Sustainable Technology and Entrepreneurship 2 (2023) 100036

Sustainable Technology and Entrepreneurship

https://www.journals.elsevier.com/sustainable-technology-and-entrepreneurship

Full Length Article

Impact of ICT-based pest information services on tomato pest management practices in the Central Highlands of Kenya

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ARTICLE INFO

Article History:
Received 14 September 2022
Accepted 28 December 2022
Available online xxx

Keywords:
ICT
Integrated pest management
Pest information service
Pre-harvest interval
Impact
Tomato

ABSTRACT

Pests are a major threat to tomato producers globally, owing to the substantial yield losses, low-quality produce, and low profitability that they cause. Integrated pest management (IPM) has been promoted as a sustainable, effective, safe, and environmentally friendly approach to manage pests. However, many tomato farmers in low- and medium-income countries still rely exclusively on synthetic pesticides. Moreover, many farmers rarely observe pre-harvest intervals (PHI) after applying pesticides, owing to lack of accurate and timely information on IPM and safe use of pesticides. Information and communication technologies (ICT) could bridge the information gaps on pests and their management and have been deployed in disseminating varied information to farmers worldwide. However, the effect of ICT on pest management practices has not been adequately evaluated. This study applies the propensity score matching (PSM) method to assess the impact of ICT-based pest information services (IBPIS) on the adoption of IPM and observance of PHI, using data collected from 170 Kenyan tomato farmers in 2021. The results show that 48.2% of the farmers adopted at least one IBPIS. Adoption of IPM was at 51.2% of the sample and significantly higher among adopters of IBPIS (64.6%) than non-adopters (38.6%). About 49% of the farmers observed PHI. Further, adopting IBPIS increased the number of pest control methods used by farmers by 22.8%, the proportion of farmers adopting IPM by 21.2%, and the observance of PHI by 61.7%. The study recommends that farmer advisory services incorporate multiple ICT tools to deliver pest information to farmers.

Introduction

Pest infestation has been identified as a significant challenge facing tomato production in Kenya and globally (Desneux, Luna, Guillemaud & Urbaneja, 2011), with the main pests being whitefly (*Bemisia tabaci*), African bollworm (*Helicoverpa armigera*), thrips (*Ceratothripoides brunneus*), red spider mite (*Tetranychus* spp.) and leaf miner moth (*Tuta absoluta*) (Balabag, Anub & Sabado, 2019; Mulugeta et al., 2020). Due to pest-related issues, farmers have reported yield losses of up to 80% per crop season (Santana, Kumar, Da Silva & Picanço, 2019). Pests also lead to low-quality tomato produce that fails to meet market standards, implying an indirect negative effect of pests on the marketing, pricing and profitability of tomatoes (Asante et al., 2013).

Many farmers in low- and middle-income nations predominantly use agrochemicals to control pests (Bebber, Holmes & Gurr, 2014). Africa has made significant progress in increasing agricultural productivity and lowering food insecurity through agrochemicals. However, there are concerns about the use of agricultural pesticides in the continent due to lax regulation, noncompliance, and enforcement, as well as low awareness of the risks associated with pesticides among farmers and handlers, which can result in pesticide poisoning (Loha, Lamoree, Weiss & de Boer, 2018; Ngigi & Mureithi, 2021).

Most farmers consider chemical control of pests to be effective, and the only viable means of pest control and management (Khan & Damalas, 2015), with 96.5% of farmers in Kenya reported using pesticides to control *T. absoluta* (Rwomushana et al., 2019). However, evidence shows that the use and misuse of synthetic pesticides have negative consequences on human health and the environment (Macharia, 2015). Humans exposed to pesticides risk developing skin, gastrointestinal, neurological, carcinogenic, respiratory, reproductive, and endocrine issues (Donkor et al., 2016). The presence of organochlorine residues in soil and water causes pesticides to harm ecosystems (Magauzi et al., 2011).

Continuous use of pesticides is ineffective due to the development of pest resistance to chemicals (Ganai, Khan & Tabasum, 2018; Guedes et al., 2019). In a recent study in Kenya, only 27% of farmers reported that chemicals effectively controlled *T. absoluta*, affecting over 98% of tomato farms (Santana et al., 2019). Further, the use of

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https://doi.org/10.1016/j.stae.2022.100036

storage pesticides such as pirimiphos-methyl (marketed as Actellic) was reported to cause resistance in red flour beetle (*Tribolium castaneum)* in wheat (Attia et al., 2020). Periodic unpredictability of pest populations leads to calendar spray programs that are sometimes erroneous, making chemical pest control less successful (Miller, 2020; Nguetti, 2019).

Observance of pre-harvest interval (PHI) is a vital aspect of chemical pest control (Halimatunsadiah, Norida, Norida & Kamarulzaman, 2016). However, some farmers reportedly harvest tomatoes before completing the intervals (Moura et al., 2020). Failure to uphold the PHI of various chemicals on crops leads to higher residues than the acceptable minimum residual levels (MRLs) (Sarkar, Gil, Keeley, Möhring & Jansen, 2021). Most small-scale farmers lack information on the PHI of different agrochemicals they apply to their crops (Mergia, Weldemariam, Eklo & Yimer, 2021). As a result, pesticide residue of neonicotinoids in honey samples has been reported in Kenya and Ethiopia (Fikadu, 2020). Besides, analysis of pesticide residues on marketed tomatoes and other vegetables in Africa has shown MRLs above the recommended European Union thresholds (Nguetti, 2019; Sarkar et al., 2021). These are evidence of the overuse and improper use of pesticides by African vegetable farmers (Okonya & Kroschel, 2015). Bekele, Obare, Mithöfer and Amudavi (2013) show that half of the smallholder producers in Kenya use more than three times the prescribed volumes of pesticides, posing health risks to human beings and the environment. Moreover, Musebe and Ogunmodede (2021) posit that 80% of Kenyan farmers are unaware of PHIs, and harvest and sell when the crop is in high demand, without caring when the crop was last sprayed. This has health implications for consumers and the environment and thus requires sensitization of farmers, especially through multiple strategies, including using information and communication technologies.

Integrated pest management (IPM), which combines various chemical, cultural, mechanical and biological pest control methods, is a sustainable, effective, safe, and environmentally friendly strategy for pest control (Alam et al., 2016). Researchers and governments widely promote IPM as a sustainable way to manage pests, boost agricultural productivity and reduce production costs (Dara, 2019; Pretty & Bharucha, 2015). However, most tomato farmers in Kenya only rely on synthetic chemicals (Nampeera et al., 2019). Their selection and use of agrochemicals for pest control have been ineffective due to inadequate up-to-date and timely information and understanding of pests (Sharifzadeh, Abdollahzadeh, Damalas & Rezaei, 2018).

