



Smallholder Tomato Farmers’ Awareness, Perceptions, and Willingness to Adopt Biological Alternatives for *Tuta absoluta* Management in Tanzania

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Abstract

Tuta absoluta is one of the most destructive pests of tomato in Sub-Saharan Africa. In Tanzania, smallholder farmers rely almost exclusively on synthetic pesticides to manage it. While biological alternatives, including semiochemicals and conservation of natural enemies, are increasingly promoted for sustainable pest management, little is known about smallholder farmers' awareness, perceptions, and access to these technologies.

This study investigated farmers' awareness, perceptions, feasibility of use, and adoption potential of biological alternatives for *Tuta absoluta* management in Mapinduzi, Iringa Rural District, Tanzania. Semi-structured interviews were conducted with 26 respondents, including 22 active tomato cultivators and four farmers who did not currently cultivate tomatoes and participated as proxy observers from the same agro-ecological zone. Data were analyzed using non-parametric methods (Spearman rank correlations, Kruskal-Wallis, Fisher's exact test) in R, supplemented by thematic analysis of qualitative interview data.

Respondents reported frequent and severe *Tuta absoluta* infestations and identified synthetic pesticides as the primary control method used locally. Awareness was low: 30.8% had general knowledge of biological alternatives, 19.2% could name a specific biological control tool such as a semiochemical or natural enemy, and 88.5% could not distinguish beneficial insects from pests. None had received extension training on biological control. Across all four feasibility dimensions (efficacy, affordability, accessibility, economic viability), most respondents reported having no experience that would allow them to compare biological alternatives with synthetic pesticides.

The strongest statistical finding was a negative correlation between health-risk perception and willingness to adopt an IPM approach combining biological alternatives with synthetic pesticides. Respondents with greater concern about pesticide-related health risks were less willing to adopt this integrated approach. However, all respondents stated that they would adopt biological alternatives if their effectiveness were demonstrated, suggesting that reluctance concerned the continued use of synthetic pesticides rather than biological alternatives themselves.

Supplementary interviews with 20 agro-dealers, conducted as part of a parallel study, indicated that only one dealer stocked a biological pest control product – a semiochemical – and that most lacked training in biological pest control, reflecting very limited availability of biological pest-control products among the dealers interviewed. The study concludes that farmer-centred demonstrations, strengthened extension capacity, improved product availability, and supportive regulatory frameworks are needed to enable more sustainable and biologically informed management of *Tuta absoluta* in Tanzanian smallholder tomato production.

Keywords: Tomato, *Tuta absoluta*, biological alternatives, semiochemicals, synthetic pesticides, Integrated Pest Management, Tanzania.

Preface

AI Use and Author Contributions

This thesis was prepared with the assistance of ChatGPT and Claude as supportive tools for the following tasks:

- Language and structure: refining wording and clarity and improving the organisation of text to align with academic writing standards.
- Statistical programming: assistance with writing, debugging, and refining R code; generating and formatting figures; and guidance on appropriate R packages.
- Statistical verification: support in cross-checking reported values against the dataset, conducting sensitivity checks, and confirming the correct application of descriptive statistics.
- Reference and formatting checks: identifying inconsistencies in citations, captions, and terminology.

The author carried out the research design, data collection, fieldwork, data analysis, interpretation of results, and thesis writing, with supervisory guidance and the AI assistance described above. The conclusions drawn and all final decisions on the content of this thesis remain the author's own. AI tools were used to support analysis and presentation, not to replace scholarly judgement, and all outputs were critically reviewed and verified by the author before inclusion.

Table of contents

List of tables	8
List of figures	9
Abbreviations	11
1. Introduction	13
2. Objectives of the study	17
3. Literature Review	19
3.1 Importance of tomato production in the world, Africa and in Tanzania.	19
3.2 Impact of <i>Tuta absoluta</i> on Tomato Production in Tanzania	20
3.3 Dominance of synthetic pesticides in pest management.	25
3.4 Biological Control Approaches: Natural Biological Control Agents	25
3.5 Semiochemicals in Pest Management: Mode of Action and Applications	28
3.6 Synergistic Effects: Integrating Semiochemicals and Biological Control	30
3.6.1 Multitrophic and Environmental Factors Influencing Semiochemical Efficacy	30
3.6.2 Mechanisms of Integration: Behavioural Manipulation, Spatial Architecture	
and Co-Formulations with Entomopathogens.....	30
3.6.3 Semiochemical Blends, Design Constraints and Genomic Perspectives for	
Future IPM.....	32
3.7 Regulatory Framework for Pesticides in Tanzania	32
3.8 Socio-economic Factors Influencing Adoption of IPM/Biological Alternatives	33
4. Methodology	36
4.1 Location of study.....	36
4.2 Sampling Strategy and Validation of Proxy Respondents (Observers)	37
4.3 Data Collection and Research Design	38
4.4 Supplementary Agro-Dealer Interviews.....	39
4.5 Data Analysis.....	39
4.6 Ethical considerations	40
4.7 Study scope.....	41
5. Results	42
5.1 Demographic Profile of Respondents	42
5.2 Current Pest Management Practices	43
5.2.1 Challenges Associated with Synthetic Pesticide Use	44
5.3 Farmer Awareness, Knowledge and Exposure to Biological Alternatives.....	45
5.3.1 Awareness of biological alternatives.....	45
5.3.2 Sources of agricultural information	46
5.3.3 Knowledge of natural enemies and biological control	46

5.3.4	Awareness and Adoption Funnel	47
5.4	Adoption Willingness and Attitudes.....	49
5.4.1	Attitudes toward IPM integration	49
5.5	Perceptions and Feasibility of Biological Alternatives	50
5.5.1	Perceived risks and benefits	50
5.5.2	Ability to evaluate biological alternatives.....	51
5.6	Factors Influencing Adoption Decisions	52
5.6.1	Ranking of adoption priorities	52
5.7	Correlations Between Socio-economic Factors and IPM Adoption Willingness	55
5.8	Summary of key findings	57
6.	Discussion	59
6.1	Introduction	59
6.2	Awareness, Knowledge and Experience of Biological Alternatives	59
6.3	Perceived Agronomic Benefits of Biological Alternatives	63
6.4	Perceived Feasibility of Adoption.....	66
6.5	Factors Influencing Willingness to Adopt.....	70
6.6	Integration: Toward an IPM Adoption Pathway	71
7.	Conclusion.....	73
7.1	Practical and Policy Implications	74
7.1.1	Demonstration-based introduction of biological alternatives	74
7.1.2	Training and strengthening of agro-dealer and extension officers' networks	
	75	
7.1.3	Improvement of product availability and regulatory support.....	76
7.1.4	Promotion of conservation biological control and farmer awareness of	
	natural enemies	77
7.2	Study Limitations and Future Research	77
7.3	Study contribution	79
	References	80
	Popular science summary	99
	Appendix 1	102
	Appendix 2	107

List of tables

Table 5.1: Demographic Summary of Survey Respondents in Mapinduzi Village (N=26)	42
Table 5.2: Synthetic Pesticide Application Frequency Among Surveyed Tomato Farmers (N=26).....	43
Table 5.3. Farmer Awareness, Field Observations, and Identification Skills Regarding Biological Alternatives (N=26).....	45
Table A1.1: Spearman Rank Correlations with Willingness to Adopt an IPM Approach..	96
Table A1.2: Key Categorical Outcomes.....	96
Table A1.3: Additional Group Comparisons Supplementing Table A1.5.....	96
Table A1.4: Tomato Cultivation Area (Active Cultivators Only, n=22).....	97
Table A1.5: Baseline Homogeneity and Methodological Validation of Survey Response Groups (N=26). .	103

List of figures

Figure 3.1. Global Distribution of <i>Tuta absoluta</i> , showing the 110 Countries Reporting its Presence and the Reported Status in each. Drawn by the Author from EPPO, 2026 Global Database Country-Level Records.	21
Figure 3.2. Life Cycle of <i>Tuta absoluta</i> , Showing the Four Developmental Stages and the Multivoltine Nature of the Pest.	22
Figure 3.3. <i>Tuta absoluta</i> Development Stages: Larva (A–D), Pupa (E) and Adult (F). Details of Larval Mining Under the Leaf Surface Shown in A–C. Reproduced from Yule et al. (2021) under a CC BY 4.0 License.	22
Figure 3.4. Typical Damage Caused by <i>Tuta absoluta</i> Larvae on Tomato Leaves (A–D) and Fruits (E). Reproduced From Yule et al. (2021) under a CC BY 4.0 License.	23
Figure 3.5. Damage Caused by <i>Tuta absoluta</i> on Tomato in Arumeru District, Tanzania: (a) Severely Damaged Field, (b) Leaf Damage Between the Upper and Lower Epidermis. Reproduced from Chidege et al. (2016) Under a CC BY 4.0 License.	24
Figure 3.6. Biologically Based Tools as One Pillar Within an Integrated Pest Management Framework, Showing the Role of the Economic Threshold in Guiding Intervention Before Pest Populations Reach the Economic Injury Level.....	26
Figure 4.1. Location of the Study Area: (a) Iringa Region Within Tanzania; (b) The Study Area Within Iringa Region; (c) Mapinduzi, Mgera Village, Kiwere Ward, Iringa Rural District. Boundaries from Natural Earth.	36
Figure 5.1. Primary Challenges Encountered by Farmers in Synthetic Pesticide Application (N=26).....	44
Figure 5.2. Primary Channels of Agricultural Advice and Information Among Surveyed Farmers (N=26).....	46
Figure 5.3. Dual-panel distribution of Farmers' Field Observation and Extension Training Regarding Natural Enemies and Beneficial Insects (N=26).....	47
Figure 5.4. Awareness and Adoption Funnel of Bio-Alternatives Among Surveyed Farmers (N=26).....	48
Figure 5.5. Attitudinal Responses and Future Intentions Toward Integrated Pest Management (IPM) and Biological Adoption Among Surveyed Farmers (N=26).	49

Figure 5.6. Boxplot Distribution of Tomato Cultivation Area Across IPM Adoption Interest Groups (n=22). The four proxy observers are excluded, as they reported no tomato cultivation area.....	50
Figure 5.7. Reported Influence of Financial Considerations, Health and Environmental Risks on Farmers' Decisions to Adopt Biological Alternatives (N=26).	51
Figure 5.8. Respondents' Basis for Comparing Biological Alternatives with Synthetic Pesticides Across Four Feasibility Dimensions (N=26).	52
Figure 5.9. Prioritization Profile of Factors Influencing the Adoption of Biological Alternatives:(a) Mean Rank Scores (n=19); (b) Single Most Important Factor (N=26).	53
Figure 5.10. Relative Importance Profile Matrix of Farmer Priorities Affecting Bio-Alternatives Adoption, Showing the Spread of Rankings Across Factors (n=19).	54
Figure 5.11. Key Socio-economic and Informational Factors Shaping Farmers' Decisions to Adopt Biological Alternatives (N=26).	55
Figure 5.12. Spearman Rank Correlation Matrix of Farmer Demographics, Risk Perceptions, and IPM Willingness (N=26).	56
Figure 5.13. Scatter Plot with Fitted Regression Line Showing the Negative Association Between the Influence of Health Risks on Farmers' Pest Management Decisions and Their Willingness to Adopt IPM Combining Biological Alternatives With Synthetic Pesticides (N=26).	57
Figure 5.14. Conceptual Dashboard Summarizing Respondent Awareness, Pest Experience, and Willingness to Adopt Biological Alternatives (N=26).	58

Abbreviations

TPHPA	Tanzania Plant Health and Pesticide Authority
EAC	East African Community
IPM	Integrated Pest Management
HIPV	Herbivore-Induced Plant Volatiles
FFS	Farmer Field Schools
SLU	Swedish University of Agricultural Sciences
FAO	Food and Agriculture Organization of the United Nations
HHP	Highly Hazardous Pesticides
GAP	Good Agricultural Practices
EIL	Economic Injury Level
EPA	United States Environmental Protection Agency
RQ	Research Question
USD	United States Dollar
USDA	United States Department of Agriculture
PPE	Personal Protective Equipment

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1. Introduction

Tomato (*Solanum lycopersicum*) is among the world's most widely cultivated horticultural crops, valued for both its economic significance and its role in human nutrition. According to FAO (2025) data, global tomato production stands at approximately 189 million tonnes, with an average yield of 37 tonnes per hectare. In contrast, total production across Africa is estimated at around 26 million tonnes, with yields averaging about 16 tonnes per hectare. This marked regional yield gap reflects multiple production constraints, including severe pest and disease pressures, climate-related stresses such as erratic rainfall, underdeveloped irrigation infrastructure and substantial post-harvest losses, all of which limit the growth of the smallholder farming sector (Osei et al., 2014; Sibomana et al., 2016; Dube et al., 2020).

