel used to cover nose and mouth, which was also used to wipe their hands. Respondents also said that they wore a long-sleeved shirt (86%), a hat (68%), and hand gloves (43%) to protect themselves during spraying. Use of other personal protective equipment was uncommon.

3.4. Knowledge and attitudes

Shown photos of common insect pests and beneficial insects, respondents tended to identify most insects as pests (Table 5). On average, men and women correctly sorted 60% and 50% of the photos, respectively, the difference being significant. This indicates a low level of knowledge as the question is binary and a random sorting would give 50% correct answers on average.

Regarding awareness of *P. absoluta*, 34% of male and 24% of female farmers in Jashore were aware of this insect pest, but most could not correctly identify it from photos (Table 5). In India, 95–100% of male farmers were aware of *P. absoluta*, but many were not able to identify the pest from photos. Across locations, women scored significantly lower than men.

Men and women had a reasonable understanding of the health risks of pesticides, with the average

Table 5. Tomato farmers' knowledge and beliefs of pests and pesticides in India and Bangladesh with test of difference in means between genders, 2017–2018.

	Andhra Pradesh, India		Karnataka, India		Jashore, Bangladesh	
	Men	Women	Men	Women	Men	Women
	($n = 248$)	($n = 248$)	($n = 241$)	($n = 241$)	($n = 208$)	($n = 208$)
Pest management knowledge:						
– Able to identify arthropod pests (proportion)	0.85	0.78***	0.79	0.68***	0.87	0.82***
– Able to identify beneficial arthropods (proportion)	0.43	0.37***	0.37	0.33***	0.30	0.22***
– Aware of leaf miner *P absoluta* (proportion)	1.00	0.95***	0.95	0.76***	0.34	0.24**
– Able to identify leafminer *P. absoluta* (proportion) [a]	0.88	0.69***	0.73	0.39***	0.14	0.08***
Pesticide beliefs:						
– Health risk understanding (proportion)[b]	0.69	0.68	0.74	0.74	0.78	0.74**
– Pesticides are effective & necessary (proportion) [c]	0.77	0.75	0.81	0.81	0.72	0.72

Notes: [a]Sample only includes respondents that were aware of *P. absoluta.* [b] Proportion of correctly answered questions on health risks. [c] Proportion of statements supporting this perception which the respondent agrees with. Comparison of means between genders using t-test and comparison of ratios between genders using z-test; ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 6. Farmers' self-reported health effects after exposure to pesticides and associated cost, in India and Bangladesh, in proportion of farmers unless stated otherwise.

	Andhra Pradesh, India		Karnataka, India		Jashore, Bangladesh	
	Men ($n = 248$)	Women ($n = 56$)	Men ($n = 240$)	Women ($n = 65$)	Men ($n = 208$)	Women ($n = 54$)
Headache	0.81	0.86	0.97	0.98	0.16	0.06
Fatigue	0.55	0.07	0.45	0.82	0.58	0.02
Dizziness	0.74	0.48	0.66	0.57	0.27	0.15
Loss of appetite with nausea	0.28	0.38	0.30	0.17	0.16	0.04
Stomach cramps	0.16	0.50	0.24	0.17	0.03	0.00
Blurred vision	0.05	0.00	0.33	0.60	0.26	0.00
Excessive sweating and salivation	0.15	0.25	0.05	0.06	0.20	0.02
Diarrhea	0.01	0.00	0.05	0.00	0.00	0.02
Vomiting	0.05	0.18	0.08	0.18	0.15	0.06
Muscle twitching	0.22	0.27	0.23	0.12	0.01	0.00
Chest discomfort and tightness	0.31	0.00	0.02	0.02	0.06	0.04
Unable to walk	0.19	0.02	0.32	0.62	0.00	0.00
Unconsciousness	0.00	0.00	0.02	0.12	0.00	0.00
Health costs (USD/person/year)[a]	28.49	9.21***	24.19	21.11**	3.72	2.49

Notes: [a]Includes money spent on treatment and opportunity cost of lost working days valued at the daily wage of hired workers in tomato production. Sub-sample of farmers who sprayed pesticides or worked in fields during or shortly after spraying. Health effects are those ever experienced, and health costs refer to a 12-month recall. T-test for comparing health costs (*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$); no test performed on health effects.

score ranging from 4.10 to 4.66 out of six statements (Table 5). Men and women had a very similar level of understanding about pesticide health risks. The same pattern applies for the high belief in the necessity of pesticide applications.