The uptake of IPM measures by farmers requires accurate and timely information. Yet, due to the reduction in public extension services, there has been reduced access to pest management information, especially by small-scale farmers (Kante, Oboko & Chepken, 2017). Even where there are extension services, reports showed that information provided to farmers was less on IPM practices and further affected by age, gender, education level and experience of the extension workers (Ochilo et al., 2018). As such, farmers have relied on the farmer-to-farmer extension approach, agro-dealers and agrochemical sales representatives to acquire pest management information (Mwenda, Muange & Ngigi, 2022).

One of the ways to increase awareness, knowledge and adoption of IPM and observance of PHI is through access to timely and reliable information delivered through digital technologies and platforms. Information and communication technologies (ICT) could bridge the information gaps on pests and pest management among tomato farmers and service providers. ICT is the new science of collecting, storing, processing and transmitting information (Milovanović, 2014). Kamau, Vitswamba and Vyas (2018), posit that ICT solutions are increasingly being integrated into all segments of the agriculture industry to address farmers' challenges in crop production. In tandem with this, the use of ICT in farming has been on the rise, and there have been calls for farmers to intensify the adoption of ICT-based interventions (Andati, Majiwa, Ngigi, Mbeche & Ateka, 2022). Drones and artificial intelligence (AI) have been used in crop observation and crop yield optimization management (Shaikh, Rasool & Lone, 2022). Insect counting and detection using mobile devices and a density map is necessary for IPM strategies to guide farmers on targeted pest control at early infection stages to decrease economic losses and reduce chemical usage (Bereciartua-Perez et al., 2022). While large-scale farmers primarily use machine learning, artificial intelligence (AI), and the internet of things (IOTs) technologies to manage pests (Shaikh et al., 2022), small-scale farmers in developing nations rely on mobile devices, radio, and television as main sources of information on pest management and agriculture in general (Mwenda et al., 2022; Ngigi & Muange, 2022).

Several studies have evaluated the impact of ICT use on farm income (Flor & Cisneros, 2015). However, there is a literature gap on the effects of ICT and ICT-based pest information services (IBPIS) on pest management practices, such as adopting IPM and observing PHI, as these have not been adequately evaluated. Therefore, this study aimed to investigate the impact of IBPIS on tomato pest management strategies among smallholder farmers, focusing on the Central Highlands of Kenya. Using cross-sectional survey data collected from 170 smallholder tomato farmers in Meru and Nyeri Counties in October 2021, the study applies the propensity score matching method to specifically assess the impact of IBPIS on the adoption of IPM and observance of PHI following application of pesticides. The findings of this study provide a guide for policy formulation and interventions that promote the use of ICT-based technologies to encourage the adoption of sustainable pest management strategies in Kenya and other developing countries.

The remainder of the article is structured as follows: Section 2 provides an overview of the study's materials and methodology, Sections 3 and 4 present the results and discussions, and Section 5 concludes, giving policy implications.

Materials and methods

Theoretical framework

This study applies the treatment effects framework, in which the "treatment effect" is measured as the influence that a given causal factor such as an intervention (treatment) has on an outcome variable of interest, once confounding effects on the causal link between the two variables been eliminated (Cerulli, 2015). For a binary treatment variable, T, taking a value of "1″ for the units assigned to the intervention group (*treatment* group) and "0″ for the units assigned to the comparison group (*control* group), the framework brings out the difference in the outcome variable (Y) between the two groups (Flores & Chen, 2018).

In empirical work, two measures of treatment effects have commonly been used: the average treatment effect (ATE), which estimates the impact of an intervention on the entire population and the average treatment effect on the treated (ATET or ATT), which measures the impact of the intervention only for the treatment group. Under sufficient assumptions in the randomized control trials (RCT), the two measures are the same and ATE can be measured simply as $E[Y_{1i} - Y_{0i}]$, which is the average (expected value, E) difference in the outcome variable for the treated units (Y_{1i}) and the control units (Y_{0i}). However, various statistical methods are commonly used to obtain an appropriate comparison (control) group and estimate treatment effects for interventions where the participation of study units is not randomized. These are well documented and include regression approaches, difference-in-differences, matching techniques and instrumental variables (IFAD, 2015).

Econometric framework

We estimated the impact of IBPIS on the adoption of IPM and the observance of PHI using the ATET measure to operationalize the theoretical framework above. Since our data is not from an RCT, estimating ATE would require strong assumptions, among them, that (i) assignment into treatment (adoption of IBPIS) is independent of potential outcomes (adoption of IPM and observance of PHI), and (ii) the treatment status and potential outcomes of every farmer are independent of those of all other farmers (StataCorp, 2017).

We calculated the impact as:

$$ATET = E[Y_{1i}|T_i = 1] - E[Y_{0i}|T_i = 1] \quad (1)$$

where $E[Y_{1i}|T_i = 1]$ is the average outcome for the treated farmers and $E[Y_{0i}|T_i = 1]$ the average outcome for the treated farmers had they not been treated. It is impossible to observe the outcome for the treated sample without treatment, because they are already treated. Hence, we used the propensity score matching (PSM) method to construct a control group of IBPIS non-adopters with characteristics comparable to those of the treated group, and, further, to calculate the impact.

Rosenbaum and Rubin (1983) define the propensity score (π) for an individual, *i*, as the conditional probability (*P*) of assigning a participant to a treatment or comparison group (*T*) given a set of observed covariates ($\boldsymbol{X}$). This method assumes that for each value of $\boldsymbol{X}$, treated and untreated cases exist, implying that each treated individual in the matched sample has an untreated match with similar characteristics (Cameron & Trivedi, 2005). However, treated and untreated cases for which matches cannot be found are preferably dropped from the sample and excluded from impact analysis (Caliendo & Kopeinig, 2008).

The propensity score is expressed as;

$$\pi_i = P(T_i = 1|X_i) \quad (2)$$

The score was calculated using a logit model, with *T = 1* for the farmers adopting IBPIS (treatment group) and *T = 0* for the non-adopters (control group). Variables used in the model are described under the sample characteristics (Table 1). A nearest-neighbor matching algorithm with 5 neighbors and a caliper of 0.2 was applied and implemented using Stata's *psmatch2* command. A region of common support with an overlap of propensity scores between adopters and non-adopters of IBPIS was imposed, and farmers who could not find their matches within this region were discarded. The quality of the matching outcome was assessed using Stata's *pstest* command and the results are shown in table 4. After identifying the matched treatment and control groups, the impact of the adoption of IBPIS was estimated using a modified form of Eq. (1) above, as follows:

$$ATET = E[Y_{1i}|T_i = 1, P(X)] - E[Y_{0i}|T_i = 0, P(X)] \quad (3)$$

where $P(X)$ is the propensity score – the probability of an individual adopting IBPIS given their observed characteristics *X*, and the other expressions are as earlier defined.