Within sub-Saharan Africa, Tanzania is one of the leading tomato-producing countries, and tomatoes are the most significant vegetable crop cultivated by smallholder farmers in the country (Kilimo Kwanza, 2024). Recent production statistics indicate that Tanzania produced approximately 572,000 tonnes of tomatoes in 2023 (World Population Review, 2026). This production is of substantial economic importance, as the broader agricultural sector contributes approximately 30% to Tanzania's national Gross Domestic Product (GDP), with tomato cultivation serving as an important source of income within the horticultural sub-sector (Kongolo & Tesha, 2023; World Population Review, 2026). However, average tomato yields remain low at approximately 10.5 t/ha, well below both the African average of 16 t/ha and the global average of 37 t/ha (Kongolo & Tesha, 2023).

Despite the importance of tomato production for smallholder livelihoods, productivity and value-chain development are constrained by both abiotic and biotic factors, particularly pests and diseases (Kilimo Kwanza, 2024). Among these, the tomato leafminer (also known as tomato pinworm), *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), recently reclassified as *Phthorimaea absoluta*, is one of the most economically damaging invasive pests. If left unmanaged, *T. absoluta* infestations can cause yield losses of 80% to 100% (Zekeya, 2019; Mawcha et al., 2026). Since its initial detection in Tanzania in 2014, *Tuta absoluta* has rapidly spread across all major tomato-growing regions in the country (Smith et al., 2018). The management of this pest is complicated by its broad host range; crops such as potatoes (*Solanum tuberosum*) and eggplants (*Solanum melongena*) serve as alternative hosts, facilitating a constant reservoir for infestation (Smith et al., 2018; Mahlangu et al., 2022).

Furthermore, traditional chemical interventions have proven to be largely ineffective. This is primarily due to the cryptic feeding behaviour of the larvae, which remain protected within the mesophyll galleries mined in leaves, stems, and fruits, thereby shielding them from direct contact with foliar-applied insecticides (Maerere, 2018). This challenge is exacerbated by documented pesticide resistance across a range of chemical classes (Guedes & Picanço, 2012; Smith et al., 2018). Consequently, the heavy reliance on these synthetic pesticides has imposed a significant environmental burden on the agroecosystem without achieving adequate pest suppression.

Several approaches have been proposed to address this pest problem. Some are well established, such as Good Agricultural Practices (GAP), including crop hygiene, monitoring of pest populations and crop damage, and responsible pesticide use (Chepchirchir et al., 2021), while others remain at the experimental stage, including efforts to breed tomato varieties resistant to *Tuta absoluta* (Rakha et al., 2017; Bitew, 2018). The integration of biological alternatives, including semiochemicals and natural enemies, within an Integrated Pest Management (IPM) framework represents a more recent approach that is gaining attention (Desneux et al., 2022; Basit et al., 2025).

Overall, smallholder tomato farmers in Tanzania rely heavily on synthetic pesticides to manage *Tuta absoluta*, despite concerns about pesticide exposure, crop damage, and the increasing challenges associated with synthetic pesticide use (Chawda & Ninave, 2021; Zekeya et al., 2022; Chilipweli et al., 2025). Although safer approaches, including semiochemicals and natural enemies, can be integrated within an IPM framework, there is limited evidence on Tanzanian smallholders' awareness of these alternatives, their perceptions of the effectiveness of these approaches, and the practical conditions required for their adoption. Addressing these knowledge gaps is important for supporting a transition toward safer and more sustainable pest-management options.

The present thesis is relevant because it addresses the critical intersection of food security, environmental sustainability, and smallholder welfare in Tanzania. This study seeks to examine smallholder farmers' awareness, perceptions, and willingness to adopt biological agents as sustainable complements to synthetic pesticides for managing *Tuta absoluta*. This objective is directly supported by and dependent upon the Tanzania Plant Health and Pesticides Authority (TPHPA), the national regulatory and implementing body whose collaboration ensures that research translates into policy.

Significantly, the relevance of this work also extends across borders owing to regional cooperation on *Tuta absoluta* and pesticide management. The East African Community (EAC) is a regional intergovernmental organization of eight Partner

States (including Tanzania) pursuing social, economic and political integration across East Africa. Its harmonized guidelines for biopesticide registration are designed to enable rapid sharing of trial data across member countries.

Tanzania adopted the Plant Health Act No. 4 of 2020, which provided a national legal framework for pesticide and biopesticide registration (EAC, 2019; Mawcha et al., 2025). The Act therefore provides the national legal basis through which Tanzania could operationalize the regional guidelines, although their full incorporation into national registration procedures remains incomplete. Strengthening this framework could help ensure that solutions developed against a transboundary pest benefit the entire East African region, thereby consolidating regional resilience and cooperation against a common threat (EAC, 2019).

Management options for *Tuta absoluta* include crop sanitation, insect-proof netting, pheromone-based monitoring and mass trapping, mating disruption, biological control and selective insecticide use within an IPM programme (Desneux et al., 2022). These methods serve different functions, ranging from monitoring pest populations and disrupting reproduction to directly suppressing the pest. European greenhouse trials have combined pheromone-based approaches with predatory insects and microbial biological control agents, reducing synthetic pesticide applications while controlling *T. absoluta* (PURE, 2015).

There is a difference between experimental evaluation and commercial availability of a product. The former uses trials to assess how a product performs under certain conditions, while the latter means that a product is available to the public for sale. Examples include Isonet T, a commercial pheromone-based mating-disruption product evaluated in greenhouse tomatoes in Italy (Sannino et al., 2025), and Dipel, a commercial microbial insecticide containing *Bacillus thuringiensis*, which has been evaluated against *Tuta absoluta* larvae under laboratory conditions in Turkey (Bayindir Erol & Erdoğan, 2022).

For instance, Sannino et al. (2025) evaluated the commercial pheromone-based mating-disruption product Isonet T alongside an experimental biodegradable dispenser in greenhouse tomatoes in Italy. When combined with the farm's synthetic pesticide programme, the pheromone treatments reduced *Tuta absoluta* infestation and crop damage compared with the synthetic pesticide programme alone.

In Tanzania, pheromone traps and a commercially available microbial biological-control product (biopesticide) containing the fungus *Metarhizium anisopliae*, have been evaluated under field conditions during wet and dry seasons. The study also noted that commercial use of pheromone traps remained low in sub-Saharan Africa at the time (Zekeya et al., 2022).

Natural enemies investigated for managing *Tuta absoluta* include predatory insects and parasitoid wasps. In Spain, greenhouse experiments demonstrated that the predator *Nesidiocoris tenuis* could significantly reduce pest populations (Calvo et al., 2012). Evidence is also available from Africa: field trials in Egypt found that releases of the egg parasitoid *Trichogrammatoidea bactrae*, combined with pheromone-based mass trapping, reduced infestation levels (Goda et al., 2015).

These studies demonstrate the potential of natural enemies, although they do not establish their availability or effectiveness under smallholder conditions in Tanzania. Against this background, the present study examines farmers' awareness and perceptions of biological alternatives and the conditions influencing their willingness to adopt them.

2. Objectives of the study

The aim of this study is to examine smallholder tomato farmers' awareness, perceptions, and willingness to adopt biological alternatives, specifically semiochemical-based tools and natural enemies, as sustainable complements to synthetic pesticides for managing *Tuta absoluta* in tomato production systems in Tanzania. This study explores how farmers perceive these tools in terms of crop productivity, plant health, effectiveness, affordability, and accessibility, and how these perceptions compare with their experiences of synthetic pesticides. The findings are used to identify pathways for integrating biological pest-management approaches into smallholder farming systems.

Specific objectives

- i. To assess farmers' awareness, knowledge, and reported experiences of semiochemicals and natural biocontrol agents for *Tuta absoluta* management.
- ii. To evaluate farmers' perceptions of the agronomic and practical benefits of biological alternatives relative to synthetic pesticides, with particular emphasis on human safety, plant and environmental health, labour demands, and pest-suppression efficacy.
- iii. To analyze farmers' perceptions of the feasibility of adopting semiochemicals and natural biocontrols, focusing on affordability, accessibility, perceived effectiveness, and economic viability relative to chemical programs.
- iv. To identify the socio-economic and perception-related factors associated with farmers' willingness to integrate semiochemicals and natural biocontrols into existing pest-management practices.

Research Questions

- i. What is the level of awareness and knowledge of semiochemicals and natural biocontrol agents for managing *Tuta absoluta* among smallholder tomato farmers, and what experiences, if any, do they report with using these biological alternatives?
- ii. How do smallholder farmers perceive the agronomic and practical benefits of biological alternatives relative to conventional synthetic pesticides, particularly in terms of human safety, plant and

environmental health, labour demands, and pest-suppression efficacy?

- iii. How do smallholder tomato farmers perceive the feasibility of adopting semiochemicals and natural biocontrols, with respect to affordability, accessibility, perceived effectiveness, and economic viability compared with existing chemical pest management programs?
- iv. Which socio-economic and perception-related factors are associated with farmers' willingness to adopt and integrate semiochemicals and natural biocontrols into their existing pest-management practices?

3. Literature Review

3.1 Importance of tomato production in the world, Africa and in Tanzania.

The tomato (*Solanum lycopersicum*) is the most extensively cultivated vegetable crop worldwide (FAO, 2025). Growing in over 150 countries, it is arguably the most geographically distributed vegetable globally (World Population Review, 2026). Historically originating from Central and South America, the species is classified within the family Solanaceae, which includes economically significant relatives such as potatoes (*Solanum tuberosum*), eggplants (*Solanum melongena*), and peppers (*Capsicum annuum*) (Gatahi, 2020). Global production is currently estimated at 189 million tonnes, with China, India, Turkey and the United States collectively accounting for over half of global production (World Population Review, 2026).

In 2023, China remained the world's leading tomato producer, with approximately 61.5 million tonnes, followed by India with 20.4 million tonnes, Turkey with 13.3 million tonnes, and the United States with 12.4 million tonnes (FAO, 2025). Globally, approximately 40 million tonnes of tomatoes are processed into products such as pastes, sauces, and canned goods (World Processing Tomato Council, 2024). Africa produces approximately 26 million tonnes of tomatoes annually, with Egypt and Nigeria serving as the continent's primary production hubs, producing an estimated 6.2 million and 3.8 million tonnes, respectively, in 2023 (World Population Review, 2026).

Despite this production base, tomato value chains across Sub-Saharan Africa continue to experience substantial post-harvest losses associated with infrastructure and handling constraints, while evidence from Tanzania also points to a limited number of processing industries. Together, these constraints signal considerable untapped potential for storage, processing and other value-addition activities along the chain (Sibomana et al., 2016; Izdori et al., 2025).