3.5. Self-reported health effects of pesticide exposure

We recorded self-perceived pesticide poisoning symptoms experienced by a subsample of respondents, who were involved in pesticide spraying or worked in the field during or shortly after spraying (Table 6). We do not test if the means are different between men and women because they were exposed to pesticides in different ways.

Commonly experienced symptoms included headaches, fatigue, and dizziness. In some locations, a high proportion of respondents had experienced severe symptoms; for instance, 32% of men and 62% of women in Karnataka reported that they had been unable to walk after exposure to pesticides, and 12% of women there had experienced unconsciousness.

The lower row in Table 6 shows the immediate health costs of pesticide exposure resulting from lost labor days and medical expenses over a 12-month period. In Jashore, the health costs were USD 3.7 for men and USD 2.5 for women. Costs were much higher in India at USD 26.3 for men and USD 15.2 for women. The lower health cost for women could arise from their smaller involvement in pesticide spraying.

3.6. Correlates of pesticide use

The covariates could explain 30–33% of the observed variation in pesticide use. Farmers who are keen to use technologies and are concerned about the health effects of pesticides use significantly less pesticides (reduced model; Table 7). However, this effect disappears when controlling for alternative means of pest control (full model), suggesting that innovative and

Table 7. Determinants chemical pesticide use (ln kg/ha/month), log-log specification.

	Reduced model		Full model	
	Coefficient	Std. error	Coefficient	Std. error
Household and personal characteristics:				
– Farm size (ha)	0.081*	(0.042)	0.081*	(0.043)
– Age of person in charge of pest management	0.093	(0.123)	0.101	(0.121)
– Education of person in charge of pest management (years)	0.019	(0.023)	0.014	(0.024)
– Woman participates in decision making (1 = yes)	0.121	(0.140)	0.130	(0.138)
– Respondent advised >5 farmers (1 = yes)	0.184**	(0.082)	0.305***	(0.095)
– Keen to use new technologies (1 = yes)	−0.114*	(0.068)	−0.003	(0.068)
– Concern about health effects (0–6)	−0.239*	(0.141)	−0.043	(0.163)
– Perceives pesticides as effective and necessary (0–6)	−0.038	(0.108)	−0.040	(0.108)
– Respondent is more risk averse (BDT/INR)[a]	−0.015	(0.053)	−0.036	(0.054)
Household tomato production:				
– Tomato area planted (ha)	−0.476***	(0.074)	−0.496***	(0.072)
– Experience producing tomato (years)	0.038	(0.059)	0.041	(0.058)
– Training in crop protection (1 = yes)	−0.232***	(0.074)	−0.216***	(0.077)
– Identified harmful arthropods (%)	0.159	(0.137)	0.216	(0.144)
– Identified beneficial arthropods as pests (%)	0.190***	(0.067)	0.200***	(0.072)
– Identified *P. absoluta* (1 = yes)[b]	0.049	(0.092)	0.068	(0.091)
– Main advice from pesticide dealer (1 = yes)	0.246*	(0.142)	0.254*	(0.140)
Spatial lag of reported pest damages:				
– Viruses and vectors	0.037**	(0.016)	0.035**	(0.016)
– Other insects	−0.029	(0.017)	−0.026	(0.018)
– Fungal diseases	0.042	(0.057)	0.058	(0.056)
– Bacterial diseases	−0.034	(0.023)	−0.010	(0.023)
– Diseases without effective pesticide control	−0.033	(0.036)	−0.053	(0.035)
Applied IPM techniques (1 = yes):				
– Resistant variety			−0.092	(0.112)
– Plastic mulch			−0.029	(0.076)
– Sticky traps			−0.113	(0.080)
– Rotating with non/host crop			0.005	(0.085)
– Trap crop			0.060	(0.053)
– Barrier crop			−0.278***	(0.082)
– Seedlings in nethouse			0.219*	(0.132)
– Purchase healthy seedlings			0.131	(0.162)
– Pick and destroy insects by hand			0.166**	(0.081)
Observations	744		744	
R^2	0.303		0.334	