Measurement of key variables

Adoption of ICT-based pest management information services (IBPIS)

IBPIS was measured as a binary variable taking a value of 1 for a farmer who had used at least one IBPIS and 0 for a farmer who had not used any IBPIS. The current IBPIS available to farmers include radio stations (such as Inooro FM, Kameme FM, Mwariama FM, Muga FM, Thiiri FM and Rware FM); Television stations (Citizen TV, NTV and KTN, KTN farmer's TV), which air programs such as Shamba Shape-up, Seeds of Gold, and Mugambo wa Murimi (voice of the farmer); and mobile and internet-based pest information services that include WhatsApp, Facebook, YouTube, mobile applications, iShamba services, SMS services and Ujuzi Kilimo.

Integrated pest management (IPM)

IPM is the ability of a farmer to adopt different pest management methods concurrently (Pretty & Bharucha, 2015). The methods considered in this study include synthetic pesticides, bio-pesticide, traps, good field sanitation, crop rotation and resistant tomato varieties. IPM was measured by the number of methods used by farmers in tomato pest management. We generated a binary variable equal to one if the farmer had adopted more than one pest management method, and zero otherwise.

Pre-Harvest interval (PHI)

PHI refers to the number of days that must lapse, between the final pesticide application day and crop harvest, for pesticide residuals to fall below the tolerance level established for a particular crop (Prodhan, Akon & Alam, 2018). PHI for each pesticide is indicated on

Table 1
Descriptive characteristics of the sample.

Variable	Sample *Mean*	Adopters of IBPIS *Mean*	Non-adopters of IBPIS *Mean*	Difference *t*-test/χ^2-test (p-value)
Age (years)	37.08	37.49	36.70	0.78
Household size	5.13	5.52	4.76	0.76
Land size (total production area)	2.25	2.15	2.35	−0.20
Land size (area under tomato)	1.33	1.39	1.28	0.11
Distance to market (km)	5.85	5.34	6.32	−0.98
ICTs owned		4.04	3.31	0.73***
	% sample	*% sample*	*% sample*	
Male household head	55.53	63.41	44.31	19.10**
Formal education level				
Primary	28.24	26.83	29.55	−2.72
Secondary	29.41	23.17	35.23	−12.06*
Tertiary	27.06	30.49	23.86	6.63
University	15.29	19.51	11.36	8.15
Off-farm employment	62.35	73.17	52.27	20.89***
Member in a social group	78.24	86.59	70.45	16.13**
Green house system	14.71	8.54	20.45	−11.92**
Solar power	50.59	53.66	44.73	5.93
Generator	4.71	6.10	3.41	2.69
Rechargeable electric battery	25.88	30.49	21.59	8.90*
Nyeri	42.94	42.68	43.18	−0.50
Meru	57.06	57.32	56.82	0.50
N	170	82	88	

*, **, *** difference is significant at 10%, 5% and 1% level of significance, respectively.

the label. A binary variable was created to measure PHI observance, with a value of one if the farmer observes PHI and a value of 0 indicating PHI non-observance.

Study area and sample

The study was conducted in Meru and Nyeri Counties, located in the Central Highlands of Kenya, using a cross-sectional farm survey carried out in October 2021. The two counties were purposively selected based on their agricultural potential, rich and fertile agricultural soils and reliable rainfall that is conducive for tomato production. Tomato is among the main horticultural crops produced in these counties, and many farmers make a living from its production. The sample size for the survey was 170 farmers, who were chosen using a four-stage sampling method. In the first stage, the two counties were selected purposively as explained above. One sub-county per county and one ward per sub-county were purposively sampled in the second and third stages respectively, based on the number of tomato producers. The sampled wards were Kamakwa, Rware and Gatitu in Nyeri; and Kariene, Gatimbi and Katheri in Meru. In the fourth stage, farmers were randomly selected from a sampling frame constructed using a list of tomato farmers obtained from the Horticultural Crops Directorate offices in the two counties. Proportionate distribution of the farmers in all the administrative locations within the wards was done, where 28 farmers were sampled per ward.

Data collection

A structured questionnaire was used for data collection. Data was collected on socio-demographic characteristics of the sample, such as membership in farmer groups, employment and land size; tomato production details such as the varieties of tomato grown, sources of pest and pest management information, pest management methods used, and observance of PHI. The questionnaire was pretested in an area with similar environmental and climatic conditions to the targeted study areas. The questionnaire was revised to integrate the concerns noted during the pretest.

The data collection was conducted in October 2021, during which the sampled households were visited by an enumerator to administer the questionnaire. In each household, the respondent was the person most responsible for tomato farming. The research assistants were trained on fundamental research ethics, how to use the toolkit for data collection, how to conduct interviews, and how to gather the actual data. Before the data was collected, verbal consent was sought from respondents after being taken through the purpose of the study and assured that the information will be confidential and used for research purposes only. The questionnaires were administered using the Kobo Toolkit, an open-source Android app used for survey data collection.

Results

Descriptive statistics

The use of IBPIS was assessed, and findings show that about 48.2% of the farmers had used at least one IBPIS. About 34.1% of the farmers used information from radio programs, while 30.6% and 28.2% used information from TV programs and mobile and internet-based pest information services (MIBPIS), respectively, to acquire pest management information.

Table 1 shows the sample descriptive statistics. The mean values or proportions for each variable were compared statistically between users and non-users of IBPIS using *t*-test and chi-square. The results indicate that adopters and non-adopters did not differ statistically by age, household size, education levels (except secondary school), ownership of key assets such as land and energy sources (solar and generator) and county of residence. However, there was a statistically significant difference in the number of ICT tools owned between adopters and non-adopters of IBPIS, which can be explained by the fact that adopters of IBPIS would want to own several ICT tools to gain information from different sources. The proportion of male-headed households was significantly higher among the adopters than non-adopters of IBPIS, implying that the gender of the household head could play an important role in adopting IBPIS. The use of the greenhouse tomato production system was significantly lower among adopters of IBPIS than non-adopters. Further, membership in social groups differed substantially between adopters and non-adopters of IBPIS, with membership in such groups being higher among adopters than non-adopters. Adopters of IBPIS were more engaged in off-farm employment than non-adopters, perhaps because access to digital information comes with the cost of buying and maintaining ICT devices, airtime and data. Moreover, ownership of energy sources such as solar power systems and rechargeable batteries was higher among adopters than non-adopters, perhaps because ICT tools require direct connection to a power source or regular charging for effective use.