Beyond its economic importance, the tomato is a nutrient-dense fruit commonly consumed as a vegetable and is important for human health (Ali et al., 2021). A 100g serving of tomatoes contains approximately 18 kcal, 95% water, 3.9g of carbohydrates, 0.9g of protein, 13 to 23 mg of vitamin C, 200 to 300 mg of potassium, 1 to 8 mg of lycopene and 449 µg of beta-carotene (Bjarnadottir, 2023; USDA, 2024). Overall, it provides a diverse supply of macronutrients, vitamins, minerals and bioactive compounds (Ali et al., 2021).

Importantly, it is a significant source of health-promoting bioactive compounds, including carotenoids such as lycopene and beta-carotene, noted for their potent antioxidant properties (Ali et al., 2021). It also contains polyphenols, including a varied range of flavonoids and phenolics that contribute to disease prevention (U.S. Department of Agriculture, 2024). Epidemiological studies have shown that lycopene contributes to a reduced risk of prostate cancer, while flavonoids increase anti-inflammatory activities in the body (Lu et al., 2021; Kapała et al., 2022; Al-Khayri et al., 2022).

3.2 Impact of *Tuta absoluta* on Tomato Production in Tanzania

Despite the numerous benefits derived from the production and consumption of tomatoes, several challenges impede both the cultivation and post-harvest stages of the crop, including storage, transportation, and marketing inefficiencies. These factors have resulted in reduced yields and a corresponding increase in production costs (Osei et al., 2014).

During the production phase, key abiotic constraints include limited water access, extreme temperatures, and declining soil fertility, while the limited genetic diversity of commercial varieties further constrains production (Osei et al., 2014; Dube et al., 2020). Furthermore, tomato growers face significant biotic stresses, including major diseases such as bacterial wilt and late blight, as well as severe pressure from insect pests. Among these, the South American tomato pinworm, with the scientific name *Phthorimaea absoluta* Meyrick (Lepidoptera: Gelechiidae), has emerged as a primary constraint to sustainable tomato production worldwide (Basit et al., 2025; Mawcha et al., 2026).

Tuta absoluta is native to South America, particularly Peru, where it was first identified as a major pest in the 1910s and experienced a substantial increase in importance during the 1970s. It subsequently expanded beyond South America, invading Europe, the Middle East, and Asia (Guedes & Picanço, 2012; Zappalà et al., 2013; Gabarra et al., 2014). Following its initial detection in North Africa in 2008, the pest rapidly expanded its range to nearly every country across the African continent (Chidege et al., 2016; Giorgini et al., 2019).

In Tanzania, *T. absoluta* was first detected in 2014 and has since spread across the country's major tomato-growing regions (Smith et al., 2018). Although tomato is its primary host, the pest also infests other solanaceous crops, including potatoes, peppers, and eggplants, providing additional hosts that may facilitate the persistence and spread of infestations (Caparros Megido et al., 2014; Visser et al.,

2016; Smith et al., 2018; Mahlangu et al., 2022). While *T. absoluta* remains a major biosecurity concern for the United States, it is not yet established there (NISIC, 2024). Its global distribution is presented in Figure 3.1.

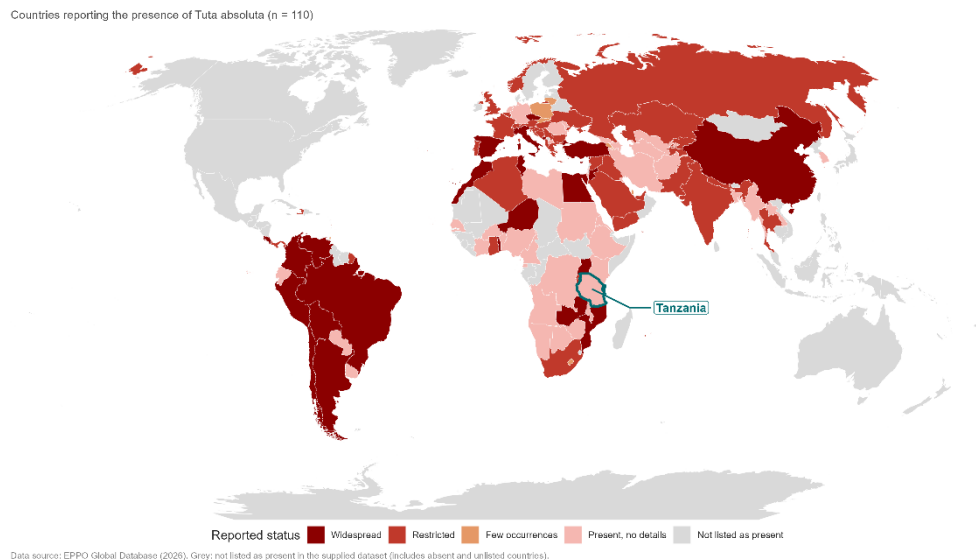


Figure 3.1. Global Distribution of Tuta absoluta, showing the 110 Countries Reporting its Presence and the Reported Status in each. Drawn by the Author from EPPO, 2026 Global Database Country-Level Records.

The life cycle of *T. absoluta* is completed in approximately 30 to 40 days, depending on environmental temperatures, and includes four distinct larval instars (Desneux et al., 2010; Visser et al., 2016; Rwomushana et al., 2019). Upon hatching, the larvae penetrate the plant tissues, mining into the leaf mesophyll, stems, and fruits (Biondi et al., 2018). While pupation frequently occurs in the soil, it can also take place within the leaf mines or on the plant surface, especially under limited soil access (Desneux et al., 2010; Tonnang et al., 2015; Giorgini et al., 2019; AHDB, 2026). The complete life cycle is illustrated in Figure 3.2, with the morphology of each developmental stage shown in Figure 3.3.

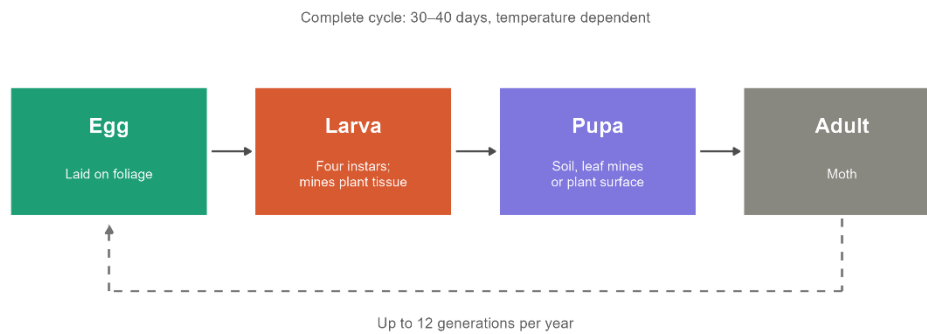


Figure 3.2. Life Cycle of Tuta absoluta, Showing the Four Developmental Stages and the Multivoltine Nature of the Pest.



Figure 3.3. Tuta absoluta Development Stages: Larva (A–D), Pupa (E) and Adult (F). Details of Larval Mining Under the Leaf Surface Shown in A–C. Reproduced from Yule et al. (2021) under a CC BY 4.0 License.

Under favourable conditions, the pest is multivoltine, in that it is capable of producing up to 12 generations annually with rapid, continuous reproduction. By infesting the foliage, stems, and reproductive organs – including the apical buds – the larvae severely inhibit the plant’s vegetative growth and structural development (Figure 3.4) (Biondi et al., 2018; Mansour et al., 2018; Giorgini et al., 2019).

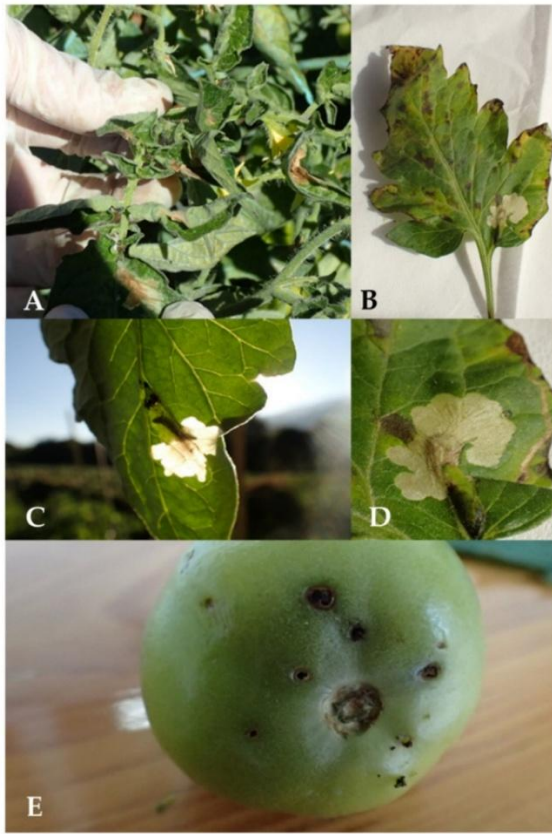


Figure 3.4. Typical Damage Caused by *Tuta absoluta* Larvae on Tomato Leaves (A–D) and Fruits (E). Reproduced From Yule et al. (2021) under a CC BY 4.0 License.

Specifically, the extensive gallery formation in the leaves significantly reduces photosynthetic capacity, leading to stunted growth and substantial yield losses (Biondi et al., 2018; Mansour et al., 2018; Giorgini et al., 2019; Mahlangu et al., 2022). Furthermore, the physiological stress and physical wounds caused by larval mining and burrowing create entry points for secondary infections by opportunistic pathogens. These secondary infestations often exacerbate the initial damage, accelerating plant senescence and further compounding yield destruction (Mawcha et al., 2026).

The extent of yield loss attributed to *T. absoluta* depends heavily on prevailing climatic factors and the efficacy of management interventions implemented by growers (Mawcha et al., 2026). Unfortunately, smallholder farmers remain particularly vulnerable to such losses due to limited access to technical information, a lack of institutional support, and a scarcity of affordable, effective control technologies (Materu et al., 2016; Constantine et al., 2020).

Consequently, these resource-constrained producers often resort to suboptimal management practices, which further compromise both crop productivity and household income. While some regions have documented losses of approximately

45%, many countries report total crop failure, up to 100% yield loss, particularly in the absence of effective insecticide treatments (Korycinska & Moran, 2009; Rwomushana et al., 2019).

In Tanzania, such catastrophic losses occur regularly, posing a severe threat to food security and farmer livelihoods (Figure 3.5) (Zekeya, 2019). These losses carry severe economic consequences for smallholder farmers, for whom even moderate reductions in marketable yield can represent a significant financial setback. It is estimated that global economic losses reaching several billion USD annually are linked to this pest, driven by both direct yield destruction and the surging costs of intensive chemical control measures (Rwomushana et al., 2019).



Figure 3.5. Damage Caused by Tuta absoluta on Tomato in Arumeru District, Tanzania: (a) Severely Damaged Field, (b) Leaf Damage Between the Upper and Lower Epidermis. Reproduced from Chidege et al. (2016) Under a CC BY 4.0 License.

3.3 Dominance of synthetic pesticides in pest management.

Modern pesticide use expanded rapidly in the mid-20th century, driven largely by the widespread adoption of DDT (dichlorodiphenyltrichloroethane), a synthetic organochlorine insecticide, during and after World War II (Jarman & Ballschmiter, 2012). Although highly effective, DDT's persistence and negative ecological impacts – brought to public attention by Rachel Carson's *Silent Spring* (1962) – raised serious concerns about its widespread use, eventually leading to its phase-out and the development of newer chemical classes such as organophosphates, carbamates, and pyrethroids (Gaydou-Miller, 2023). While some of these alternatives were less persistent, they continued to pose risks to human health, non-target organisms, and ecosystems (Mdeni et al., 2022).

Synthetic pesticides nevertheless remain a dominant tool for crop protection in smallholder systems and have contributed significantly to agricultural productivity, but their intensive and prolonged use has raised serious concerns about biodiversity, ecosystem stability, and long-term sustainability (Pimentel, 2005; Lu et al., 2010). These concerns have driven growing interest in biological alternatives, including semiochemicals and natural enemies, as potentially safer components of integrated pest management (Reddy et al., 2020; Ayilara et al., 2023; Fenibo & Matambo, 2025).