Notes: [a]Safe payout chosen in a hypothetical lottery following the staircase approach, ranging from 2,500 to 77,500 local currency units; [b]Identified at least two of four pictures correctly. Log-log specification. Constant, region, and season dummies not reported. Robust standard errors in parentheses; *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

concerned farmers can reduce pesticide use through alternative approaches. The planting of barrier crops is associated with a 25% reduction in pesticide use. Surprisingly, handpicking of pests and raising seedlings under nets are associated with increased pesticide use. Pesticide use is higher for larger farms (+0.08% per 1% increase in farm size) but is lower for farms planting more tomatoes (−0.48% per 1% increase in planted area). The coefficient on risk aversion (i.e. the secure payout in the staircase task) is not significant ($p > 0.10$). Pest management training is associated with 21% less pesticide use. This effect reduces only slightly when controlling for specific IPM techniques, suggesting pathways beyond the tested techniques. The ability to identify insect pests correctly had no significant effect on the pesticide quantity, but farmers who mistook beneficial insects for pests applied significantly more (+0.19% per 1% increase in the share of wrongly identified photos). Farmers who relied on information from pesticide dealers used significantly more pesticides (+27%) and those giving regular advice to others also had higher application rates. Lastly, the estimated pest pressure did not have a strong influence. Only the spatial lag of damages caused by viruses and their vectors showed a small positive and significant effect on pesticide use.

3.7. Pest damage

Self-perceived tomato yield losses from insect pests and diseases averaged 13.0 t/ha in Karnataka, 9.4 t/ha in Andhra Pradesh, and 3.1 t/ha in Jashore (Table 8). The total damage corresponds to 30% of the mean yield (adjusted for the lower value of damaged fruit) in the Indian locations and 9% in Bangladesh.

Across the three locations, farmers assigned the largest damage to insect pests and fungal diseases, both causing an average damage of 4.3 t/ha. *P. absoluta* was reported to cause the most serious damage of all insects, reducing yields by 1.8 t/ha in Andhra Pradesh and 2.6 t/ha in Karnataka. However, *P. absoluta* was largely absent in Jashore during the 2017–2018 tomato season, so the perceived damage there was low. Fungal diseases were the largest cause of perceived losses in Karnataka but not much of a problem in Jashore. Bacterial diseases were of major concern to farmers in Andhra Pradesh, but not in the other locations. The perceived damage of viral diseases and their vectors (aphids, thrips, whiteflies) was 1.2 t/ha in Jashore, but minor in India.

Experts estimated that a future insect resistant cultivar would allow for average reductions in damages over current farmer practices by 86% for spider mite, 73% for white fly, 74% for thrips, 65% for *P. absoluta*, 73% for bollworm (*Helicoverpa armigera*), 67% for fruit borer (*Spodoptera litura*), 66% for tomato yellow leaf curl disease, and 66% for tospoviruses. The application of the IPM package for *P. absoluta* was estimated to reduce the damage from that pest by 59%. These expert estimates were combined with farmers' yield estimates to calculate the potential yield effect of these technologies. Insect resistant cultivars were estimated to raise tomato yields by 11% over current levels in Andhra Pradesh, 4% in Karnataka, and 2% in Jashore (Table 8). The potential yield gain was higher in Andhra Pradesh because insect pests and viral diseases were bigger problems there. The IPM package for the control of *P. absoluta* would raise the average tomato yield by 5% in Andhra Pradesh, 4% in Karnataka, but 0% in Jashore as *P. absoluta* caused little damage there. As the IPM package specifically targets *P. absoluta*, we conservatively assumed that there will be no effect on other pests.

Table 8. Farmers' self-perceived tomato yield loss from pests and potential effects of new mitigation technologies.

	Andhra Pradesh, India	Karnataka, India	Jashore, Bangladesh	Total
	(*n* = 252)	(*n* = 250)	(*n* = 250)	(*n* = 752)
Yield, adjusted for value of damaged fruits (t/ha)[a]	34.01 (13.08)	41.81 (9.39)	33.28 (6.68)	38.00 (11.71)
Self-reported yield loss from pest damage (t/ha)	9.43 (7.25)	13.03 (5.98)	3.13 (2.67)	10.96 (6.92)
Self-reported pest damages by category (t/ha):				
– Insects (excluding virus vectors)	3.75 (5.36)	4.93 (3.61)	1.59 (1.83)	4.25 (4.47)
– … of which *P. absoluta*	1.78 (3.59)	2.57 (2.48)	0.04 (0.17)	2.10 (3.02)
– Fungal diseases	1.83 (2.42)	6.69 (4.63)	0.14 (0.54)	4.25 (4.48)
– Bacterial diseases	2.06 (2.23)	0.41 (1.16)	0.04 (0.25)	1.11 (1.88)
– Viruses and vectors[b]	0.47 (0.92)	0.30 (0.91)	1.17 (1.52)	0.42 (0.97)
– Other causes[c]	0.00 (0.00)	0.17 (0.76)	0.01 (0.11)	0.09 (0.55)
Potential yield gains (proportion):[d]				
– Insect resistant cultivars	0.11 (0.32)	0.04 (0.04)	0.02 (0.03)	0.07 (0.21)
– IPM package against *P. absoluta*	0.05 (0.13)	0.04 (0.04)	0.00 (0.00)	0.04 (0.09)