Pest management practices and observance of PHI

Table 2 shows that tomato farmers use different methods to manage pests, with 51.2% of the sample adopting IPM. The average number of pest control methods used by the farmers was 1.84. The difference in the average number of pest control methods used between the adopters and non-adopters of IBPIS was statistically significant, with adopters using more methods (2.10) than non-adopters

Table 2
Use of different pest control methods and observance of PHI.

Variable	Sample	Adopters of IBPIS	Non-adopters of IBPIS	Difference *t*-test/χ^2-test (p-value)
Outcome variable				
Adoption of IPM (% sample)	51.18	64.63	38.63	26.0***
Number of pest control methods (mean)	1.84	2.10	1.59	0.51***
Observed PHI (%)	49.41	51.2	47.7	3.5
Pest control method used (% sample)				
Synthetic pesticides	99.41	98.8	100	−1.2
Synthetic pesticides only	48.82	35.4	61.4	−26.0***
Bio-pesticides	0.59	1.2	0.0	1.2
Good field sanitation	22.35	25.6	19.3	6.3
Use of insect traps	25.29	35.4	15.9	19.5***
Crop rotation	31.18	40.2	22.7	17.5***
Resistant varieties	4.71	8.5	1.1	7.4**
N	170	82	88	

, * difference is significant at 5% and 1% significance levels, respectively.

(1.59). Almost all farmers (99.4%) used synthetic pesticides in tomato production. However, the exclusive use of synthetic pesticides was significantly higher among non-adopters (61.4%) than adopters (35.4%). This implies that IBPIS adopters also use other pest control methods rather than relying only on synthetic pesticides. Specifically, the findings indicate that adopters of IBPIS had higher levels of use of pest traps, crop rotation and resistant tomato varieties compared to non-adopters. The results further show that the use of good field sanitation and synthetic pesticides was not significantly different between adopters and non-adopters of IBPIS. Slightly more than half (51.2%) of the sampled farmers adopted IPM. However, adoption of IPM was significantly higher among adopters of IBPIS (64.6%) than non-adopters (38.6%). Although the observance of PHI was higher among adopters of IBPIS (51.2%) than non-adopters (47.7%), this difference was not statistically significant.

Propensity score matching results

Logit results of PSM

Table 3 presents the logit results of PSM for control variables hypothesized to influence the adoption of IBPIS as explained in Eq. (2) above. These factors explain the differences in the adoption of IBPIS by tomato farmers. The findings show that farmers owning a higher number of ICTs devices had a higher propensity to adopt IBPIS. Further, male farmers, those with a source of off-farm income, belonging to social groups, as well as those who owned rechargeable electric batteries, had a higher propensity to adopt IBPIS. Level of education influenced the adoption propensity score negatively, with farmers educated up to secondary level having a significantly lower propensity to adopt IBPIS than farmers with primary schooling. Farmers using the greenhouse production system had a lower likelihood of using IBPIS, probably because this production system has fewer pest infestation challenges, thus, low demand for pest information services.

The quality of the matching procedure is presented in Table 4. The high values of Pseudo R^2 and LR Chi^2 show that the propensity score model before matching was significant (p<0.001). This implies that the assignment to adopters and non-adopters of IBPIS was not random but influenced by some farmer and farm characteristics as described above. After matching, the Pseudo R^2 and LR chi^2 values dropped, and the propensity score model became statistically insignificant, meaning that the adopters and non-adopters of IBPIS in the matched sample did not differ significantly on observable characteristics. In addition, results of a t-test that is inbuilt in the *pstest* command showed that although the unmatched sample differed significantly in some of the observable characteristics, none of these characteristics differed significantly between adopters and non-adopters of IBPIS in the matched sample. Moreover, there was a considerable reduction in mean and median biases between the unmatched and matched samples. These results imply that our treatment group (79 farmers) and control group (81 farmers) obtained after PSM were statistically similar.

Table 3
Logit results of PSM estimation.

Variable	Coef.	Std. Err.	Z
Male household head	0.470	0.380	1.95*
Household size	0.046	0.080	0.57
Age	0.009	0.019	0.48
Off-farm employment	1.499	0.532	2.87***
Formal education level			
Secondary	−0.938	0.620	−1.81*
Tertiary	−0.573	0.634	−0.9
University	−0.456	0.733	−0.62
Membership in social groups	1.171	0.493	2.41**
Number of ICTs owned	0.625	0.214	2.92***
Land size	0.041	0.112	0.37
Production area	0.181	0.157	1.16
Greenhouse system	−1.253	0.573	−2.19**
Solar power system	−0.029	0.394	−0.07
Generator	0.742	0.886	0.84
Rechargeable electric battery	0.831	0.486	1.71*
Distance to market	0.010	0.042	0.23
Nyeri	−0.281	0.462	−0.61
Constant	−4.159	1.340	−3.1***
N	170		
Prob>χ^2	0.000		
Pseudo R^2	0.184		

* $p < 0.1$,.
** $p < 0.05$,.
*** $p < 0.01$.

Table 4
Matching quality.

Sample	Pseudo R^2	LR chi^2	p>chi^2	Mean Bias	Median Bias
Unmatched	0.156	36.84	0.001	21.2	17.6
Matched	0.033	7.03	0.957	9.4	7.7
Bias reduction (%)				*55.7*	*56.3*

Impact of IBPIS on pest management practices

Table 5 shows the impact of adopting IBPIS on pest management practices and observance of PHI, from the results of the PSM model. The results show significant positive treatment effects of farmer adoption of IBPIS on the number of pest control methods used, use of IPM and observance of PHI. On average, the treatment effect on the number of pest control methods used was 0.381, implying that adopting IBPIS increased the number of pest control methods used by about 0.38, translating to a 22.8% increase. Adopting IBPIS further increased the proportion of farmers using IPM by 21.2% points from 42.5 to 63.6 (49.6% increase) and the proportion of farmers observing PHI by 20.4% points from 32.9 to 53.2, which is equivalent to 61.7% increase.

Discussion

This study contributes to the growing body of evidence demonstrating the impact of IBPIS on pest management practices. This study assessed the impact of IBPIS on the adoption of IPM and the observance of pre-harvest interval (PHI).