3.4 Biological Control Approaches: Natural Biological Control Agents

According to the United States Environmental Protection Agency (EPA), Integrated Pest Management (IPM) is defined as “an effective and environmentally sensitive approach to pest management that relies on a combination of common-sense practices” (EPA, 2023). It represents a holistic, systems-based approach to agroecosystem management, operating in direct contrast to conventional, pesticide-intensive practices that rely primarily on the routine application of broad-spectrum chemicals (Kumar et al., 2025).

By strategically combining biological, cultural, physical, and targeted chemical interventions, IPM manages pest populations in ways that minimize risks to human health, non-target organisms, and the wider environment. Central to IPM decision-making is the concept of the Economic Injury Level (EIL), defined as the pest density at which the expected economic loss caused by pest damage equals the cost of control. In practice, intervention is normally initiated at a lower economic threshold to prevent pest populations from reaching the EIL (Figure 3.6) (Stern et al., 1959; Pedigo & Rice, 2009).

Biological control is one of the core components of IPM, in which living organisms such as predators, parasitoids and pathogens are used to keep pest populations below levels where they cause economic damage. The broader term biological alternatives, as used in this study, includes biological control as well as biopesticides and semiochemicals. These tools complement other IPM practices by reducing reliance on synthetic insecticides. In particular, conservation biological control can provide preventive suppression by protecting and enhancing natural enemies before pest populations reach economically damaging levels.

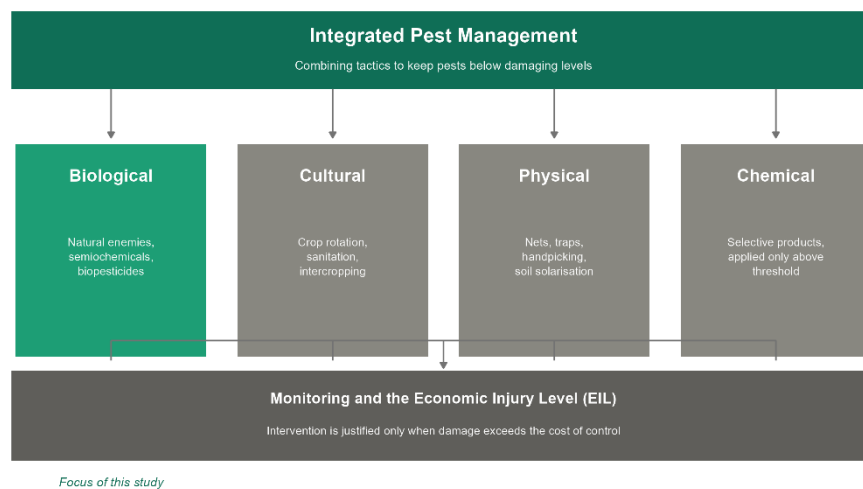


Figure 3.6. Biologically Based Tools as One Pillar Within an Integrated Pest Management Framework, Showing the Role of the Economic Threshold in Guiding Intervention Before Pest Populations Reach the Economic Injury Level.

The organisms that perform this role are termed biological control agents, and within an agroecological framework they are grouped into three functional categories: predators, parasitoids, and pathogens/competitors (Godfray, 1994; Singh et al., 2020). By harnessing natural enemies, biocontrol contributes to restoring ecological balance, reducing dependence on synthetic inputs, and promoting the long-term sustainability of crop production (Bale et al., 2008; Alston, 2011).

Biocontrol predators are organisms that actively search for and consume pest species, often feeding on multiple prey individuals throughout their life cycle; many are generalists and can prey on a wide range of pest species, such as lady beetles (Coccinellidae) foraging on soft-bodied insects like aphids and whiteflies (Chandler, 2006).

By contrast, parasitoids are usually highly specialized insects – predominantly from the orders Hymenoptera and Diptera – that oviposit (lay eggs) on or within a single

host (Godfray, 1994). The larvae feed on host tissues and ultimately kill the host; for example, *Trichogramma* wasps attacking the eggs of lepidopteran pests such as the Fall Armyworm (*Spodoptera frugiperda*) (Navik et al., 2023). Owing to this intimate and obligate association, parasitoids tend to exhibit high host specificity and often target particular pest species or life stages of the pest host (Van Lenteren, 2012).

The third group, entomopathogens, consists of microorganisms – including bacteria, fungi, viruses, and nematodes – that infect and colonize pest tissues, causing disease and mortality (Vega & Kaya, 2012). A prominent example is *Bacillus thuringiensis* (Bt), a bacterium that produces crystalline (Cry) proteins (Bravo et al., 2007; Khan et al., 2016). When susceptible insect larvae ingest these toxins, the activated proteins bind to specific receptors in the midgut epithelium, forming pores in the gut lining. This disruption causes gut paralysis, allowing septicemia to develop, which ultimately leads to the death of the insect (Tomar & Yadav, 2024).

There are three main approaches to biological control: classical, augmentative, and conservation, which differ in where the natural enemy originates and how often it is released (Alston, 2011). In classical biological control, natural enemies are sourced from the pest's native range and introduced into regions where the pest has invaded without its natural predators (Dent & Binks, 2020). Because this involves releasing non-native species, it requires strict regulatory oversight (Hoddle et al., 2015).

Augmentative biological control relies on the deliberate mass rearing and release of natural enemies to supplement existing populations when natural levels are insufficient for effective suppression (Hajek, 2004; Van Lenteren, 2012). This can occur in two forms: inoculative releases, where relatively small numbers of agents are released early in the cropping season as a preventative measure, allowing them to establish and reproduce for long-term control; and inundative releases, where large numbers are released at once to achieve a rapid “knock-down” of high pest densities, functioning similarly to a biological pesticide (Parrella et al., 1992; Sivinski, 2013; Perez-Alvarez et al., 2019).

In contrast, conservation biological control focuses on modifying the environment or management practices to protect and enhance natural enemy populations that are already present, so that they can maintain pest densities below economic thresholds (Jahnke & Da Silva, 2021; Vargas et al., 2023). This typically involves habitat management, such as planting floral strips or hedgerows, providing refuges, and reducing or carefully selecting pesticide applications – to improve the survival,

reproduction, and overall effectiveness of beneficial organisms over the long term (Settele & Settle, 2018; Girling et al., 2022).

The success of biological control as a standalone tactic is often constrained by a complex interplay of biotic and abiotic factors, including the biology, fitness, and field performance of the natural enemy, characteristics of the target pest, local environmental conditions, farm management practices, and interactions such as intraguild predation and climatic variability (e.g., temperature and humidity) (Nicot et al., 2012). Because these factors can limit both the reliability and the speed of pest suppression, biological control is generally most effective when embedded within a robust Integrated Pest Management (IPM) framework rather than used in isolation (Nicot et al., 2012; EPA, 2023).

Integrating biocontrol with complementary tactics, such as cultural practices (intercropping, crop rotation, sanitation, habitat management), and judicious use of selective pesticides that are compatible with natural enemies (biopesticides), creates a synergistic environment that supports natural enemy persistence, reduces pest colonization, and enhances both immediate pest reduction and long-term agroecological sustainability (Bale et al., 2008; Pocius & Kersch-Becker, 2024).

3.5 Semiochemicals in Pest Management: Mode of Action and Applications

Semiochemicals are chemical compounds that organisms use to communicate, triggering behavioural responses such as mate finding, aggregation, or alarm signalling in the receiver (Abd El-Ghany, 2019). They are divided into two broad categories: pheromones, which operate within the same species, and allelochemicals, which act between different species (Petroski et al., 2005). In agroecosystems, these signals regulate key processes including host-plant selection, pest colonization, and the recruitment of natural enemies, making them directly relevant to biological pest management (Smart et al., 2014).

Pheromones operate within species and include sex pheromones for mate finding and aggregation pheromones that promote group formation (McNeil & Millar, 2012). Allelochemicals act between species: kairomones benefit the receiver, such as a parasitoid locating its host; allomones benefit the emitter through defensive or repellent compounds; and synomones benefit both parties, as when herbivore-damaged plants release volatiles that attract natural enemies (Brown et al., 1970; Nielsen et al., 2015). A further category, apneumones, are volatile signals from non-living sources such as decaying organic matter, which certain natural enemies use to locate prey or oviposition sites (Johansen et al., 2014; Bakthatvatsalam et al., 2022).

By exploiting these signalling pathways, semiochemicals provide a non-toxic, behaviour-modifying tool that aligns closely with the principles of Integrated Pest Management (IPM), enabling pest suppression, improved monitoring accuracy, and reduced reliance on broad-spectrum insecticides (Komala, Manda & Seram, 2021; Guerrero & Reddy, 2023).

Semiochemicals are deployed either as standalone tools or alongside biological and cultural methods within IPM. They are typically applied through controlled-release devices such as rubber septa, polymer matrices, vials or twist ties that release active compounds gradually into the field or greenhouse environment (Acácio et al., 2024). Their effectiveness depends on factors including the chemical formulation, dispenser release rate, planting density, and environmental conditions like temperature, wind, and solar radiation, all of which affect how long the signal lasts and how far it reaches (Hellmann et al., 2024).

Semiochemical-based pest control in IPM relies on three main strategies: attraction, mating disruption, and push-pull (Oliveira da Silva et al., 2016). Attraction-based methods use species-specific pheromones or host plant volatiles to lure insects to a target point. In mass trapping, insects are physically removed from the population, while attract-and-kill approaches, such as the SPLAT matrix, combine the lure with a lethal agent in a slow-release formulation to kill pests on contact (El-Shafie & Faleiro, 2017).

Mating disruption functions by saturating the agroecosystem with synthetic sex pheromones to impede the male's ability to locate a mate (Tabata, 2018). This occurs through mechanisms such as sensory adaptation, plume confusion, or false-trail following, effectively lowering the reproductive rate and the subsequent population density (Barclay & Judd, 1995; Rizvi et al., 2021).

Finally, the push-pull strategy (stimulo-deterrent diversion) employs a dual-action mechanism; it integrates repellent or masking cues to 'push' pests away from the primary crop while simultaneously utilizing attractive semiochemicals or trap crops to 'pull' them toward alternative locations (Cook et al., 2007). This site-specific manipulation concentrates the pest population into a defined area, enabling more efficient monitoring and allowing control measures to be applied in a highly targeted manner (Eigenbrode et al., 2016).

In addition to their direct behavioural effects, semiochemicals provide valuable indirect benefits by supporting monitoring and decision-making. Pheromone-baited traps are utilized to track pest population dynamics, seasonal activity patterns, and flight activity (Smart et al., 2014). The resulting monitoring data allow interventions such as the release of biological control agents or other IPM measures to be precisely timed in relation to the Economic Threshold, thereby improving

control efficacy while enhancing both the economic and ecological sustainability of the management programme (Bakthatvatsalam et al., 2022).

3.6 Synergistic Effects: Integrating Semiochemicals and Biological Control

3.6.1 Multitrophic and Environmental Factors Influencing Semiochemical Efficacy

Semiochemical-based strategies hold strong promise for IPM, but their implementation in open-field and greenhouse systems is highly context-dependent and far from straightforward. The performance of integrated semiochemical-biocontrol systems is shaped by a complex web of environmental, mechanical and biological variables, and the same combination can yield synergistic, neutral or even antagonistic outcomes depending on context (Pickett et al., 1989; Simpson et al., 2012). Abiotic factors such as temperature, relative humidity and solar radiation shape how semiochemicals evaporate, degrade and disperse, whereas the design of dispensers and their release rates control whether their concentrations remain high enough to elicit behavioural responses in target organisms (Oliveira da Silva et al., 2016; Mauchline et al., 2018; Mafra-Neto et al., 2026).

