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Economic, health, and environmental burden of *Tuta absoluta* (Lepidoptera: Gelechiidae), in tomato production in Kenya and Uganda

Fridah Chepchirchir[1,2], Beatrice Wambui Muriithi[2,*], Jackson Langat[1], Shepard Ndlela[2], Samira Abuelgasim Mohamed[2], Fathiya Khamis[2]

[1]Department of Agricultural and Agribusiness Management, Egerton University, P.O Box 536-20115, Egerton, Kenya, [2]International Centre of Insect Physiology and Ecology (icipe), P.O. Box 30772-00100, Nairobi, Kenya *Corresponding author, mail: bmuriithi@icipe.org

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The negative effects of pest infestation on agricultural production cannot be underestimated. There have been several efforts to control these pests, chiefly through the use of synthetic pesticides. However, the continuous use of the chemicals causes pest resistance and resurgence and presents high human and environmental risks. This study examines the economic, health, and environmental impacts of *Tuta absoluta* (Meyrick 1917), an economically important pest in tomato production, among smallholder farmers in selected counties in Kenya and Uganda. Economic Impact Quotient and gross margin analysis were used on data obtained from a random sample of 316 and 345 tomato growers in Kenya and Uganda, respectively. The results show a significant impact of *T. absoluta* on tomato production in both countries. On average, the tomato growers earned a gross income of $38,123 and $11,627 in Kenya and Uganda, respectively, with synthetic chemicals for the management of *T. absoluta* contributing 66–78% of the cost of production. The opportunity cost lost due to forgoing pesticide for management of the pest, and instead replacing it with an integrated pest management package was valued between $8 and $646 in Kenya and $895 in Uganda, respectively, using net present value through the most pessimistic scenario, while benefit–cost ratio was $1 and $5 in Kenya and Uganda, respectively.

Key words: economic burden, economic impact quotient, *Tuta absoluta*, East Africa

Introduction

Tomato enterprises are essential to improving the livelihoods of smallholder farmers of various regions in sub-Saharan Africa (SSA). Tomato (*Lycopersicon esculentum*) is among the high-value horticultural crops in SSA in terms of volume and profit margins (Research Solutions Africa [RSA] Ltd 2015). Tomato ranks sixth in terms of economic value in Africa, contributing 21.5 million tonnes annually, with Egypt being the top producer with 7,297,108 tonnes produced per year. East Africa on the other hand produces about 2 million tonnes annually, with Kenya generating 283,000 tonnes and Uganda contributing more than 40,124 tonnes (FAOSTAT 2019). In Kenya, tomato is the second most important exotic vegetable contributing about 20% of the total value of these vegetables each year (HCDA 2010). Uganda is known for producing traditional staple foods like bananas, but the country has experienced a shift to producing quick-maturing vegetables like tomatoes (IPC 2017), driven mainly by the high profitability of horticultural production compared to staple crops.

Compared with other major tomato-producing countries such as Egypt, Kenya, and Uganda are yet to reach their tomato production potential. This can be attributed to several factors, with biotic factors, chiefly pests, and diseases, contributing the most to the production gap (HCDA 2016). The most important abiotic factors include erratic rainfall, climate risks, high postharvest losses, and soil infertility (HCDA 2016). The major diseases affecting tomato production are early blight and late blight, wilt diseases, nutritional diseases, nematodes, and pests (Mwangi et al. 2015), while pests of economic importance are tomato leaf miner, *Tuta absoluta* (Meyrick 1917), followed by other nematodes (Nderitu et al. 2018). *Tuta absoluta* affects the quality and quantity of tomatoes. By increasing not only the cost of production but also the pest limits the product's access to markets due to quarantine restrictions to prevent the movement of the pest to some high-value markets (Never et al. 2017). The larva is the most destructive stage of the pest, causing perforated holes in stems, leaf mines, and fruit rots, with severe invasions resulting in the drying up of the whole field. The seedlings can also be severely affected by the pest (Gabarra et al. 2014). Adult pests are difficult to detect and control since they are primarily active at night. The pest has continued to be a considerable burden to farmers, causing up to 80–100% loss in yield, both in protected (greenhouse) and native (open) tomato fields if left uncontrolled (Desneux et al. 2010).

To manage the *T. absoluta* pest, farmers adopt disparate strategies, including the use of chemical insecticides, resistant tomato varieties, pruning, and crop rotation, among others (Kaoud 2014). The use of synthetic pesticides is the most commonly used method, mainly due to easy access and availability of the chemicals (Chepchirchir et al. 2021). Although the contribution of pesticides in reducing insect pests and diseases' infestation and enhancing production cannot be underestimated (Mansour et al. 2018), over(mis)use of chemical pesticides in horticultural production is evident (Macharia et al. 2008). For instance, studies in Central Uganda show that tomato producers in the area use up to 6 times more than the recommended quantity of insecticides by the manufacturers (Kaye et al. 2015). *Tuta absoluta* becomes resistant to several insecticides over time, encouraging farmers to use multiple pesticides, a combination of different pesticide brands, to increase their effectiveness (Muriithi et al. 2016, Biondi et al. 2018). This use of multiple pesticides increases production costs and thus reduces the profitability of the farming enterprise (Ii 2016). In addition, the over(mis)use of chemical pesticides is often associated with high health and environmental risks, which most farmers are ignorant about, but posing a threat to their health and those of the consumers as well as the environment including loss of biodiversity (Never et al. 2017, Rwomushana, Day, et al. 2019). The use of chemical pesticides is attributed to approximately 20,000 annual deaths in the world, and according to the WHO classification, the pesticides used by smallholder farmers in Africa, particularly in the horticultural industry range from moderate to highly hazardous (Abdou & Hend 2018).

To sustainably manage *T. absoluta*, in Africa, the International Centre of Insect Physiology and Ecology (*icipe*) and its partners have spearheaded the development and implementation of an integrated pest management (IPM) strategy as an alternative solution to the expensive and hazardous chemical pesticides (Mahmoud et al. 2020, Kabaale et al. 2022). The proposed IPM strategy is based on mass trapping, entomopathogenic fungal-based biopesticides, biorationals, host plant resistance, orchard sanitation, and biological control. These integrations of modified practices seek to sustainably manage *T. absoluta* by preventing the pest from infestation or containing them to the accepted economic threshold. Many studies have suggested using IPM as an alternative to pesticides, as it offers sustainability and intensification, hence increasing agricultural productivity (Pretty & Bharucha, 2015). The majority of growers, however, only use a few components of the package. Previous research on the use of IPM to manage tomato pests, such as the fruit borer *Helicoverpa armigera* (L), has demonstrated increased success rates through lower costs and higher production compared with the use of pesticides (Gajanana et al. 2006).