The results show that 48.2% of farmers used at least one IBPIS. About 34.1% of farmers used radio, 30.6% used television, and 28.2% used mobile and internet-based pest information services. The study offers proof of the growing prominence of the internet and social media platforms like Facebook and WhatsApp in disseminating knowledge about agriculture and pest control. In order to assist extension agents and farmers in the sustainable management of pests, recent studies have emphasized the need to employ a variety of ICTs, including radio programs, the internet, mobile texting, social media, and visual communication (Sharifzadeh & Abdollahzadeh, 2021; Tambo et al., 2019; Wright et al., 2016).

The results show a significant difference between adopters and non-adopters of IBPIS regarding the use of tomato pest management methods. The use of insect traps, crop rotation, and planting of resistant tomato varieties was significantly higher for IBPIS adopters than non-adopters because, the information needed for their application can easily be obtained through IBPIS. The traps work through the use of sticky substances with pheromones that attract pests for mating, and when the pests follow the pheromone, they get stuck or trapped in the containers containing the chemical. Insect traps come in different types and colors. Recent research indicates insect traps can effectively reduce the tomato leaf miner population in open-field tomato production (Polat, 2019), aphids, whiteflies and thrips in French beans and fruit flies in mangoes (Mwangi, 2015). Sticky traps are also

Table 5
Average treatment effect on the use of IBPIS on IPM and PHI.

Variable	Sample	Treatment	Control	Difference (ATET)	S.E.	t-stat
No. of pest control methods used (mean)	Unmatched	2.098	1.591	0.507	0.148	3.420
	Matched	2.052	1.671	0.381**	0.191	1.990
IPM adoption (% sample)	Unmatched	0.646	0.386	0.260	0.075	3.490
	Matched	0.636	0.425	0.212**	0.099	2.140
Observance of PHI (% sample)	Unmatched	0.512	0.477	0.035	0.077	0.450
	Matched	0.532	0.329	0.204**	0.101	2.020

Note: **ATET is significant at 5% level.

helpful in monitoring insects and developing an effective IPM strategy (Bashir, Alvi & Naz, 2014). However, insect traps have not been used systematically for the best results because they require knowledge, technical skills and information (Littin, Fisher, Beausoleil & Sharp, 2014). This information can be disseminated through IBPIS. A good example is using camera-equipped traps to identify and count insect species using pictures and develop an effective IPM strategy (Preti, Verheggen & Angeli, 2020). Nahar, Uddin, de Jong, Struik and Stomph (2020) found that farmers were unwilling to use insect traps to manage pests because they perceived it as ineffective and time-consuming compared to other pest management methods such as chemical control. This notion has limited the use of the traps.

Crop rotation also has principles that should be followed for successful pest management. Just like other methods of pest control, crop rotation needs to be understood and used correctly to get the most effectiveness (Buhre, Kluth, Bürcky, Märländer & Varrelmann, 2009). All this information can easily be obtained from IBPIS. The difference between adopters and non-adopters in applying synthetic pesticides was insignificant. This is because information about different pesticides and their application can be obtained from agrochemical sales agents, agro-dealers and even other farmers (Mwenda et al., 2022). However, despite this information being available to farmers, calendar applications and failure to follow PHI are still being practised (Halimatunsadiah et al., 2016), as also reported in this study. This indicates the need for continuous sensitization of farmers through various forms of IBPIS. There was a significant difference in the number of pest control methods used between the adopters and non-adopters of ICT-based pest information services. Singh and Gupta (2016) found that to correctly implement IPM, the farmers need timely access to relevant pest management information, knowledge and expertise and with adoption of these ICT services, have access to knowledge and information about different methods of controlling pests and are in a position to implement as many methods of control as possible.

The results show a positive impact of adopting IBPIS on the adoption of IPM by farmers. A treatment effect of 0.381 implies that adopting IBPIS increased farmers' pest control methods by 22.8%. By adopting IBPIS, the proportion of farmers using multiple pest control methods (IPM) increased by 21.2%. IPM measures are is both human- and environmentally-friendly and adopting them provides economic benefits (Midingoyi, Kassie, Muriithi, Gracious Diiro & Ekesi, 2018). The adoption of IPM by tomato farmers means a reduction in toxic pesticides, farmers being able to meet prescribed MRLs and reduced exposure of pesticides to farm workers and the environment. Evidence shows that through ICT, farmers can be enlightened and provided with information on different methods of controlling pests and how to apply them appropriately (Voss, Jansen, Mané & Shennan, 2021). Mass media coverage has been reported to be positively associated with adoption of IPM (Sadique, 2020). Wright et al. (2016) similarly found that using ICTs that included tablets and short message service (SMS) helped extension workers reach out to more farmers, improving access to plant health information and providing better advice on pest management. Tambo et al. (2019) reported that the adoption of ICT in pest control increased the farmers' knowledge of different pests and the adoption of various methods, technologies and practices in pest management.

The adoption of IBPIS positively impacted the observance of PHI by tomato farmers. There was a significant impact of IBPIS adoption on observance of PHI. This is because IBPIS provide farmers access to crucial information on the pesticide regulations, such as the MRLs, different PHIs for various pesticides and crops and recommended application measures. Using ICTs by farmers will promote appropriate use of pesticides, less use of toxic pesticides and observance of PHI that will reduce pesticide residues and promote consumer safety. For instance, the European Union has been putting efforts into reducing pesticide use in pest control through projects like "ENDURE". However, access to such information by farmers has been limited because it can only be found on the internet (Meissle et al., 2010). Farmers who adopt ICT-based pest information services will have knowledge and skills in observing PHIs.

The impact of the adoption of IBPIS on the observance of PHI was 0.204, which meant that by adopting IBPIS, the proportion of farmers observing PHI increased by 20.4 percentage points or 61.7%. Sharifzadeh and Abdollahzadeh (2021) found that using educational strategies, including pamphlets, mobile texting and web-based social media about the safe use of pesticides, positively influenced farmers' knowledge and attitude and practice (KAP) about pesticide use in Iran. The use of mobile phones was reported as one way of enhancing accurate information sharing among farmers (Khan et al., 2020). Farmers in Kenya reported that accurate and timely information on pest management and weather information among other management practices, which is made possible through adoption of ICT, contributed positively to higher quality and increased productivity (Ireri, Awuor, Ogalo & Nzuki, 2021).

Conclusions and policy implications

This article explores the impact of IBPIS on the adoption of IPM and the observance of PHI by tomato farmers in Kenya. The study found that the adoption of IPM was significantly higher among adopters of IBPIS (64.6%) than non-adopters (38.6%). Adopters of IBPIS had observed field sanitation and used insect traps and crop rotation to control pests, while a higher percentage of non-adopters used synthetic pesticides. About 49% of farmers observed PHI, with a notably higher rate being reported among those adopting IBPIS.