Biotically, outcomes are moulded by the identity and density of pest and non-target insect populations, host-plant genetics, and the composition and functional roles of natural enemies in the system, among other factors. Rather than functioning as simple, linear plant–herbivore–natural enemy chains (tritrophic networks), these systems behave as multitrophic networks in which chemical signals are constantly modified, masked or amplified by background environmental ‘noise’ and non-target organisms (Dicke & Takken, 2006; Gross, 2016; Thomas & Tabanca, 2025).

3.6.2 Mechanisms of Integration: Behavioural Manipulation, Spatial Architecture and Co-Formulations with Entomopathogens

Semiochemicals can be combined with biological control agents through both direct and indirect behavioural manipulation. Direct approaches involve using attractant semiochemicals to modify the behaviour of released natural enemies, increasing their retention within crops and improving their ability to locate and suppress target pests (Peñaflor, 2019). Indirect strategies include the use of herbivore-induced plant volatiles (HIPVs) as synomones to mimic crop distress and recruit foraging predators or parasitoids to infested plants, as well as “pheromone eavesdropping,” where natural enemies exploit pest aggregation or alarm pheromones to locate prey or hosts (kairomones). These mechanisms enhance the probability that natural enemies encounter their targets at the right time and place, thereby improving the

efficiency of biological control (Cabello et al., 2017; Peñaflor, 2019; Gaffke et al., 2021).

Beyond simple long-range attraction, semiochemicals can be arranged to manipulate the spatial distribution of pests and natural enemies. In modified push-pull systems, synthetic repellent (“push”) cues drive pests away from the main crop, while synthetic attractant (“pull”) cues draw them towards trap areas, reducing reliance on traditional intercrops or trap crops alone. Attract-and-reward strategies, on the other hand, use semiochemicals to attract natural enemies into the crop and floral strips or other nectar sources to retain them by providing carbohydrates (Greenstone & Dickens, 2005; Simpson et al., 2011; Cabello et al., 2017).

A critical limitation of this approach is that floral supplements cannot fully substitute for prey-derived nutrients required for egg formation and larval development, so low prey density remains a structural bottleneck for long-term retention. To mitigate this, recent studies have evaluated the use of synthetic natural enemy-derived semiochemicals (e.g. predator or parasitoid aggregation cues) to recruit and sustain beneficial populations when pest densities are low, effectively “pre-positioning” natural enemies ahead of outbreaks. Non-host plant volatiles also contribute to this design space: their profiles can both mask host crop odours from pests and serve as attractive cues for parasitoids, expanding options for companion planting and trap-crop design (Usha Rani, 2014; Sharma et al., 2019).

Co-formulations of semiochemicals with entomopathogens represent an expanding area in IPM (Sharma et al., 2019). In some systems, macerates from entomopathogenic-nematode-infected cadavers, when combined with infective juveniles of entomopathogenic nematodes, have been shown to enhance nematode activity and directional movement relative to nematodes applied alone (Wu et al., 2018). Similarly, integrating pest sex or aggregation pheromones with entomopathogenic fungi (e.g. *Metarhizium* spp., *Beauveria* spp.) supports auto-dissemination strategies, in which pheromone-baited devices contaminate visiting insects with fungal spores; the infected individuals then return to the wild population and transmit the pathogen between individuals during mating or aggregation (Gogi et al., 2024).

Certain phytopathogenic or opportunistic fungi can also alter the volatile compounds emitted by plants. These induced HIPVs may attract insect vectors, thereby facilitating pathogen spread, while simultaneously attracting primary parasitoids. As a result, fungal-induced changes in plant volatiles can influence both disease transmission and biological control (Martini et al., 2014; Jagodič et al., 2019; Shapiro-Ilan et al., 2019; Hummadi et al., 2021; Li et al., 2024).

3.6.3 Semiochemical Blends, Design Constraints and Genomic Perspectives for Future IPM

Successful deployment of semiochemical mixtures requires careful attention to chemical specificity. Slight changes in blend composition or stereochemical ratios can invert behavioural responses, turning a strong attractant into a neutral stimulus or repellent for pests or natural enemies. Some kairomones and HIPVs exhibit dual-attraction properties, simultaneously attracting both target pests and their natural enemies; while potentially useful, this overlap requires precise spatial and temporal targeting to avoid drawing pests into previously uninfested crop zones. These constraints highlight the need for careful tuning of concentrations, ratios, deployment patterns and timing, as well as compatibility with other IPM components (Zhang & Schlyter, 2010; Ayelo et al., 2021; Gaffke et al., 2021; Morrison et al., 2021).

Looking ahead, a promising direction for strengthening semiochemical-biocontrol integrations lies in functional genomics and chemical ecology. Researching the genes and biosynthetic pathways that regulate semiochemical production, release and perception in both plants and insects could enable the breeding of cultivars with optimized volatile profiles and the design of exact synthetic lures tailored to specific natural enemies or pest guilds. Such advances would support the development of more robust, climate-resilient and context-adapted semiochemical-biocontrol strategies for sustainable pest management (Colebatch et al., 2002; van Straalen & Feder, 2012; Kelly et al., 2014; Gaffke et al., 2021; Kansman et al., 2023).

3.7 Regulatory Framework for Pesticides in Tanzania

The registration and regulation of pesticides, including biopesticides, biological control agents, and semiochemicals in Tanzania is overseen by the Tanzania Plant Health and Pesticides Authority (TPHPA) under the Plant Health Act No. 4 of 2020 and the Plant Health Regulations of 2023 (EAC, 2019; Mawcha et al., 2025). Within the broader East African Community (EAC) framework, Tanzania's Plant Health Regulations of 2023 provide for the use of regional harmonized guidelines in relevant bio-efficacy trials and data-sharing processes. These include the EAC Harmonized Guidelines for the Registration of Biopesticides and Biocontrol Agents for Plant Protection and the EAC Regional Guidelines for Evaluating and Reporting the Efficacy of Pest Control Products for Plants (EAC, 2019; Mawcha et al., 2025).

This regulatory design requires applicants to submit a comprehensive technical dossier for product registration, including detailed information on product chemistry, environmental fate, ecotoxicology, human safety, and bio-efficacy based on at least two seasons of locally conducted efficacy trials. The limited availability of such locally generated, data-intensive dossiers is widely

acknowledged as a major bottleneck to the commercialization of new, low-risk, behaviour-modifying pest control products in the region (Malek et al., 2026).

Recognizing that the pervasive use of synthetic pesticides, including those classified as highly hazardous conventional pesticides (HHPs), has compromised crop quality, contributed to environmental degradation and posed significant health risks for farming communities, EAC Partner States initiated a coordinated regional process to promote safer alternatives (Kapeleka et al., 2025). With technical support from international organizations, including the Food and Agriculture Organization of the United Nations (FAO), regional experts and national regulatory authorities collaborated to begin the domestication of the EAC Harmonized Guidelines.

The EAC Harmonized Guidelines for the Registration of Biopesticides and Biocontrol Agents for Plant Protection, define data requirements and evaluation criteria for microbial, botanical, semiochemical and macrobial products. They also align with the EAC Regional Guidelines for Evaluating and Reporting the Efficacy of Pest Control Products for Plants, which standardize trial design, conduct, and reporting formats across diverse cropping systems (EAC, 2019; Mawcha et al., 2025). Together, these instruments provide a consolidated, legally grounded regulatory pathway intended to streamline product registration, facilitate mutual recognition of data and decisions, and support the integration of safer, bio-based and semiochemical tools into sustainable IPM programmes throughout East Africa.

In practice, however, these instruments have yet to be fully translated into enforceable national procedures, as most EAC Partner States, including Tanzania, have not yet fully operationalized the guidelines. Biological products consequently continue to be registered and assessed under procedures designed for synthetic pesticides, a mismatch that raises costs and delays market entry. The resulting gap between regulation as designed and regulation as implemented constitutes a significant constraint in itself on the availability of biological alternatives (Mawcha et al., 2025; ICGEB, 2025; Alwora et al., 2026).

3.8 Socio-economic Factors Influencing Adoption of IPM/Biological Alternatives

Despite strong global policy support for IPM and its well-documented environmental and health benefits, adoption on the ground remains limited in many low-and-middle-income countries, including those in Sub-Saharan Africa, revealing a persistent disconnect between high-level promotion and field-level implementation. On-the-ground adoption rates among smallholder producers remain low in these countries (Bajwa & Kogan, 2003; Bergvinson, 2004; Alwang et al., 2019; Cherotich & Mireri, 2025).

Empirical studies show that smallholders often rely on synthetic pesticides despite awareness of some pesticide-exposure risks. This reliance is shaped by economic constraints, limited extension support, and gaps between safety knowledge and practice (Ngowi et al., 2007; Lekei et al., 2014). Barriers to adopting biological alternatives include perceptions that they act more slowly or are less effective than synthetic pesticides, limited farmer and advisor knowledge, weak local availability through agro-dealer networks, and affordability constraints (Constantine et al., 2020; Mulugeta et al., 2024; Russo et al., 2025).

Beyond localized farm economics, adoption is further shaped by broader context-specific factors, such as regional geopolitical conditions, local market structures, and the strength of public extension and training systems. A primary institutional bottleneck is the lack of government support, tailored extension training, and input subsidies to shoulder the high upfront costs of biological innovations. Without these institutional incentives to level the economic playing field against relatively cheap, heavily marketed synthetic inputs, smallholders face prohibitive financial risks when transitioning to IPM (Maumbe et al., 2003; Brewer et al., 2004; Bailey et al., 2010:131–147; Brewer & Goodell, 2012; Rejesus & Jones, 2020).

Furthermore, agricultural technology dissemination is heavily dependent on social processes like peer learning and trust in information sources. Smallholder farmers are highly risk-averse and naturally rely on empirical, visible validation before altering their management habits. Farmers are significantly more willing to adopt new practices when they can directly observe treatment effects in localized on-farm field demonstrations, and when these recommendations are reinforced through word-of-mouth communication from neighbouring farmers or trusted local leaders (Bonabana-Wabbi, 2002; Eichhorn et al., 2026). In the absence of such visible evidence, active demonstration plots, and social proof, IPM and biological alternatives continually struggle to gain a firm foothold or displace conventional chemical dependencies (Hammond et al., 2006; Wyckhuys & O’Neil, 2007; Gott & Coyle, 2019; Samuel & Liburd, 2022; Creissen & Meador, 2024).

Although the agro-ecological performance of individual biological alternatives is increasingly documented (Calvo et al., 2012; Zekeya et al., 2022), an acute disconnect remains in connecting these innovations to the socioeconomic realities of smallholder producers in sub-Saharan Africa. In East African and comparable African tomato production systems, farmers’ decisions are shaped by severe capital constraints, localized labour demands and unstable market access, all of which influence the practicality of adopting new pest management technologies (Musebe et al., 2014; Kihoro et al., 2021; Kirui et al., 2023; Charles, 2025; Tham-Agyekum et al., 2025).

This challenge is evident in a study conducted in the Ruaha River Basin of Iringa, Tanzania, in which 97.7% of interviewed tomato farmers reported awareness of *Tuta absoluta* and its impacts, and 86.7% relied on synthetic pesticides as their main control method. The commercial varieties tested proved more susceptible to infestation than the local landrace, and the majority of farmers who resorted to mixing pesticides reported that this was ineffective. More importantly, while 11% of respondents were aware of pheromone traps, 88.8% reported no awareness of any alternative control strategy against the pest (Kombe et al., 2022). Overall, awareness of the pest is high, but awareness of alternative management options is low.

Taken together, these findings highlight that promoting *Tuta absoluta* IPM in smallholder systems requires not only quantifying the biological effectiveness of semiochemicals and natural enemies but also understanding how farmers perceive and relate to these alternatives – including their awareness, views on effectiveness, and the conditions required for adoption (Rwomushana et al., 2019; Chepchirchir et al., 2021; Desneux et al., 2022; Basit et al., 2025; Tito et al., 2025).