Over the past decades, IPM has become a dominant crop protection approach, being recommended by scientists, development agencies, and policymakers. This is because it involves an integration of complementary methods to manage pests to an economically acceptable threshold. The IPM approach ensures that the use of pesticides is at a minimum level to ensure plant, human, and animal health (FAO 2017). According to FAO (2017), the IPM approach is cost-saving, discourages pest resistance, is environmentally friendly, and assures the safety of agricultural goods for consumption. A study by Kibira et al. (2015) on the impact of an IPM package for the management of mango-infesting fruit flies, for instance, shows a significant economic difference between those who used the IPM strategy compared with those who used the conventional (synthetic pesticides) approach. The pre- and postharvest mango losses and expenditure on pesticides were reduced, while income generated from the enterprises increased significantly (Kibira et al. 2015). Similar impacts of the fruit fly IPM are also documented in later studies, including Muriithi et al. (2016), Midingoyi et al. (2019), and Mulungu et al. (2023). The results are further supported by Atuhaire et al. (2017) whose study revealed reduced levels of pesticide exposure to the farmers and the environment after Ugandan small-scale farmers received training on IPM technology.

To sustainably support the promotion of the sustainable IPM approach for the management of the tomato-infesting *T. absoluta*, it is important to understand the economic burden of the pest, which is currently limited. Furthermore, wider scaling of the IPM strategy would require evidence-based recommendations as an economically feasible alternative to the conventional use of synthetic pesticides. This study, therefore, was conducted ex-ante introduction of the strategy to address these gaps that will guide the successful implementation of the technology among smallholder tomato growers in East Africa.

Materials and Methods

Study Area and Data Sources

The study was conducted in selected tomato-producing regions in Kenya and Uganda. A multistage sampling technique was adopted. First, 2 counties in Kenya (namely Kirinyaga and Kajiado) and 2 districts in Uganda (namely Mbale and Masaka) were selected purposively based on their predominance in tomato production (Abo 2018). The locations are also the project's benchmark sites. In the second stage, subcounties were purposively selected again based on the predominance of tomato production. In Kenya, 2 subcounties in Kirinyaga County (namely Mwea East and Mwea West) and 1 in Kajiado County (namely Kajiado South subcounty) were selected, while in Uganda, 1 subcounty from each district, that is, Bukhungu North, and Bokoto from Mbale and Masaka Districts, respectively. The locations of the study sites are shown in Figures 1a and 1b. A list of smallholder tomato growers from each of the subcounties was developed with the support of the extension officers, which provided a sampling frame for the survey. In the third stage, the probability proportional to size sampling technique was used to determine the sample of tomato growers to be selected in each location and then the sample was randomly selected for interviews.

Cross-sectional data were collected using face-to-face household interviews conducted with semistructured questionnaires, which were programed in Census and Survey Processing System (CSPro) software. A sample of 662 respondents, 316 and 345 from Kenya and Uganda, respectively, were interviewed. The size of the sample was determined using the standard field sample calculation procedure given by Bartlett et al. (2001).

The questionnaire obtained comprehensive information on tomato production including variables for computation of the gross margin, opportunity cost, health, and environmental effects of chemical use on tomato farmers from the management of *T. absoluta*. The specific information collected included the proportion of tomato