Using the PSM framework, the study concludes that the adoption of IBPIS increased the number of pest control methods used by farmers by 22.8%; the proportion of farmers adopting IPM by 21.2%; and the observance of PHI by 61.7%. This shows that IBPIS adopters are more informed and hence more likely to adopt IPM and adhere to the safe use of pesticides. IBPIS provides the necessary information concerning different methods of pest control and information on post-pesticides management practices such as PHI. This implies that the farmers who adopt the IBPIS acquire necessary information for making timely decisions concerning the best methods to control pests and the combination of methods that can be more effective in the pest management.

The findings point out the need of an extension approach that uses a variety of ICTs, including radio and TV programs, mobile phones, and internet-based channels. This will promote and offer necessary information on IPM, sustainable pest management practices and safe use of pesticides to make pest management and control effective and efficient. There is also a need to train and sensitize farmers on using IBPIS to obtain timely and appropriate information on IPM for the safe and environmentally friendly production of high-quality tomatoes in the wake of climate change.

The major limitation of the study was that it was carried out in only two counties, due to financial and logistical constraints. While simple random sampling was used to collect data, the results cannot be generalized at the country level. As a result, nationally representative data is required to fully evaluate the role of ICT in promoting IPM and sustainable agricultural technologies. Further investigation is needed to determine how ICT use in agriculture affects more comprehensive welfare measures, including farm income, food security and poverty alleviation.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.Equation 3 not needed in under this section.

Declaration of Competing Interest

The authors report there are no competing interests to declare.

References

Alam, M. Z., Crump, A. R., Haque, M., Islam, M., Hossain, E., Hasan, S. B., et al. (2016). Effects of integrated pest management on pest damage and yield components in a rice agro-ecosystem in the Barisal region of Bangladesh. *Frontiers in Environmental Science*, *4*, 22. doi:10.3389/fenvs.2016.00022.

Andati, P., Majiwa, E., Ngigi, M., Mbeche, R., & Ateka, J. (2022). Determinants of adoption of climate smart agricultural technologies among potato farmers in Kenya: Does entrepreneurial orientation play a role? *Sustainable Technology and Entrepreneurship*, *1*,(2) 100017. doi:10.1016/j.stae.2022.100017.

Asante, B. O., Osei, M. K., Dankyi, A. A., Berchie, J. N., Mochiah, M. B., Lamptey, J. N. L., et al. (2013). Producer characteristics and determinants of technical efficiency of tomato-based production systems in Ghana. *Journal of Development and Agricultural Economics*, *5*(3), 92–103. doi:10.5897/JDAE12.054.

Attia, M. A., Wahba, T. F., Shaarawy, N., Moustafa, F. I., Guedes, R. N. C., & Dewer, Y. (2020). Stored grain pest prevalence and insecticide resistance in Egyptian populations of the red flour beetle *Tribolium castaneum* (Herbst) and the rice weevil *Sitophilus oryzae* (L.). *Journal of stored products research*, *87*, 101611. doi:10.1016/j.jspr.2020.101611.

Balabag, N. M., Anub, R. R., & Sabado, E. M. (2019). Survey of Insects and Other Arthropods in Tomato (*Lycopersicon esculentum* Mill.) in Lanaodel Sur Province, ARMM, Philippines. *International Journal of Science and Management Studies*, *2*, 45–53.

Bashir, M. A., Alvi, A. M., & Naz, H. (2014). Effectiveness of sticky traps in monitoring insects. *Journal of Environmental and Agricultural Sciences*, *1*(5), 1–2.

Bebber, D. P., Holmes, T., & Gurr, S. J. (2014). The global spread of crop pests and pathogens. *Global Ecology and Biogeography*, *23*(12), 1398–1407. doi:10.1111/geb.12214.

Bekele, N., Obare, G., Mithöfer, D., & Amudavi, D. (2013). The impact of group-based training approaches on crop yield, household income and adoption of pest management practices in the smallholder horticultural sub sector of Kenya. *Journal of Sustainable Development in Africa*, *15*(1), 117–140.

Bereciartua-Perez, A., Gomez, L., Picon, A., Navarra-Mestre, R., Klukas, C., & Eggers, T. (2022). Insect counting through deep learning-based density maps estimation. *Computers and Electronics in Agriculture*, *197*, 106933. doi:10.1016/j.compag.2022.106933.

Buhre, C., Kluth, C., Bürcky, K., Märländer, B., & Varrelmann, M. (2009). Integrated control of root and crown rot in sugar beet: Combined effects of cultivar, crop rotation, and soil tillage. *Plant Disease*, *93*(2), 155–161. doi:10.1094/PDIS-93-2-0155.

Caliendo, M., & Kopeinig, S. (2008). Some practical guidance for the implementation of propensity score matching. *Journal of Economic Surveys*, *22*(1), 31–72. doi:10.1111/j.1467-6419.2007.00527.x.

Cameron, A. C., & Trivedi, P. K. (2005). *Microeconometrics: Methods and applications*. New York: Cambridge University Press.

Cerulli, G. (2015). *Econometric evaluation of socio-economic programs theory and applications*. Springer.

Dara, S. K. (2019). The new integrated pest management paradigm for the modern age. *Journal of Integrated Pest Management*, *10*(1), 12. doi:10.1093/jipm/pmz010.

Desneux, N., Luna, M. G., Guillemaud, T., & Urbaneja, A. (2011). The invasive South American tomato pinworm, *Tuta absoluta*, continues to spread in Afro-Eurasia and beyond: the new threat to tomato world production. *Journal of Pest Science*, *84*(4), 403–408. doi:10.1007/s10340-011-0398-6.

Donkor, A., Osei-Fosu, P., Dubey, B., Kingsford-Adaboh, R., Ziwu, C., & Asante, I. (2016). Pesticide residues in fruits and vegetables in Ghana: A review. *Environmental Science and Pollution Research*, *23*, 18966–18987. doi:10.1007/s11356-016-7317-6.

Fikadu, Z. (2020). Pesticides use, practice and its effect on honeybee in Ethiopia: A review. *International Journal of Tropical Insect Science*, *40*, 473–481. doi:10.1007/s42690-020-00114-x.