This study differs from Kombe et al. (2022) in that, while Kombe et al. examined farmers' awareness of *Tuta absoluta* and its management and evaluated pheromone-trap performance in the Ruaha River Basin, the present study focuses on farmers' awareness and perceptions of biological alternatives, particularly semiochemicals and natural enemies, and the conditions influencing their willingness to adopt them. It examines perceived effectiveness, affordability, accessibility and health and environmental considerations, supplemented by agro-dealer interviews providing context on local product availability.

4. Methodology

4.1 Location of study

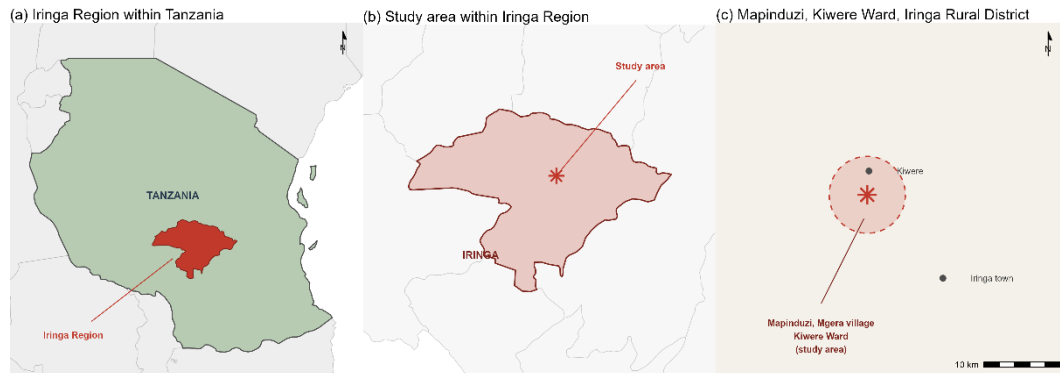


Figure 4.1. Location of the Study Area: (a) Iringa Region Within Tanzania; (b) The Study Area Within Iringa Region; (c) Mapinduzi, Mgera Village, Kiwera Ward, Iringa Rural District. Boundaries from Natural Earth.

The study was conducted in one major tomato-producing region of Tanzania: Iringa, specifically Mapinduzi in the Mgera locality, Kiwera Ward, Iringa Rural District (Figure 4.1). The wider Iringa region is characterised by diverse altitudes, from mid-altitude to highland areas, and varying climatic conditions that influence *Tuta absoluta* pressure and pest population dynamics. It also presents distinct pest management challenges and diverse farmer experiences with *T. absoluta* control, making it a suitable setting for a socio-behavioural and economic baseline survey.

The present study was conducted within a single village in this zone. The shaded extent in Figure 4.1c is indicative rather than exact. Because smallholders face intense, climate-variable pest pressures and have differing histories of reliance on conventional synthetic pesticides, this site provided a suitable socio-economic context in which to investigate current farming practices, baseline awareness of biological alternatives, and local perceptions of their safety, cost and perceived efficacy.

Studying this location, therefore, enabled the collection of empirical, field-level data on the practical and financial realities of smallholder tomato producers. These data provide essential evidence for assessing whether integrated semiochemical and biocontrol strategies would be socially adoptable and economically viable within Tanzanian tomato production systems, in light of regional evidence on *T. absoluta* impacts and farmer responses. (Rwomushana et al., 2019; Zekeya, 2019; Chepchirchir et al., 2021). It is noteworthy that the same locality had previously hosted a semiochemical-based attract-and-kill field demonstration against *Tuta*

absoluta. Although the results of that trial are not yet published, its execution confirms that such technologies are already being tested in this context rather than being purely hypothetical.

4.2 Sampling Strategy and Validation of Proxy Respondents (Observers)

Due to a highly constrained regional sample size ($N = 26$), four respondents who did not actively cultivate tomatoes were retained in the study as proxy observers. These individuals primarily grew other crops but farmed within the same agro-ecological zone and were closely engaged with the local tomato-growing community, making their testimonies potentially informative. To verify that their responses did not differ meaningfully from those of the active tomato farmers ($n = 22$), comparative non-parametric statistical tests were applied: baseline continuous demographic characteristics were evaluated using Kruskal-Wallis rank sum tests, while categorical response profiles were tested via Fisher's exact test.

Statistical testing showed no significant differences between active tomato farmers and proxy observers across the baseline characteristics assessed ($p > 0.05$), indicating that both groups shared comparable regional knowledge, operational challenges, and perceptions. Specifically, Kruskal-Wallis tests found no significant differences in biological age ($\chi^2 = 0.4112$, $df = 1$, $p = 0.5214$) or years of general farming experience ($\chi^2 = 0.0223$, $df = 1$, $p = 0.8813$), while Fisher's exact tests indicated no significant association between respondent type (active farmer vs. proxy observer) and either formal education level ($p = 0.0987$) or prior awareness of biological pest-control alternatives ($p = 0.5633$).

Two additional distinctions emerged in supplementary analyses (Appendix 1): proxy observers reported slightly higher environmental-risk perceptions, and both female respondents in the sample were proxy observers, meaning that their exclusion would have resulted in an entirely male dataset. Overall, the non-parametric results presented in Appendix 1 confirm that the two subgroups were sufficiently homogeneous to justify pooled analysis.

As a further check, a sensitivity analysis was conducted using only the 22 active tomato farmers. All main conclusions remained unchanged. For example, the correlation between health-risk perception and willingness to adopt IPM stayed strongly negative ($\rho = -0.66$, $p < 0.001$), closely matching the pooled estimate of $\rho = -0.70$. On this basis, the two groups were pooled into a single, unified dataset for subsequent analyses while acknowledging differences between the groups.

4.3 Data Collection and Research Design

Because Swahili was the primary language of the farming community, bilingual interpreters translated questions from English into Swahili and farmers' responses back into English in real time during each interview. Responses were recorded directly onto the survey instrument by the researcher.

A pretest was conducted with 6 respondents before the main interviews, focusing on the clarity and accuracy of the Swahili translation. Minor wording adjustments were made; as the substantive content of the questions was unchanged, pretest responses were retained in the final dataset ($N = 26$). A total of 26 respondents were interviewed, comprising 22 active tomato cultivators and 4 proxy observers farming in the same agro-ecological zone. The sample was predominantly male (24 of 26 respondents), reflecting cultural dynamics in which men typically represent households in public forums; Section 7.2 discusses the challenges and implications of this gender imbalance.

The data collection instrument combined structured survey questions (closed-ended questions using Likert scales and categorical responses) with open-ended interview prompts (a semi-structured approach, using predetermined questions to guide the conversation while allowing respondents to explain their answers or introduce new topics). It therefore served simultaneously as both a quantitative survey instrument and a qualitative interview guide, consistent with a mixed-methods approach. The instrument is provided in Appendix 2. For interpreting the ranking factors, "knowledge" refers to farmers' existing awareness and understanding of biological alternatives, while "training" refers to access to instruction and practical guidance on how to use them.

The introductory text was used for interviewer orientation; the consent statement was read aloud to each participant, and questions were posed flexibly through an interpreter. This approach allowed respondents to express their perceptions, explain the factors influencing their pest management decisions and discuss the considerations shaping those choices, rather than being limited to fixed response categories.

Drawing on adoption literature, the analytical framework is structured around four dimensions that correspond to the study's research questions: (1) awareness and knowledge of biological alternatives, (2) perceived agronomic benefits compared with synthetic pesticides, (3) feasibility of adoption, including affordability, accessibility, and perceived effectiveness, and (4) the socio-economic and perception-related factors influencing willingness to adopt. These dimensions are well-supported in adoption literature (Rogers, 2003; Feder et al., 1985; Kassie et al., 2015) and provided the lens for assessing whether integrated semiochemical

and biocontrol innovations are viable, practical, and sustainable within smallholder production systems.

Given the unpredictable daily schedules typical of smallholder households, participants were recruited using convenience sampling, whereby individuals within the target community were invited to participate based on their availability and willingness to share their experiences. To promote respondent comfort and support open, candid dialogue, all interviews were conducted in informal, open-air field settings that reflected farmers' natural working environments.

4.4 Supplementary Agro-Dealer Interviews

To provide supply-side context for farmers' reported access to biological pest-management products, this study draws on semi-structured interviews conducted with 20 agro-dealers in Iringa Town, within Iringa Municipality, which had a population of 202,490 in the 2022 census (National Bureau of Statistics, 2022). These interviews formed part of a parallel MSc study led by a fellow researcher, who designed the protocol and conducted 10 of the interviews; the author conducted the remaining 10. Findings are used here with permission (Manda, unpublished data, 2026).

Agro-dealers were asked about their knowledge of and training in biological control, their familiarity with the Plant Health Act and TPHPA registration requirements, and, where applicable, the proportion of their inventory comprising biological products and the advice they typically provide to farmers. Unlike the farmer survey, these interviews differed in both scope and structure and were not intended to constitute a representative survey of agro-dealers. Rather, they provided contextual evidence that complemented the farmer survey by illustrating the availability, awareness, and promotion of biological alternatives within local agricultural input markets.

4.5 Data Analysis

Responses were recorded directly onto the printed survey instrument during each of the 26 interviews. Completed instruments were subsequently copied into a structured Google Form to standardize question flow and minimise transcription inconsistencies, and the resulting dataset was exported as a Microsoft Excel spreadsheet. All quantitative analysis was conducted in R version 4.4.2 (R Core Team, 2024) on a Windows x86_64 platform.

Data were imported using `readxl` v1.4.5, with column names standardized using `janitor` v2.2.1. Data cleaning, recoding, and manipulation were performed using `dplyr` v1.2.1 and the wider `tidyverse` suite (Wickham et al., 2019). Figures were

generated with `ggplot2` v4.0.3 (Wickham, 2016), with multi-panel layouts assembled using `patchwork` and `cowplot` v1.2.0. Correlation matrices were computed and visualized using `Hmisc` and `corrplot`.

The study-area map was produced using `sf` v1.1.0 (Pebesma, 2018) and `ggspatial` v1.1.10, with boundary data sourced from `naturalearth`. Ordinal responses were numerically recoded before analysis: willingness variables were coded No = 0, Maybe = 1, Yes = 2; five-point Likert items were coded 1 (strongly disagree) to 5 (strongly agree); and education level was coded 1 (none) to 4 (college/university). Risk-influence ratings were retained on their original 1–5 scale.

Given that the dataset consisted predominantly of ordinal and categorical variables from a small sample ($N = 26$), non-parametric procedures were used throughout. Associations between socio-economic characteristics, risk perceptions, and adoption intentions were examined using Spearman rank correlations. Differences between respondent subgroups were tested using the Kruskal-Wallis rank-sum test for ordinal and continuous variables and Fisher's exact test for categorical variables, with the Wilcoxon rank-sum test applied for two-group comparisons of continuous variables. Statistical significance was assessed at $\alpha = 0.05$.

Qualitative material from the open-ended interview questions was analyzed using thematic analysis to identify recurring patterns and viewpoints across respondents. Themes were derived inductively from the interview notes and used to contextualize and deepen interpretation of the quantitative findings, following established thematic-analysis procedures (Braun & Clarke, 2006).

Rather than categorizing responses, this approach allowed close attention to farmers' narratives, helping to reveal the barriers that create hesitation and the factors that encourage change. By tracing these recurring themes, the analysis aimed to capture the practical realities, values and everyday reasoning that shape how smallholder communities decide whether to adopt new agricultural tools.

4.6 Ethical considerations

Before each interview, a formal consent statement was read aloud to every participant to ensure they clearly understood the purpose of the study and the voluntary nature of their involvement. Participants were explicitly informed of their right to skip any question, pause the interview or withdraw from the study at any time without any negative consequences. Interviews proceeded only after respondents provided written informed consent. Beyond securing informed consent and maintaining confidentiality, the study posed no major ethical risks to participants, as it focused exclusively on farming practices and perceptions.