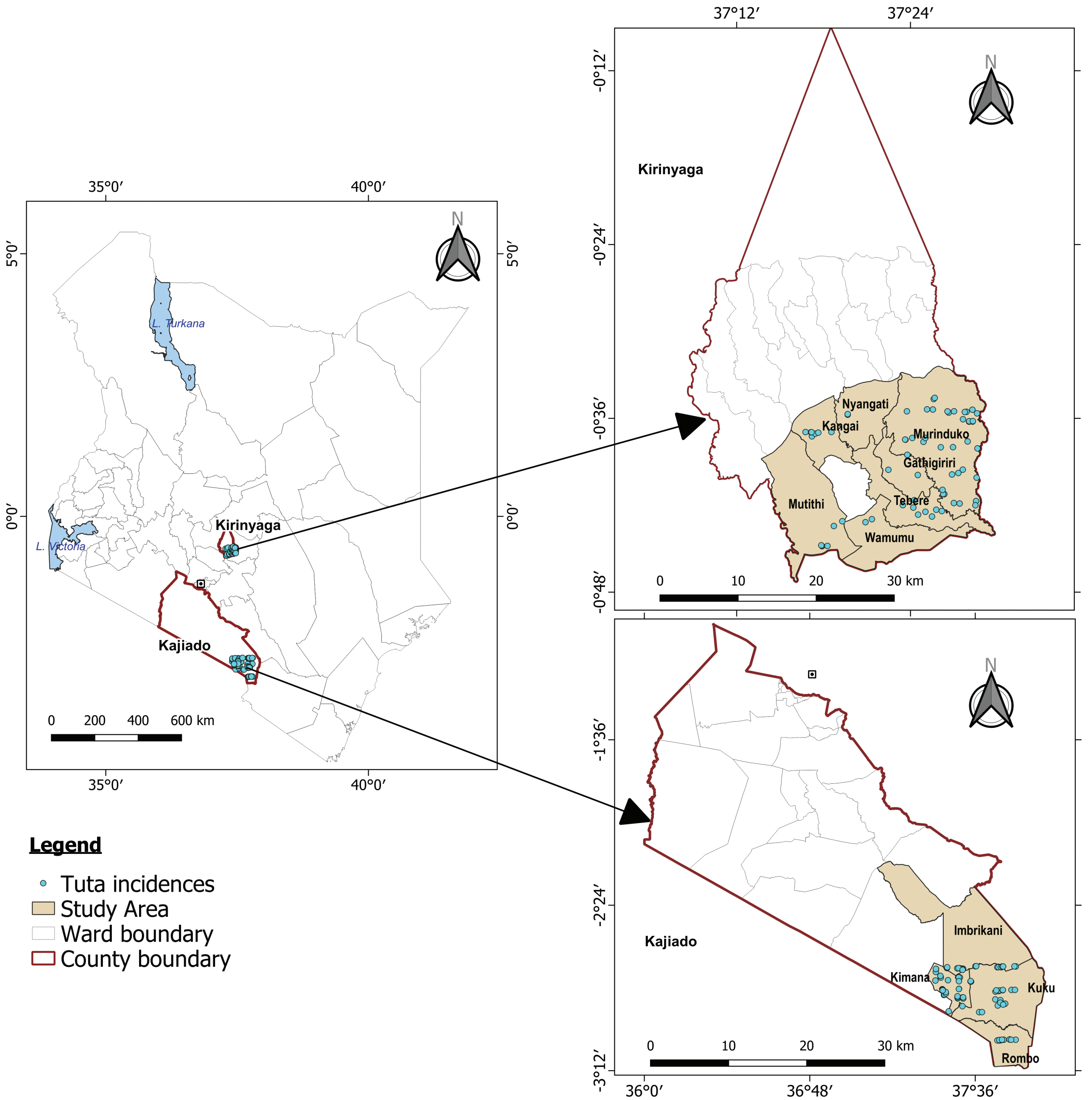

Fig. 1. A) Map of Kenya showing the target areas in Kirinyaga and Kajiado counties. b) Map of Uganda showing the target areas in Mbale and Masaka districts. *Source*: Chepchirchir et al. (2021).

losses incurred due to *T. absoluta*, and from other pests and diseases; the type of pesticides used to manage *T. absoluta*, and their expenditure; synthetic pesticides' safe handling practices; and health and environmental effects of pesticides. Farmers were also made aware of the *T. absoluta* IPM components and asked if they would be willing to try the technology and their adoption plans. In addition to the tomato enterprise-specific questions, contextual data, such as farm and farmer characteristics, were also collected during the survey.

Analytical Approach

Gross margin.

Gross margin (GM) analysis was calculated to determine the viability of tomato farming. GM is defined as the difference between total revenue and the total variable cost (FAO 1995), specified as:

$$\mathrm{GM} = \mathrm{TR} - \mathrm{TVC} \tag{1C}$$

where GM = gross margin, TR = total revenue, and TVC = total variable cost.

This can then be expanded as;

$$\sum_{j=1}^{m} p_{ij}q_{ij} - \sum_{g=1}^{n} p_{ig}x_{ig} \tag{2}$$

where p_{ij} = unit price of jth output in relation to ith the respondent, q_{ij} = quantity of the jth output$(j = 1, 2, 3, ..m)$, p_{ig} = unit price of ith variable input in relation to ith the respondent, x_{ig} = the quantity of the ith variable output ($i = 1, 2, 3, \ldots n$).

Total revenue was computed as the total net production in kilograms multiplied by the average price per kilogram. Total

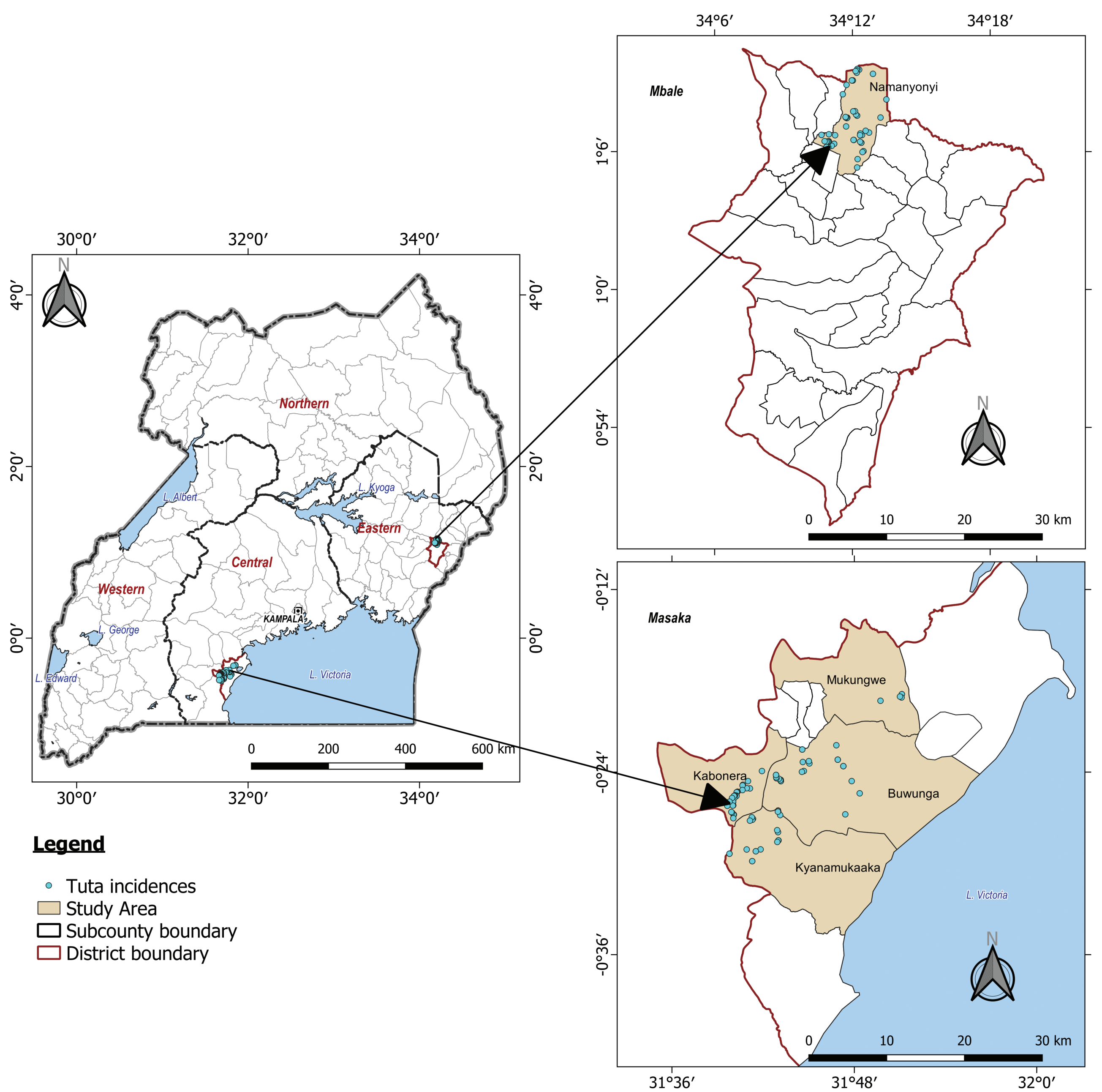

Fig. 1. Continued

variable costs included the purchase of pesticides, seedlings, seeds, manure, and fertilizers, as well as hired labor costs. The key labor costs included the cost of weeding, harvesting, manure, chemical application, planting, and trailing. The gross margins were then compared between the 2 countries.