Flor, A.G., .& Cisneros, A.J. (.2015). e-Agriculture. The International Encyclopedia of Digital Communication and Society. *In: International encyclopedia of digital communication and society edition: First chapter: EAgriculture*. Publisher: John Wiley and Sons Ltd, Editors: Mansell, R. & Hwa, A.P. 9999(9999), 1–6. doi: 10.1002/9781118767771.wbiedcs110

Flores, C. A., & Chen, X. (2018). *Average treatment effect bounds with an instrumental variable: Theory and practice*. Springer.

Ganai, M., Khan, Z., & Tabasum, B. (2018). Challenges and constraints in chemical pesticide usage and their solution: A review. *International Journal of Fauna and Biological Studies*, *5*(3), 31–37.

Guedes, R. N. C., Roditakis, E., Campos, M. R., Haddi, K., Bielza, P., Siqueira, H. A. A., et al. (2019). Insecticide resistance in the tomato pinworm Tuta absoluta: Patterns, spread, mechanisms, management and outlook. *Journal of Pest Science*, 1–14. doi:10.1007/s10340-019-01086-9.

Halimatunsadiah, A. B., Norida, M., Norida, D., & Kamarulzaman, N. H. (2016). Application of pesticide in pest management: The case of lowland vegetable growers. *International Food Research Journal*, *23*(1), 85.

IFAD. (2015). *Evaluation manual* (2nd Edition). Rome: International Fund for Agricultural Development (IFAD).

Ireri, D. M., Awuor, M., Ogalo, J., & Nzuki, D. (2021). Role of ICT in the dissemination and access of agricultural information by smallholder farmers in South Eastern Kenya. *Acta Informatica Malaysia (AIM)*, *5*(1), 31–41. doi:10.26480/aim.01.2021.31.41.

Kamau, T., Vitswamba, E., & Vyas, H. (2018). *Trend analysis of post-harvest ict solutions in East Africa*. . https://www.engineeringforchange.org/research/trend-analysis-post-harvest-ict-solutions-east-africa/.

Kante, M., Oboko, R., & Chepken, C. (2017). Influence of perception and quality of ICT-based agricultural input information on use of ICTs by farmers in developing countries: Case of Sikasso in Mali. *The Electronic Journal of Information Systems in Developing Countries*, *83*(1), 1–21. doi:10.1002/j.1681-4835.2017.tb00617.x.

Khan, N., Siddiqui, B., Khan, N., Khan, F., Ullah, N., Ihtisham, M., et al. (2020). Analyzing mobile phone usage in agricultural modernization and rural development. *International Journal of Agricultural Extension*, *8*(2), 139–147. doi:10.33687/ijae.008.02.3255.

Khan, M., & Damalas, C. A. (2015). Factors preventing the adoption of alternatives to chemical pest control among Pakistani cotton farmers. *International journal of pest management*, *61*(1), 9–16. doi:10.1080/09670874.2014.984257.

Littin, K., Fisher, P., Beausoleil, N. J., & Sharp, T. (2014). Welfare aspects of vertebrate pest control and culling: Ranking control techniques for humaneness. *Revue scientifique et technique (International Office of Epizootics)*, *33*(1), 281–289. doi:10.20506/rst.33.1.2281.

Loha, K. M., Lamoree, M., Weiss, J. M., & de Boer, J. (2018). Import, disposal, and health impacts of pesticides in the East Africa Rift (EAR) zone: A review on management and policy analysis. *Crop Protection*, *112*, 322–331. doi:10.1016/j.cropro.2018.06.014.

Macharia, I. (2015). Pesticides and health in vegetables production in Kenya. *BioMed Research International*, *2015*, 241516. doi:10.1155/2015/241516.

Magauzi, R., Mabaera, B., Rusakaniko, S., Chimusoro, A., Ndlovu, N., Tshimanga, M., et al. (2011). Health effects of agrochemicals among farm workers in commercial farms of Kwekwe district, Zimbabwe. *The Pan African Medical Journal*, *9*(26), 1–8. doi:10.4314/pamj.v9i1.71201.

Meissle, M., Mouron, P., Musa, T., Bigler, F., Pons, X., Vasileiadis, V. P., et al. (2010). Pests, pesticide use and alternative options in European maize production: Current status and future prospects. *Journal of Applied Entomology*, *134*(5), 357–375. doi:10.1111/j.1439-0418.2009.01491.x.

Mergia, M. T., Weldemariam, E. D., Eklo, O. M., & Yimer, G. T. (2021). Small-scale farmer pesticide knowledge and practice and impacts on the environment and human health in Ethiopia. *Journal of Health Pollution*, *11*,(30) 210607. doi:10.5696/2156-9614-11.30.210607.

Midingoyi, S. G., Kassie, M., Muriithi, B., Gracious Diiro, G., & Ekesi, S. (2018). Do farmers and the environment benefit from adopting integrated pest management practices? Evidence from Kenya. *Journal of Agricultural Economics*, *70*(2), 452–470. doi:10.1111/1477-9552.12306.

Miller, J. R. (2020). Sharpening the precision of pest management decisions: Assessing variability inherent in catch number and absolute density estimates derived from pheromone-baited traps monitoring insects moving randomly. *Journal of Economic Entomology*, *113*(5), 2052–2060. doi:10.1093/jee/toaa152.

Milovanović, S. (2014). The role and potential of information technology in agricultural improvement. *Economics of Agriculture*, *61*(2), 471–485. doi:10.5937/ekoPolj1402471M.

Moura, A. C. M., Lago, I. N., Cardoso, C. F., Nascimento, A. R., Pereira, I., & Vaz, B. G. (2020). Rapid monitoring of pesticides in tomatoes (*Solanum lycopersicum* L.) during pre-harvest intervals by paper spray ionization mass spectrometry. *Food Chemistry*, *310*, 125938. doi:10.1016/j.foodchem.2019.125938.

Mulugeta, T., Muhinyuza, J. B., Gouws-Meyer, R., Matsaunyane, L., Andreasson, E., & Alexandersson, E. (2020). Botanicals and plant strengtheners for potato and tomato cultivation in Africa. *Journal of Integrative Agriculture*, *19*(2), 406–427. doi:10.1016/S2095-3119(19)62703-6.

Musebe, R., & Ogunmodede, A. (2021). Do farmers adopt advice on good pesticidepractices? A case study of plant doctor recommended pesticide use in maize and tomatoproduction. *CABI Study Brief Impact*, *39*. doi:10.1079/CABICOMM-62-8162.

Mwangi, F. N. (2015). *Evaluation of botanical pesticides and coloured sticky insect traps for management of insect pests (thrips, whiteflies and aphids) in french beans (*Phaseolus vulgaris *L.)*. Kenya: University of Nairobi MSc. Thesis.