Reliability was addressed through both qualitative trustworthiness criteria and standard quantitative checks. Baseline similarity between respondent subgroups was verified statistically before pooling (see Chapter 5 and Appendix 1), and the consistency of the Swahili translation was assessed through a pretest of the survey instrument. Study limitations affecting reliability, transferability and broader applicability are discussed in Section 7.2.

4.7 Study scope

This study focuses on smallholder tomato farmers in Mapinduzi village, Iringa Rural District, Tanzania, including four proxy observers retained in the pooled sample (see Appendix 1). It examines farmers' awareness, perceptions, perceived feasibility assessments, and willingness to adopt biological alternatives as a complement to synthetic pesticides, with particular attention to semiochemicals and natural enemies for *Tuta absoluta* management. The study assesses farmer perspectives and feasibility but does not experimentally measure the agronomic efficacy of these technologies. The findings describe the study population and context and should not be generalized to all Tanzanian tomato farmers.

5. Results

5.1 Demographic Profile of Respondents

The sampled population represented a varied cross-section of smallholder tomato producers in Mapinduzi village, located in the Mgera locality of the Iringa region. Of the 26 participating farmers, the sample was heavily dominated by men (24 respondents; 92.3%), with only 2 women (7.7%) represented; both female respondents were proxy observers rather than active tomato cultivators. Respondents' ages ranged from 20 to 66 years, with a median of 31. Production scales were modest, with a median of 3 acres per household devoted to tomato cultivation (range 0.5–23 acres).

Educational backgrounds were largely limited to foundational schooling. The majority of respondents (22 farmers; 84.6%) had completed primary school as their highest level of formal education, while the remaining 4 farmers (15.4%) had attained secondary education. Agricultural experience was considered along two dimensions: general lifetime farming and specialized tomato cultivation. General farming experience varied widely (median 9.5 years, range 1.5–50), whereas specialized tomato experience was considerably lower (median 3 years, range 1–45). This difference indicates that while respondents are generally experienced farmers, most are relatively new to tomato cultivation specifically, with half of them having three years' experience or less. A comprehensive breakdown is presented in Table 5.1. A graphical summary of the sample's demographic profile is provided in Appendix 1.

Table 5.1: Demographic Summary of Survey Respondents in Mapinduzi Village (N=26)

Demographic Variable	Classification	Frequency (n)	Percentage (%)
Gender	Male	24	92.3%
	Female	2	7.7%
Age	Range	20–66	—
	Median	31	—
Education level	Primary School	22	84.6%
	Secondary School	4	15.4%
Tomato Land Allocation (acres)	Range	0.5–23	—
	Median	3	—

General Farming	Range	1.5–50	–
Experience (years)	Median	9.5	–
Specialized Tomato	Range	1–45	–
Experience (years)	Median	3	–

Note: Medians and ranges are reported for continuous variables. One “over 30 years” response was standardized to 31.

5.2 Current Pest Management Practices

All 26 respondents relied on synthetic pesticides as their primary pest-management strategy. All reported using insecticides (100%), while 21 (80.8%) also reported using fungicides and seven (26.9%) herbicides. Respondents could report more than one pesticide type. Three farmers additionally reported observing naturally occurring biological agents (ants and birds) or using a locally available input (rabbit urine) that appeared to reduce pest pressure, although none had used commercial biological products. Table 5.2 summarizes their pesticide application schedules.

The results reveal intensive reliance on synthetic pesticides, with half of the respondents (50.0%, $n = 13$) applying them on a strict weekly schedule. When combined with those spraying two to three times per week, 88.5% of farmers applied synthetic pesticides at least once weekly. Only a small minority reported flexible or condition-dependent application schedules, such as adjusting treatments in response to weather conditions or, in one case, limited farming experience. Overall, these findings suggest that pesticide application has become a routine preventative practice rather than a threshold-based response to pest infestation.

Table 5.2: Synthetic Pesticide Application Frequency Among Surveyed Tomato Farmers (N=26).

Application Frequency	Number of Farmers (n)	Relative Proportion (%)
Weekly	13	50.0%
Twice per week	7	26.9%
Thrice a week	3	11.5%
I am not sure as I just started	1	3.8%
For single application (weekly), for systemic	1	3.8%

application (twice a week)		
Bad weather (weekly), good weather (once every two weeks)	1	3.8%
Total Sample Population	26	100.0%

5.2.1 Challenges Associated with Synthetic Pesticide Use

The dominant challenges farmers reported with synthetic pesticides were insufficient knowledge of correct use and dosage, and a lack of PPE, each cited by 6 respondents (23.1%) (Figure 5.1).

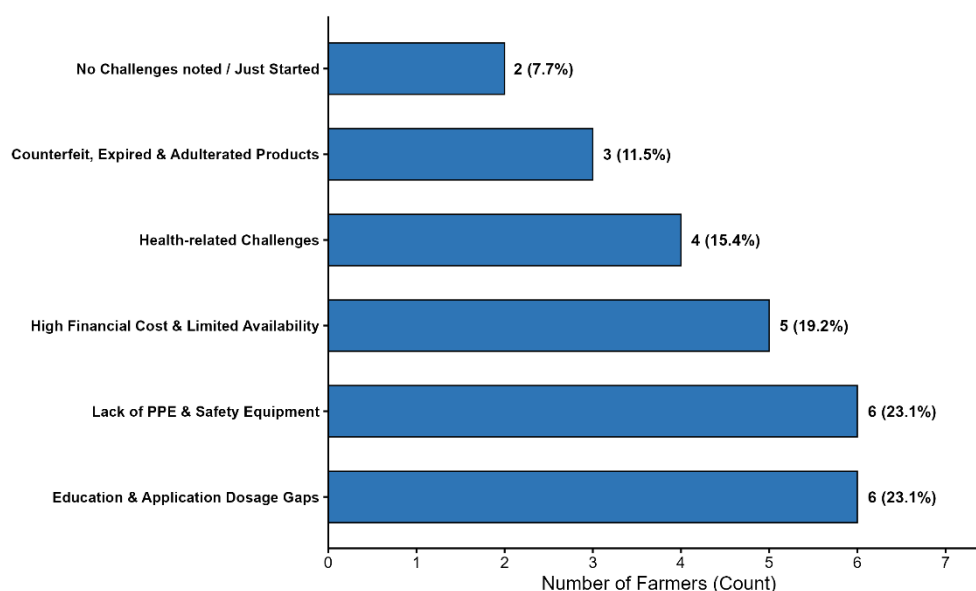


Figure 5.1. Primary Challenges Encountered by Farmers in Synthetic Pesticide Application (N=26).

Five farmers (19.2%) identified the high cost of chemicals and limited PPE availability, and 4 (15.4%) reported health effects such as irritation during or after spraying. Interview data further revealed that farmers experienced pesticide ineffectiveness, which led them to mix different products in an attempt to improve performance – a practice not captured in the structured survey categories. Farmers also described coping behaviours such as drinking milk, bathing immediately after spraying, or consuming large amounts of water to counteract the perceived toxicity of synthetic pesticides. Although crop damage (leaf burn, withering, and plant death after spraying) was not captured in the survey, these effects were repeatedly

mentioned during interviews and further illustrate the negative experiences associated with synthetic pesticide use.

Only two respondents (7.7%) reported no challenges: one had recently started farming and had limited exposure to synthetic pesticide use, while the other stated that following product label instructions closely prevented most problems. Overall, the distribution shows that farmers face a combination of knowledge gaps, safety limitations, cost pressures, product quality issues, and inconsistent efficacy when relying on synthetic pesticides.

5.3 Farmer Awareness, Knowledge and Exposure to Biological Alternatives

5.3.1 Awareness of biological alternatives

A sharp decline in farmers' reported knowledge was evident as the measures shifted from general conceptual awareness to applied field skills (Table 5.3). Nearly a third of respondents (30.8%, $n = 8$) reported a baseline awareness of agricultural biological alternatives in a general sense, but this familiarity dropped to 19.2% ($n = 5$) for specific biocontrol tools such as semiochemicals and natural enemies. The gap was most pronounced at the functional field level, where only 11.5% ($n = 3$) possessed direct field-observation experience with natural enemies or the ability to distinguish beneficial insects from crop pests. These observations were incidental rather than the result of deliberate biological control practices. Among those unable to identify beneficial organisms, most explicitly reported a complete absence of knowledge or a need for structured training.

Table 5.3. Farmer Awareness, Field Observations, and Identification Skills Regarding Biological Alternatives (N=26).

Key Indicator	Aware (n, %)	Unaware (n, %)
General Biological Alternatives	8 (30.8%)	18 (69.2%)
Specific Tools (Semiochemicals & Natural Enemies)	5 (19.2%)	21 (80.8%)
Field Observations of Natural Enemies	3 (11.5%)	23 (88.5%)*
Pest vs. Beneficial Insect Identification	3 (11.5%)	23 (88.5%)*

*Includes 21 “No” and 2 “Not sure” responses.

^Includes 9 “Cannot distinguish”, 10 “No idea”, and 4 “Would need training” responses.

5.3.2 Sources of agricultural information

All 26 respondents reported frequent and severe *Tuta absoluta* infestations in their tomato fields, causing substantial agronomic and economic losses. None had received any training or extension guidance on conserving beneficial insects or other environmentally friendly approaches.

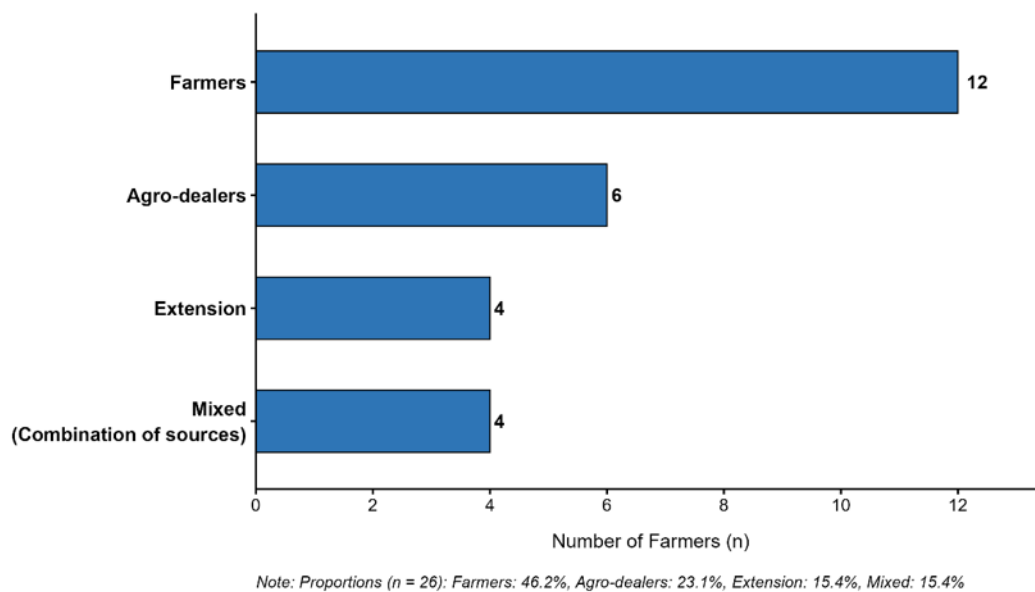


Figure 5.2. Primary Channels of Agricultural Advice and Information Among Surveyed Farmers (N=26).

The results summarize the main sources from which farmers obtain agricultural information (Figure 5.2). The distribution shows a clear reliance on informal, peer-to-peer networks: fellow farmers are the dominant information channel, accounting for 46.2% (n = 12) of respondents. Agro-dealers form the second most common source at 23.1% (n = 6), providing advice on pest-management inputs, although their recommendations may be influenced by the commercial products they stock. Formal extension services and mixed combinations of channels each represent 15.4% (n = 4).