Environmental and human health impacts of synthetic pesticides.

To evaluate pesticides’ environmental and health risks, the study used the EIQ developed by Kovach et al. (1992). This method compares the different effects of pesticides on producers, consumers, and the environment using weights. It estimates pesticide effects on a 3-point scale, where 1 represents the lowest, 3 is intermediate, and 5 is the highest level of risk. The EIQ formula is defined as follows:

$$\begin{aligned} EIQ = & \{C[(DT*5)+(DT*P)]+[C*((S+P)/2)*SY) \\ & +(L)]+[(F*R)+(D*((S+P)/2)*3) \\ & +(Z*P*3)+(B*P*5)]\}/3 \end{aligned} \qquad (3)$$

where C = chronic toxicity, DT = dermal toxicity, P = plant surface residue half-life, S = soil residue half-life, SY = systematicity, L = leaching potential, F = fish toxicity, R = surface loss, D = bird toxicity, Z = bee toxicity, and B = beneficial arthropod activity.

The parameter values in this study were determined by toxicity information from several sources, such as the extension toxicology network (EXOXNET), individual chemical manufacturers, and public sources. EIQ field use was then computed to account for the number of applications for each farmer in different pesticide uses (Kovach et al. 1992), as follows:

Table 1. Tomato production, losses, and pesticide expenditure

Variable	Kenya		Uganda	
	Mean	SD	Mean	SD
Gross tomato production (kg/ha)	38,123.24	35,202.32	11,628.66	10,039.83
Loss due to all pests (kg/ha)	9,530.15	9,358.34	1,022.16	993.34
Loss due to *T. absoluta* (kg/ha)	6,079.16	6,054.42	417.18	406.51
Loss due to diseases (kg/ha)	2,207.41	2,178.00	1,118.69	1,112.96
Net tomato production (kg/ha)	19,432.58	19,004.35	8,978.13	7,897.13
Total Insecticide cost due *to all* pests (except *T. absoluta*) and diseases (USD)	377.833	355.89	28.02	7.23
Insecticide cost spent on *T. absoluta* (USD)	736.776	293.41	23.87	23.51

$$\text{EIQ field use} = \text{EIQ} \times \%\ \text{active ingredient} \times \text{frequency of application} \times \text{dose} \tag{4}$$

The study then determined the pesticide risk, which is correlated with the danger of the active ingredient, its innate ability to cause harm, and the possibility that exposure to the chemical will cause harm (Kovach et al. 1992). The use of an item, its route through the environment, and the incidence of uptake by exposed organisms are all considered in risk assessments, along with information on toxicity.

$$\text{Risk} = \text{Hazard} \times \text{Likelihood of exposure} \tag{5}$$

Lost opportunity cost.

The demand for the proposed IPM strategy may be affected by several factors in addition to farmers' willingness to pay, hence uncertain demand. Based on the study of Gong et al. (2014) on the economic impacts of vertebrate pests in Australia, sensitivity analysis is applied to assess the financial viability of adopting a technology such as IPM strategy in the face of uncertainty. The authors conducted a sensitivity analysis to assess the opportunity cost lost, which aimed at minimizing the avoidable costs caused by the invasion. Opportunity cost, in our case, is the potential benefit forgone from using pesticides to control *T. absoluta*. These expected returns were analyzed through the benefit–cost ratio (BCR) and the net present value (NPV). While the BCR only reflects the efficiency of the project, ignoring the magnitude, the NPV identifies the best project and the highest benefit, therefore, making the 2 ratios conform.

All the potential benefits and costs arising from the IPM strategy as an alternative to the use of synthetic pesticides were calculated (Gong et al. 2009). The calculations were done together with the biological team that developed the IPM package and based on their lab and field pilot experiments that tested the efficacy of the technology and the effective quantities per unit area.

BCR and NPV methods recognize the importance of lag periods in determining potential returns. The lag period was the time taken for a farmer to adopt the strategy. The longer the lag period, the lower the returns, as the returns will occur further into the future. According to the time value of money, the money one has today is worth more than the money expected in the future. Hence, discounting the future monetary benefits compared with the present value of money will show these differences in benefits over time (Zerbe and Bellas 2006). The 2 financial assessment metrics were calculated as follows:

$$\text{BCR} = \sum_{t-1}^{t} \frac{\frac{B_t}{(1+r)^t}}{\frac{C_t}{(1+r)^t}} \tag{6}$$

Table 2. Gross margin analysis of tomato production

	Kenya	Uganda
Output		
Produce (kg/ha)	38,123.24	11,628.66
Price per kg (USD)	0.56	0.35
Total output (USD)	2,1445.29	4,093.63
Variable cost (USD)		
Seed purchased	248.66	58.13
Seedlings purchased	127.86	15.47
Fertilizer	393.18	143.14
Manure	224.04	138.16
Pesticide	1,114.61	30.74
Labor cost (USD)		
Digging/ploughing	159.42	94.47
Planting	92.54	42.64
Manure application	69.69	39.66
Fertilizer application	64.08	34.10
Weeding	178.46	71.16
Trailing	295.06	48.60
Chemical application	185.49	103.16
Harvesting	374.57	91.36
Total variable cost	3,346.29	949.26
Gross margin	17,917.63	3,182.84

$$\text{NPV} = \frac{B_t}{(1+r)^t} - \frac{C_t}{(1+r)^t} \tag{7}$$

where t is the adoption lag time in years, B_t are benefits in time t, C_t are costs in time t, and r is the discounting rate/percentage of avoidable costs. Returns with positive and higher NPV or BCR were considered feasible and lucrative. Higher returns were a result of short lag periods and higher avoidable costs. Assumptions of future simulations were based on the available data. The costs and benefits were obtained from the current market prices.