Mwenda, E., Muange, E. N., & Ngigi, M. W. (2022). Determinants of adoption of ICT-based pest information services by tomato farmers in the central highlands of Kenya. *Journal of African Interdisciplinary Studies*, *6*(4), 18–36.

Nahar, N., Uddin, M. M., de Jong, P., Struik, P. C., & Stomph, T. J. (2020). Technical efficacy and practicability of mass trapping for insect control in Bangladesh. *Agronomy for Sustainable Development*, *40*(3), 1–14. doi:10.1007/s13593-020-00623-6.

Nampeera, E. L., Nonnecke, G. R., Blodgett, S. L., Tusiime, S. M., Masinde, D. M., Wesonga, J. M., Murungi, L. K., Baidu-Forson, J. J., & Abukutsa-Onyango,, M. O. (2019). Farmers' knowledge and practices in the management of insect pests of leafy Amaranth in Kenya. *Journal of Integrated Pest Management*, *10*(1), 31. doi:10.1093/jipm/pmz029.

Ngigi, M. W., & Muange, E. N. (2022). Access to climate information services and climate-smart agriculture in Kenya: A gender-based analysis. *Climatic Change*, *174* (21). doi:10.1007/s10584-022-03445-5.

Ngigi, M., & Mureithi, D. K. (2021). Safe food systems for better health outcomes: Emerging food safety issues, challenges and solutions in sub-Saharan Africa. *Contemporary healthcare issues in sub-saharan africa: Social, economic, and cultural perspectives* (pp. 153−169). Rowman & Littlefield.

Nguetti, J. H. (2019). *Pesticides residues and microbial contamination of tomatoes produced and consumed in Kenya*. University of Nairobi Unpublished PhD thesis.

Ochilo, W. N., Otipa, M., Oronje, M., Chege, F., Lingeera, E. L., Lusenaka, E., et al. (2018). Pest management practices prescribed by frontline extension workers in the smallholder agricultural subsector of Kenya. *Journal of Integrated Pest Management*, *9*(1), 15. doi:10.1093/jipm/pmy009.

Okonya, J. S., & Kroschel, J. (2015). A cross-sectional study of pesticide use and knowledge of smallholder potato farmers in Uganda. *BioMed Research International*, *2015*, 759049. doi:10.1155/2015/759049.

Polat, B. (2019). Efficacy of mass trapping of tomato leafminer (Tuta absoluta) with different types and colours of traps in open- field tomato. *Applied Ecology and Environmental Research*, *17*, 157721. doi:10.15666/aeer/1706_1572115730.

Pretty, J., & Bharucha, Z. P. (2015). Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects*, *6*(1), 152–182. doi:10.3390/insects6010152.

Preti, M., Verheggen, F., & Angeli, S. (2020). Insect pest monitoring with camera-equipped traps: Strengths and limitations. *Journal of Pest Science*, *94*(2), 203–217. doi:10.1007/s10340-020-01309-4.

Prodhan, M. D. H., Akon, M. W., & Alam, S. N. (2018). Determination of pre-harvest interval for quinalphos, malathion, diazinon and cypermethrin in major vegetables. *Journal of Environmental and Analytical Toxicology*, *8*, 553. doi:10.4172/2161-0525.1000553.

Rosenbaum, P. R., & Rubin, D. B. (1983). The central role of the propensity score in observational studies for causal effects. *Biometrika*, *70*(1), 41–55. doi:10.1093/biomet/70.1.41.

Rwomushana, I., Beale, T., Chipabika, G., Day, R., Gonzalez-Moreno, P., Lamontagne-Godwin, J., et al. (2019). Evidence Note. Tomato leafminer (*Tuta absoluta*): Impacts and coping strategies for Africa. *CABI Working Paper*, *12*, 56.

Sadique, R. M. (2020). Farmers' perceptions of integrated pest management (IPM) and determinants of adoption in vegetable production in Bangladesh. *International Journal of Pest Management*, *68*(2), 158–166. doi:10.1080/09670874.2020.1807653.

Santana, P. A., Kumar, L., Da Silva, R. S., & Picanço, M. C. (2019). Global geographic distribution of Tuta absoluta as affected by climate change. *Journal of Pest Science*, *92* (4), 1373–1385. doi:10.1007/s10340-018-1057-y.

Sarkar, S., Gil, J. D. B., Keeley, J., Möhring, N., & Jansen, K. (2021). *The use of pesticides in developing countries and their impact on health and the right to food*. Belgium: European Union Policy Department for External Relations, Directorate General for External Policies of the Union, PE 653.622 - January 2021.

Shaikh, T. A., Rasool, T., & Lone, F. R. (2022). Towards leveraging the role of machine learning and artificial intelligence in precision agriculture and smart farming. *Computers and Electronics in Agriculture*, *198*, 107119. doi:10.1016/j.compag.2022.107119.

Sharifzadeh, M. S., & Abdollahzadeh, G. (2021). The impact of different education strategies on rice farmers' knowledge, attitude and practice (KAP) about pesticide use. *Journal of the Saudi Society of Agricultural Sciences*, *20*(5), 312–323. doi:10.1016/j.jssas.2021.03.003.

Sharifzadeh, M. S., Abdollahzadeh, G., Damalas, C. A., & Rezaei, R. (2018). Farmers' criteria for pesticide selection and use in the pest control process. *Agriculture*, *8*(2), 24. doi:10.3390/agriculture8020024.

Singh, N., & Gupta, N. (2016). ICT-based decision support systems for Integrated Pest Management (IPM) in India: A review. *Agricultural Reviews*, *37*(4), 309–316. doi:10.18805/ag.v37i4.6461.

StataCorp. (2017). *Stata: Release 15. statistical software*. College Station, TX: StataCorp LLC.

Tambo, J. A., Aliamo, C., Davis, T., Mugambi, I., Romney, D., Onyango, D. O., et al. (2019). The impact of ICT-enabled extension campaign on farmers' knowledge and management of fall armyworm in Uganda. *PloS one*, *14*,(8) e0220844. doi:10.1371/journal.pone.0220844.

Voss, R. C., Jansen, T., Mané, B., & Shennan, C. (2021). Encouraging technology adoption using ICTs and farm trials in Senegal: Lessons for gender equity and scaled impact. *World Development*, *146*, 105620. doi:10.1016/j.worlddev.2021.105620.

Wright, H. J., Ochilo, W., Pearson, A., Finegold, C., Oronje, M., Wanjohi, J., et al. (2016). Using ICT to strengthen agricultural extension systems for plant health. *Journal of Agricultural & Food Information*, *17*(1), 23–36. doi:10.1080/10496505.2015.1120214.