Notes: [a]Damaged fruit weighted by the ratio of their price over the price of undamaged fruit. [b]Includes damage by aphids, thrips, and whiteflies. [c]Blossom end rot, fruit cracking, nematodes, slugs, and snails. [d]Based on expert estimates of potential effects of the technologies and farmers' perceived losses. Sample size reflects the number of tomato plots. Standard deviations are presented in parentheses.

3.8. Economic gain of innovative insect resistance traits and IPM packages

Potential yield gains of insect resistant cultivars are reported in Table 8. We used three scenarios: a baseline scenario representing our best estimate and lower and upper scenarios representing our confidence interval. We used the lowest and highest estimates among the three expert panels as lower and upper bounds on the effect on crop yields. For the *P. absoluta* IPM package, Buragohain et al. (2021) estimated crop yields equivalent to those under farmer practice, which we used as baseline scenario and lower bound. For the upper bound we use the estimate reported in Table 8. We combined these values for the yield change with the previously discussed assumptions on the reduction of production costs (Table 9). The assumed cost reduction is more conservative than the 10% cost reduction Mamaril (2009) assumed for the Philippines and the 5.95% reduction Ameriana (2009) assumed for Indonesia. As lower bound for insect resistant varieties, we assumed no reduction in costs and as upper bound we assumed that farmers half their total crop protection cost. As lower bound for the IPM package, we assumed that the cost saving is 50% smaller. For the upper bound, we used the same cost-reduction as in the baseline scenario.

Table 9. Estimated economic gains from insect resistant tomato cultivars and an IPM package against *P. absoluta*, 2020–2040.

	Insect resistant cultivar			IPM package for *P. absoluta*		
	Lower	Baseline	Upper	Lower	Baseline	Upper
Assumptions about technology:						
– Change in crop yield (%)	5.58	7.26	8.93	0.00	0.00	4.09
– Change in production cost (%)	0.00	−4.25	−8.50	−2.13	−4.25	−4.25
– Research lag before adoption (years)	6	6	6	3	3	3
Economic gain (million USD):						
– Bangladesh	498	694	890	8	16	154
– India	6,035	8,564	11,089	132	264	1,938

The panel of experts assessed that there would be a research lag of six years for the adoption of insect resistant cultivars and three years for the IPM methods. Mujuka et al. (2017) also assumed a three-year lag for the latter. The adoption of insect resistant varieties would rise from 8% in year-6 to a ceiling of 77% in year-18. The adoption of the IPM package is assumed to increase linearly for five years before reaching a ceiling of 20%, which equals current biopesticide adoption across the three study locations.

We combined these estimates with national data to *ex-ante* estimate economic gains at country levels. The baseline scenario shows that an insect resistant cultivar can be expected to create economic gains of 694 million USD in Bangladesh (lower bound 498 million, upper bound 890 million) and 8.6 billion USD in India (lower bound 6.0 billion, upper bound 11.1 billion) over a 20-year period, including the six years before adoption starts and expressed in current (2020) dollar values using a 5.2% discount rate. The IPM package is estimated to create an economic surplus of 16 million USD in Bangladesh (lower bound 8 million USD, upper bound 154 million USD) and 264 million USD in India (lower bound 132 million USD, upper bound 1.9 billion USD). In Bangladesh, the benefits would be shared equally between consumers and producers, while in India consumers would accrue 78%. Due to their reliance on yield effects, the insect resistance estimates are sensitive to a misspecification of elasticities (Table 10). As the IPM package is assumed to derive its benefits purely through a cost-saving effect, the elasticity does not affect the aggregate economic gain.

4. Discussion

Large yield losses, high pesticide application rates, and regularly observed pesticide poisoning symptoms indicate that pest control methods currently practiced in tomato production in India and Bangladesh are not serving farmers well. Especially in India, yield losses of 30% due to tomato pests and a high incidence of self-reported health problems show ample room for improvement. Our results show that training farmers, improving knowledge, and implementing alternative pest control methods can significantly reduce pesticide use. This suggests scope for expanding IPM practices and the introduction of insect resistant varieties to not only increase yields but also reduce the burden of unintended pesticide poisonings.