Results

Pest and Diseases Losses and Expenditure

The average annual value of the gross tomato production in Kenya for the tomato producers was estimated to be 38,123.24 kg/ha, while Uganda was lower with 11,628.66 kg/ha (Table 1). Comparing tomato loss due to pests and diseases, the tomato leaf miner was attributed to the highest proportion of loss in Kenya, resulting in an average loss of 6,079.16 kg/ha per year (Table 1). In Uganda, diseases contributed the highest loss of about 1,118.69 kg/ha annually, while the loss attributed to *T. absoluta* was 417.18 kg/ha per year. The economic value of *T. absoluta*, other insects, as well as diseases was obtained by asking the respondents the percentage of the total losses that they attributed to the pests. As most of these farmers are commercially oriented, they are able, with some degree of precision, to estimate pre- and postharvest losses associated with the different insects and diseases. The use of chemical pesticides was the primary method for the management of insects and diseases in both countries. In Kenya, the average annual cost of purchasing pesticides for the management of insects and diseases was $1,115 per hectare, with the management of *T. absoluta* contributing the highest cost of $737 per hectare per year. In Uganda, the cost of pesticides was significantly lower than in Kenya, having $51 spent on all insects and diseases and $23 per hectare annually on *T. absoluta* management. In both countries, the management of the *T. absoluta* pest contributed significantly to the total average cost of production. When comparing the losses from tomato leaf miners between the 2 countries, Uganda experiences lower losses than Kenya. This could be attributed to the higher perceived severity of the pest in Kenya in comparison to Uganda (Chepchirchir et al. 2021). Furthermore, while the pest was discovered for the first time in Kenya in March 2014 (IPPC 2014), in Uganda it was detected a year later in Mukono District (Tumuhaise et al. 2016). The differences in the arrival of the pest may thus contribute to adopted management strategies with significant differences in costs and the economic returns associated with the pest between the 2 countries.

Gross Margin Analysis

Despite the effects of pests and diseases, tomato production in both countries was found to be profitable. The average gross income was $17,917.63 in Kenya and $3,182.84 in Uganda (Table 2). The variable costs included the input and labor costs, which were $3,346.29 and $949.26 in Kenya and Uganda, respectively. In terms of pesticides, Kenyan tomato growers incurred on average $1,114.61, while those from Uganda incurred $30.74. The discrepancies are also observed in Table 1, where average tomato losses in Uganda were significantly less compared to Kenya. However, as highlighted in the previous section, on average tomato production was significantly higher in Kenya than in Uganda (38,123.24 and 11,628.66 kg, respectively). The high production of tomatoes in Kenya compared with Uganda can be attributed to the commercial orientation of tomato farming in Kenya, which is more advanced than in Uganda, where farming is inclined to the production of traditional staple foods like bananas, although shifting since recently to the production of quick-maturing vegetables such as tomatoes. The gross margin suggests positive returns to tomato enterprises despite the high cost of production and high pre- and postharvest losses due to *T. absoluta* and other pests.

Health and Environmental Effects of Pesticides

Farmers' perception of health and environmental effects of pesticides.

To assess the health and environmental effects of pesticides among the survey respondents, we began by evaluating their perceptions and concerns regarding the use of synthetic chemicals as presented in Table 3. Despite the high use of synthetic chemicals among the respondents, as demonstrated in the previous section, the majority of them from both countries were aware of and very concerned about the short- and long-term effects of the chemical pesticides on humans, as well as the risks to surface and groundwater and aquatic animals (Table 3). Understanding farmers' awareness of the risks of pesticide residues and their behaviors regarding pesticide applications is important in reducing human factors that negatively affect agricultural safety (Hou and Wu 2010).

Pesticide handling safety.

Pesticide handling safety further demonstrates farmers' knowledge of the negative risks associated with chemical pesticides. In addition, measures taken during pesticide application, including toxicity and dosage, determine the adverse effects on the environment (including water, soil, and air contamination, wildlife, aquatic animals, plants, and other nontarget organisms). Table 4 presents the type of safety gear reported by the survey respondents, while Table 5 presents the safety precautions taken during pesticide application.

Table 3. Perceptions and concerns of tomato farmers on health and environmental effects associated with pesticide use

Concerns about the negative effects of synthetic pesticides	Kenya (*n* = 316)			Uganda (*n* = 346)		
	Very concerned	Concerned	Not concerned	Very concerned	Concerned	Not concerned
Short-term human effects	87.69	6.72	5.6	78.22	4.62	17.16
Long-term effects	86.19	8.96	4.85	71.85	20.53	7.62
Surface and groundwater risks	78.36	16.42	5.22	65.89	21.85	12.25
Aquatic animals risk	76.87	4.48	18.6	71.94	19.14	8.91

Table 4. Percent of farmers reporting safety gear used by tomato farmers when handling synthetic pesticides

Protective gear	Kenya (*n* = 316)				Uganda (*n* = 346)			
	Always	Sometimes	Rarely	Never	Always	Sometimes	Rarely	Never
Mask (mouth and nose)	16.14	12.66	14.87	56.33	27.54	7.25	1.74	63.48
Gloves (hands)	11.08	8.23	11.39	69.30	16.52	4.06	0.87	78.55
Boots (feet)	60.44	18.35	5.38	15.82	77.39	9.57	1.45	11.59
Long-sleeved/overalls (arms)	39.24	21.20	11.39	28.16	62.90	10.72	3.19	23.19
Long protective trousers	43.99	26.27	10.13	19.62	74.49	9.86	2.03	13.62
Headgear (head)	16.44	7.28	10.13	72.15	26.38	4.64	1.45	67.54
Goggles (eyes)	2.85	0.95	2.53	93.67	8.12	0.87	0.87	90.14

Table 5. Percent of farmers reporting safety precautions taken by tomato farmers during pesticide application

Safety precautions	Kenya		Uganda	
	Yes	No	Yes	No
Consider the direction of the wind before spraying	75.32	24.68	79.07	20.93
Consider the timing of spraying (morning, afternoon, evening)	82.59	17.41	84.88	15.12
Read the expiry date on chemicals	91.46	8.54	84.88	15.12
Understand the meaning of symbols on labels	78.80	21.20	66.38	33.62
Wash hands after spraying	99.37	0.63	96.22	3.78
Bath after spraying	83.86	16.14	97.38	2.62
Eat while or after spraying	10.76	89.24	28.57	71.43
Smoke while spraying	18.67	81.33	4.96	95.04
Take milk after spraying	57.59	42.41	29.07	70.64
Wait to re-enter the field after spraying	65.82	34.18	60.52	39.18

Table 6. Pesticide intoxication

Variable	Kenya (%)	Uganda (%)
Pesticide intoxication		
Yes	15.51	61.03
No	84.49	38.97
Pesticide severity		
Mild	79	63
Severe	15	26
Very severe	6	11

Despite a majority expressing their concern about the negative effects of the pesticides as demonstrated in the previous section, a significant number of them (56% and 63% in Kenya and Uganda, respectively) never protected themselves from inhaling the chemicals through the use of masks (Table 4). Boots were the most used protective gear, reported by 60% and 77% of the survey respondents in Kenya and Uganda, respectively. The findings demonstrate that the majority of the farmers in both countries did not use protective gear when handling synthetic pesticides as required during pesticide application.

Table 5 shows that a majority of farmers in both countries observed some safety precautions while applying pesticides, including washing their hands after spraying (Kenya 99% and Uganda 96%) and taking a bath after spraying (Kenya 83% and Uganda 97%); considering the direction of the wind before spraying (Kenya 75% and Uganda 79%); considering the timing of spraying (Kenya 83% and Uganda 85%); reading the expiration date on chemicals; and understanding the meaning of symbols on labels (Kenya 91% and Uganda 84%).

Pesticide intoxication was also evident in the study area, with 16% and 61% of the survey respondents in Kenya and Uganda, respectively, reporting such experiences in the last tomato season (Table 6). This can be attributed to the farmers being exposed to pesticides because of not following the prescribed pest-handling procedures and using protective gear. However, asked about the severity of the intoxication, the majority reported mild intoxication of 79% and 63%, in Kenya and Uganda, respectively (Table 6).

We also asked farmers how they stored pesticides and disposal. A majority (60% and 59% in Kenya and Uganda, respectively) burned the plastic chemical containers, with a few from Uganda (10%) throwing the containers in pit latrines. Regarding storage, a few had designated stores for the chemicals (11% and 6% in Kenya and Uganda, respectively), while a few more in Uganda kept their chemicals in the garden or pit latrines (32% and 10%, respectively).

Environmental impact quotient.

Table 7 shows the estimated effects of pesticides on farm workers, consumers, and the environment using the EIQ approach. The analysis involved the commonly used pesticides in tomato production in both countries. According to Mazlan and Mumford (2005)'s EIQ classification rule, the values for pesticides are rated either as low (EIQ = 0–20), moderate (EIQ = 21–40), or high (EIQ 41 and above). The results show that the EIQ Total (EIQ T) in the selected tomato-producing areas in Kenya and Uganda ranged between high and moderate. The use of Karate (lambda-cyhalothrin (II)) had the highest impact on the farmers with an EIQ of 39.3, followed by Tata Alfa (Alpha-cypermethrin (II)) with an EIQ of 21.0 and Atom (EIQ of 18.0). For the consumers, score had the highest impact quotient of 23.50, while Rocket and Super cyper (Profenofos 40%) had the highest impact quotient on the environment (EIQ 167.5 for both pesticide brands). Considering Total EIQ, Super cyper (Profenofos 40%), and Rocket (Profenofos 40%) had the highest impact (i.e., EIQ 59.33 and 59.33, respectively), while atom (Deltamethrin) has the lowest EIQ with 28.4.

Field EIQ use was then used to account for the discrepancies found in the number of active ingredients used and their frequency in the application (Donga and Eklo 2018). Pesticide active ingredients that had EIQ field use below 40% included Profenofos 40% (II) (Rocket and Super cyper), lambda-cyhalothrin (II), alpha-cypermethrin (II), difenoconazole (II), imidacloprid 100 g/liter (II), abamectin (II), dimethoate (II), permethrin (II), deltamethrin (II), piperonyl butoxide (II), with the highest field use EIQ being dimethoate (II) at 30.7 and Imidacloprid 100 g/liter (II) at 30.5. For application rates, most of the farmers in both countries did not follow the recommended rates despite the pesticide packages providing clear instructions for use, and additional advice provided by the extension officers among other sources. The majority of the pesticides that were used in the 2 countries were found to come from Class II of the WHO classification that was toxic.

Lost opportunity cost.

Using sensitivity analysis, we estimated the potential returns in investing in the IPM strategy for the smallholder tomato farmers in the 2 countries. This was done by estimating the potential income that would be gained by using the alternative, that is, IPM. The study estimated the initial cost of IPM technology to be $170 per hectare per season; this price was based on the cost of producing these IPM components from manufacturers, the market price of other IPM components for the control of other pests, and the cost of research. The computation was also done in collaboration with the biological

Table 7. Estimates of pesticides' effect on farm workers, consumers, and the environment using the EIQ approach

Trade name	Active ingredient	EIQ F	EIQ C	EIQ E	EIQ T	Rate liter/acre	Field EIQ	WHO classification
Rocket	Profenofos 40%	8.1	3.1	167.5	59.5	0.3	4.8	II
Super cyper	Profenofos 40%	8.1	3.1	167.5	59.5	0.5	6.0	II
Karate	Lambda-cyhalothrin (II)	39.3	5.7	96.7	47.2	0.21	0.8	II
Tata Alfa	Alpha-cypermethrin (II)	21.0	3.0	106.0	44.0	0.57	1.9	II
Score	Difenoconazole	15	23.5	86.0	41.5	0.64	4.5	II
Thunder	Imidacloprid 100g/liter	6.9	10.4	92.9	36.7	0.56	30.5	II
Accelemectin	Abamectin	13.8	3.9	86.4	34.7	0.14	0.6	II
Dudu Fenos	Abamectine	13.8	3.9	86.4	34.7	0.68	8.8	II
Dudu cyper	Abamectine	13.8	3.9	86.4	34.7	0.36	2.2	II
Dimethoate	Dimethoate	10.4	11.5	78.6	33.5	0.75	30.7	II
Ambush	Permethrin	12.0	5.0	71.0	29.3	0.95	3.8	II
Atom	Deltamethrin	18.0	2.0	65.2	28.4	0.45	0.2	II

EIQ F refers to the EIQ component for the farmers or farm workers; EIQ C refers to the EIQ component for the consumers; EIQ E refers to the EIQ component for the environment; and EIQ T refers to the EIQ total.