Our results support earlier findings of health concerns regarding pesticide use in South Asia (Khan and Damalas 2015; Akter et al. 2018; Sharafi et al. 2018; Memon et al. 2019), which is the region with the highest incidence of unintended acute pesticide poisonings among farmers and farm workers in the world (Boedeker et al. 2020).

We find that in a quarter of the households, women are exposed to pesticides during spraying or field work. Pesticide poisoning symptoms reported by women in India showed that women's and men's health is similarly affected. The high exposure of women to pesticide residues while they only have a limited role in pesticide spraying and little voice in pest management decisions confirms the finding of Mancini et al. (2005). Especially the data from Andhra Pradesh suggest that women may have a greater role in using alternative control practices that do not require carrying heavy pesticide spraying equipment into the field. The inclusion of women into training can reduce the existing knowledge gap and allow women to gain more respect for their work (Doneys, Doane, and Norm 2020).

Many farmers are aware of the health risks of chemical pesticides but consider them indispensable in tomato production. This mirrors studies of farmers in Bangladesh (Akter et al. 2018) and India (Govindharaj et al. 2021) but the same is also observed for small-scale farmers in high-income countries (Thao et al. 2019). Our results suggest that training farmers on pesticide health risks and the role of beneficial insects, and the provision of alternative means of pest control would lower the use of chemical pesticides. Such measures would also reduce the importance of pesticide shops as a primary source of information on crop protection to farmers, which is associated with higher pesticide use as was also reported in Schreinemachers et al. (2017a), though Alam and Wolff (2016) described pesticide sellers in Bangladesh can also increase the adoption of personal protective equipment.

Table 10. Sensitivity of the *ex-ante* economic gain created by an insect resistant cultivar to changes in elasticities.

	Bangladesh			India		
Supply elasticity	0.20	0.34 (baseline)	1.00	0.20	0.50	1.00 (baseline)
Economic gain (million USD)	1,152	694	263	40,319	16,475	8,564
Demand elasticity	0.35 (baseline)	0.50	0.70	0.28 (baseline)	0.50	0.70
Economic gain (million USD)	694	695	696	8,564	8,586	8,602

The table shows the difference in the estimated economic surplus for different supply and demand elasticities; all other values are the same as in the baseline.

We find the invasive leaf miner *P. absoluta* to be the single largest cause of reported pest damage in Andhra Pradesh and Karnataka. The exact values need to be interpreted with caution because many farmers were not able to identify the pest, but farmers' assessment generally confirms reports of *P. absoluta*'s devastating effects in other regions (Eschen et al. 2021). This shows the importance of targeted measures as the insect spreads across Asia (Guimapi et al. 2020; Zhang et al. 2020).

Based on expert assessment and trials, IPM techniques and insect resistant cultivars have the potential to limit damage and reduce chemical pesticide use. Our analysis showed that these technologies could produce a large economic gain over a 20-year period, thought the large confidence interval shows a need to handle the exact values with caution. Our *ex-ante* estimate of an economic surplus of 694 million USD from insect resistant cultivars in Bangladesh and 8.6 billion USD in India over 20 years is much larger than *ex-ante* estimates of 108 million USD per year for Bt eggplant in India (Krishna and Qaim 2008) and *ex-post* estimates of 3.61 billion USD for the first 14 years of Bt Cotton in India (Ramasundaram et al. 2014). Our analysis quantified the *ex-ante* economic gain from increased yields and lower production costs, but there are other important gains associated with lower pesticide health risks to farmers, consumers, and the environment. Research on Bt cotton in Pakistan suggest that these positive externalities can account for 39% of the total gain (Kouser and Qaim 2013), which suggests that the total gains could be 64% higher if also including the environmental and human health effects.

5. Conclusion

Tomato production in India and Bangladesh is strongly affected by plant pests. Farmers rely heavily on the application of chemical pesticides to control these, but the use of personal protective equipment is low, and pesticide poisoning symptoms are common. Our study shows that crop protection decisions are mostly made by male farmers, but female farmers are highly exposed to the health risks associated with farm-level pesticide use. The harm of pesticides and persistent yield losses point to the need for intervention. Farmer training and the promotion of alternative control methods can reduce pesticide use but are not sufficient. Recently validated IPM methods for *P. absoluta* should be part of such efforts as our study shows that this insect causes most yield damage in India. These IPM methods could potentially create economic gains of USD 264 million over a 20-year period while insect resistant tomato cultivars could generate economic gains of USD 8.6 billion over the same period. Though these estimates rely on several assumptions and come with a considerable level of uncertainty, they suggest that policy makers should try to support the development of these technologies.

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