Table 8. Sensitivity analysis of the opportunity cost lost because of foregoing the use of pesticides for the management of *T. absoluta*

	Avoidable costs (USD)					
	5%	10%	15%	20%	25%	30%
Net present value (NPV)						
Kenya						
Immediately	2,851.75	2,851.75	2,851.75	2,851.75	2,851.75	2,851.75
After 1 yr	1,476.45	1,409.33	1,348.06	1,291.89	1,240.21	1,192.51
After 2 yr	13.56	12.35	11.30	10.38	9.56	8.84
Uganda						
Immediately	832.04	832.04	832.04	832.04	832.04	832.04
After 1 yr	667.30	636.97	609.27	583.89	560.53	538.97
After 2 yr	990.64	902.63	825.84	758.46	698.99	646.26
Benefit–cost ratio (BCR)						
Kenya						
Immediately	17.77	17.77	17.77	17.77	17.77	17.77
After 1 yr	10.12	10.12	10.12	10.12	10.12	10.12
After 2 yr	1.09	1.09	1.09	1.09	1.09	1.09
Uganda						
Immediately	5.89	5.89	5.89	5.89	5.89	5.89
After 1 yr	5.12	5.12	5.12	5.12	5.12	5.12
After 2 yr	7.42	7.42	7.42	7.42	7.42	7.42

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team that developed the package and validated using field trials on the efficacy of the products.

The opportunity cost lost considered tomato losses as a result of *T. absoluta*. It shows the costs to be avoided with a primary focus on the probability that the farmer was likely to use IPM. As presented in Table 8, the NPV in Kenya ranged from $2,851 to $8, while in Uganda, it ranged from $990.64 to $646. This implies that $2,851 would be saved in Kenya as a result of the immediate change from pesticide to using IPM. In Uganda, the highest amount that would have been saved was $992 if the switch from synthetic insecticides to IPM was done after 2 yr.

For BCR, it was highest in Kenya when immediate change ($18) occurs and the lowest change was $1.09 after 1 yr, while in Uganda, the highest change would be realized after 2 yr ($7) and the lowest ($5) after 1 yr. For both NPV and BCR, the disparity in values between Uganda and Kenya can be linked to Kenya's higher severity of the pest invasion and use of pesticides than Uganda. The most intriguing part of the findings is that investing in the IPM strategy is economically desirable, whether adopting the IPM strategy immediately or adopting it after 2 yr. A benefit–cost analysis of several scenarios on investment in IPM strategy for management of *T. absoluta* was carried out to evaluate the potential avoided loss of switching from the hazardous use of synthetic chemicals.

Discussions

The present study used rigorous descriptive statistics to establish the economic, health, and environmental burden of tomato production in selected areas in Kenya and Uganda. With respect to gross production, the 2 countries reported higher levels than those reported by Aliyi et al. (2021) (i.e., 6,300 kg/ha) in Ethiopia. Despite the impressive production levels, *T. absoluta* was attributed to significant levels of tomato losses of about 6,079 and 417 kg/ha in Kenya and Uganda, contributing highest to tomato loss than any other tomato-infesting pest or disease. The findings corroborate several recent studies that highlight the economic importance of the invasive pest in tomato production in SSA (e.g., Brévault et al. 2014, Rwomushana, Beale, et al. 2019).

The gross margin analysis shows that on average, farmers generated a gross margin of $17,917.63 in Kenya and $3,182.84 in Kenya and Uganda, respectively. Surprisingly, an earlier study conducted before the invasion of *T. absoluta*, by Geoffrey et al. (2014), found a significantly lower gross margin for an open field tomato plot (i.e., $6,394.64 per ha) in Kenya. The variation however could be explained by the high prices of tomatoes during our survey compared to the former study. Similarly to the gross production, our estimates of the variable costs (i.e., $3,346.29 and $949.26 in Kenya and Uganda, respectively), were significantly higher than those reported by Aliyi et al. (2021) in Ethiopia. The difference can be attributed to the high cost of pesticides and labor, especially in Kenya compared with Ethiopia.

Farmer's awareness of the health and environmental risks of synthetic pesticides is a prerequisite to adopting alternative sustainable methods such as IPM (Kishi 2002, Hou and Wu 2010). We, therefore, assessed the study respondents' attitudes and concerns about the use of synthetic chemicals. In general, a majority displayed deep concern for the short- and long-term health effects of the chemicals, as well as the potential environmental risks of chemical pesticide exposure. Slovic (2010) notes that the higher the perceived risk of pesticide use, the more people want to see strict regulations employed to reduce the risk. Subsequently, the more concern about the negative effects of synthetic pesticides, the more farmers are likely to embrace the IPM components for the management of *T. absoluta*. These results further corroborate with Jallow et al. (2017) and Godfrey et al. (2018), who found that most farmers are well informed of the health and environmental effects associated with pesticide use, despite continued use of the pesticides, primarily due to the absence of alternative pest control methods.

Focusing on pesticide handling, Damalas and Eleftherohorinos (2011) note that agricultural workers suffer occupational exposure, particularly in open fields due to lack or inadequate use of protective gear and not observing safety precautions while spraying the crops. Our study revealed that most farmers in both countries did not wear protective equipment when handling synthetic pesticides. This is in contrast to earlier studies, for instance, Mohamed et al. (2018) found that 100% of the farmers in Sudan used personal protective equipment while handling chemical pesticides. Our results are however in agreement with Nyang'au et al. (2020) who found that a significant number of vegetable farmers were taking precautions when handling pesticides such as considering the direction of the wind, washing and taking a bath after sparing, reading the expiration date of chemicals, and understanding their symbols.

Our study went further to assess possible short-term human effects of chemical pesticides experienced by those who applied the synthetic chemicals in the respondents' tomato farms. In contrast with Silva et al. (2019) who observed a low prevalence of acute poisoning by pesticides in Mato Grosso, Brazil, high pesticide intoxication was reported in Kenya and Uganda. Rosenstock et al. (1991) warn that although farmers may perceive a single episode of pesticide poisoning as mild, long-term exposure may cause acute intoxication, which results in a persistent decrease in neuropsychological performance. The disposal of leftover chemicals and pesticide containers may also expose humans as well as the environment to risks. Ngowi et al. (2001) in their study on pesticide-handling practices in agriculture in Tanzania observe that the location of pesticide spraying, storage, disposal, and equipment correlates with the extent of protection to farm workers' families from the hazardous risk associated with synthetic chemicals.

The EIQ analysis using the reported insecticides in tomato production in Kenya and Uganda showed that farmers were using pesticides of EIQ ranging between high and moderate. The finding supports Mwungu et al. (2020) who found that active chemicals present in mango production were lower than Field EIQ 40. The pesticides used in tomato production in Kenya and Uganda fall under Class II of the WHO pesticide classification, suggesting that they have a potentially adverse impact on the environment, consumers, and farmers.

The study concluded by conducting a sensitivity analysis to estimate the potential income lost as a result of using synthetic pesticides in tomato production, as opposed to using IPM practices. The analysis showed positive gains from the use of IPM, with an NPV ranging from $8 to $2,851 in both countries. While in Kenya significant gains would be realized if the farmers switched to IPM immediately, in Uganda, significant gains would only be registered after 2 yr of IPM implementation, with the difference attributed to the high cost of pesticides in Kenya in comparison with Uganda. In both scenarios, the NPV and BCR are positive; even with the most pessimistic avoidable cost of 5%, the opportunity cost is still evident (Gong et al. 2009).

Conclusions and Policy Implications

This study sort to assess the economic, health, and environmental implications of using pesticides for managing *T. absoluta* in tomato production. We utilized cross-sectional household-level survey data gathered from over 650 tomato growers in selected regions in Kenya and Uganda. While there is significant literature on the effects of *T. absoluta* on tomato production, there is limited research on the economic burden of the pest as well as the implications of pesticide use on human health and the environment particularly in SSA, gaps that this study attempted to address.

With regard to economic burden, we find that *T. absoluta* causes significant losses in tomato production, estimated at 64% and 41% of the total loss attributed to insect pests in Kenya and Uganda, respectively. Similarly, the pest is attributed to over half of the total cost incurred in the management of insects and diseases in tomato production (66% and 78% in Kenya and Uganda, respectively). This suggests the economic importance of the pest in tomato production as it lowers the gross margin and overall returns that would be generated from the farming enterprise. The burden of pesticides is also demonstrated in the gross margin analysis, where they attributed to a third of the variable costs in Kenya.

With synthetic chemicals observed as the primary approach to the management of pests, farmers and the environment surrounding their tomato farms are exposed to risks. While the majority of the surveyed farmers in both countries were aware of the negative risks associated with pesticides and took some precautions while using, storing, and disposing of them, there were notable gaps particularly in the use of protection gears, exposing the pesticide applicants to the negative health risks associated with the chemicals. We adopted the EIQ methodology to assess the effects of pesticides on farm workers, consumers, and the environment. The results show that the EIQ for the pesticides used in the selected tomato-producing areas in Kenya and Uganda ranged between high and moderate, with some of the insecticides causing hazardous effects either on the farmers or producers, consumers, and the environment. Most of the pesticides are from Class II of the WHO classification, which is toxic and hence exerts negative effects on the environment, consumers, and farmers. IPM strategy is a sustainable alternative to the use of synthetic pesticides, and it reduces the health and environmental effects of these pesticides significantly. Researchers and development agencies have endorsed the use of IPM as an alternative to chemical pesticides as it offers sustainability and intensification, thus significantly increasing agricultural yield.

We went further to assess the lost opportunity or gains from using alternative methods of pest management other than pesticides, that is, the use of proposed IPM strategies. The sensitivity analysis showed positive returns in both countries, with estimated savings of $2,851 per hectare per season in Kenya if the IPM was adopted immediately. In Uganda however, significant gains would only be achieved after about 2 yr (i.e., $992 per hectare per season), perhaps because the cost of pesticides was lower in Uganda than in Kenya, as well as the earlier arrival of the pest in Kenya compared with Uganda. Therefore, the adoption of the IPM strategy by the smallholder farmers in both countries immediately or in 2 yr would contribute to significant returns.

It is worth mentioning that the study used cross-sectional data and therefore did not fully exploit all the changes as a result of *T. absoluta* invasion. However, our findings underscore the need for IPM sensitization and adoption. Given that the majority of pesticides used in tomato production are toxic, farmers should be encouraged to adopt the use of the IPM strategy as a sustainable and eco-friendly alternative to the use of chemical pesticides. Poliymakers on the other hand should use these findings to promote wider dissemination of the IPM practices. Future studies could consider using panel data to evaluate the medium- and long-term effects of chemical pesticides on humans and the environment.

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Author Contributions

Fridah Chepchirchir (Conceptualization [Equal], Data curation [Equal], Formal analysis [Equal], Investigation [Equal], Methodology [Equal], Supervision [Equal], Validation [Equal], Visualization [Equal], Writing – original draft [Equal], Writing – review & editing [Equal]), Beatrice Muriithi (Conceptualization [Equal], Data curation [Equal], Formal analysis [Equal], Funding acquisition [Equal], Investigation [Equal], Methodology [Equal], Project administration [Equal], Supervision [Equal], Validation [Equal], Visualization [Equal], Writing – original draft [Equal], Writing – review & editing [Equal]), Jackson Langat (Data curation [Equal], Formal analysis [Equal], Investigation [Equal], Validation [Equal], Writing – original draft [Equal], Writing – review & editing [Equal]), Shepard Ndlela (Conceptualization [Equal], Funding acquisition [Equal], Project administration [Equal], Validation [Equal], Visualization [Equal], Writing – review & editing [Equal]), Samera Mohamed (Conceptualization [Equal], Funding acquisition [Equal], Project administration [Equal], Validation [Equal], Visualization [Equal], Writing – review & editing [Equal]), and Fathiya Khamis (Conceptualization [Equal], Funding acquisition [Equal], Project administration [Equal], Resources [Equal], Supervision [Equal], Validation [Equal], Visualization [Equal], Writing – review & editing [Equal])

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