5.3.3 Knowledge of natural enemies and biological control

The results reveal a clear gap in farmers’ familiarity with natural enemies in their tomato fields and in the training available to them (Figure 5.3).

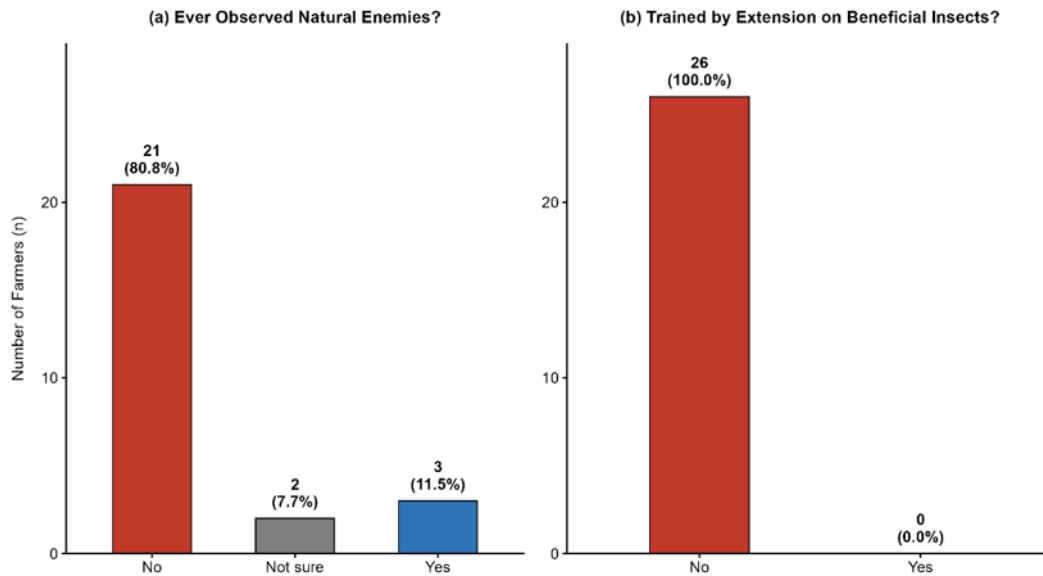


Figure 5.3. Dual-panel distribution of Farmers' Field Observation and Extension Training Regarding Natural Enemies and Beneficial Insects (N=26).

In the first panel, 80.8% (n = 21) reported never having observed natural enemies, while the rest were unsure (7.7%, n = 2) or believed they had (11.5%, n = 3). However, examination of their responses showed that only two respondents described encounters with natural enemies; the third referred to the use of rabbit urine. The second panel shows that all respondents (100%, n = 26) had never received any training on natural enemies from extension officers.

5.3.4 Awareness and Adoption Funnel

Farmers' engagement with biological alternatives narrowed sharply from universal pest exposure down to almost no uptake (Figure 5.4).

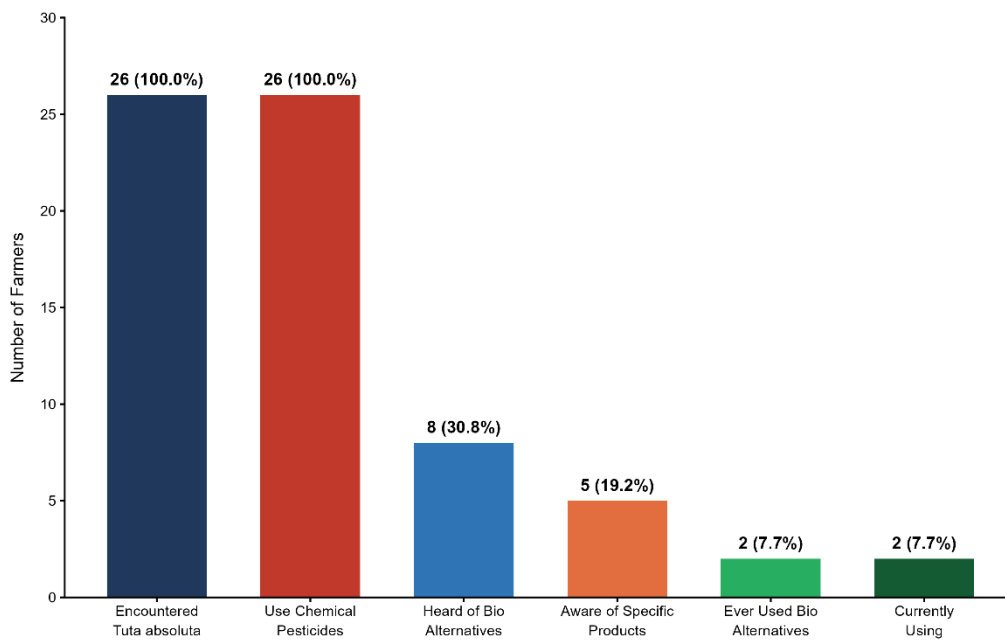


Figure 5.4. Awareness and Adoption Funnel of Bio-Alternatives Among Surveyed Farmers (N=26).

The first two tiers show a universal baseline: all 26 respondents had encountered *Tuta absoluta*, and all relied on synthetic pesticides as their primary control method. The funnel then narrows: only 30.8% (n = 8) had ever heard of biological alternatives, fewer could name specific products, and just 2 farmers (7.7%) had ever trialled or currently used any biological control option.

5.4 Adoption Willingness and Attitudes

5.4.1 Attitudes toward IPM integration

The horizontal stacked bar chart summarizes farmers' attitudes toward IPM and their willingness to adopt biological pest-management options under different conditions (Figure 5.5).

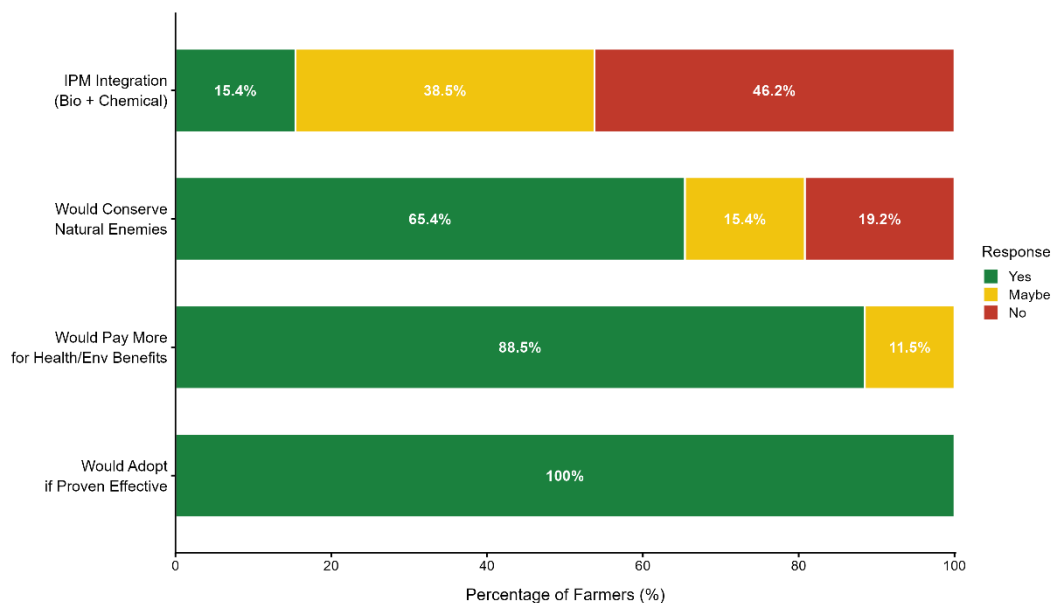


Figure 5.5. Attitudinal Responses and Future Intentions Toward Integrated Pest Management (IPM) and Biological Adoption Among Surveyed Farmers (N=26).

When asked whether they would integrate biological alternatives with synthetic pesticides in an IPM approach, only 15.4% of respondents agreed, 38.5% were unsure, and 46.2% rejected the idea. In contrast, attitudes toward conservation biocontrol were much more positive: 65.4% indicated they would conserve natural enemies of *Tuta absoluta* if these were shown to be effective. Economic willingness was even stronger, with 88.5% of farmers stating they would pay more for biological alternatives that offer clear health or environmental benefits, and the remaining 11.5% expressing neutrality. Most importantly, all respondents (100%) said they would adopt biological alternatives if their effectiveness in controlling *Tuta absoluta* were proven.

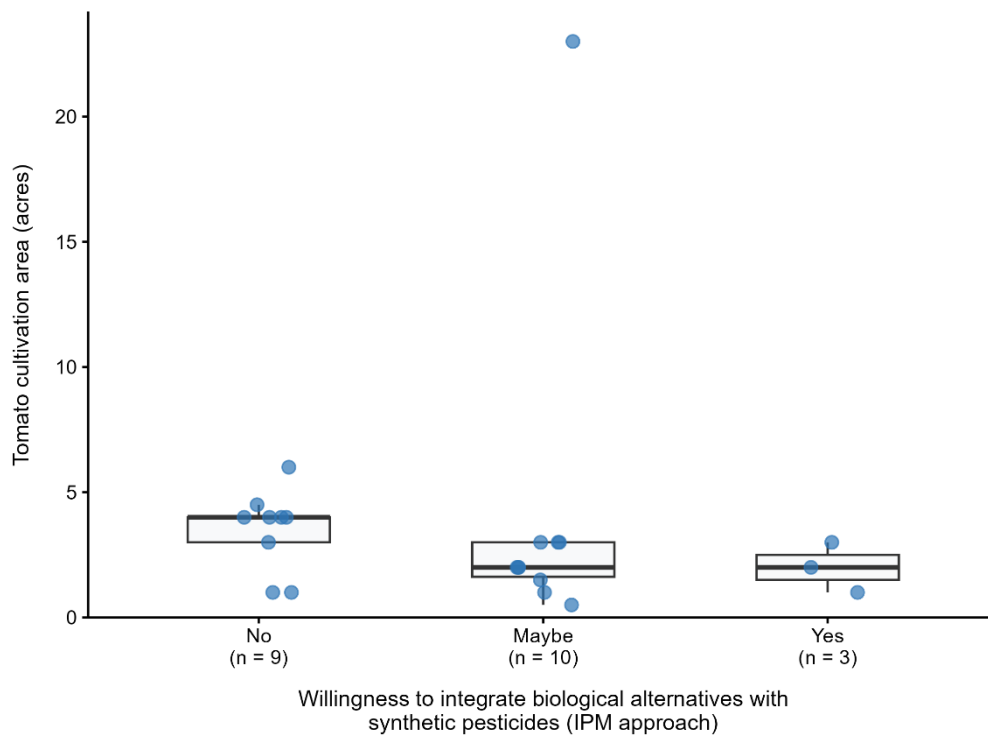


Figure 5.6. Boxplot Distribution of Tomato Cultivation Area Across IPM Adoption Interest Groups (n=22). The four proxy observers are excluded, as they reported no tomato cultivation area.

The boxplot compares tomato farm size across willingness to adopt IPM among the 22 active tomato cultivators (Figure 5.6). Median farm sizes were 4 acres in the “No” group (n = 9) and 2 acres in both the “Maybe” (n = 10) and “Yes” (n = 3) groups. The “Maybe” group showed the widest spread, including the smallest holding (0.5 acres) and the largest outlier (23 acres). Although median farm sizes differed, the association between farm size and IPM willingness was not statistically significant.

5.5 Perceptions and Feasibility of Biological Alternatives

5.5.1 Perceived risks and benefits

The horizontal distribution illustrated below summarizes farmers’ perceptions of financial, health, and environmental risks in relation to adopting biological alternatives (Figure 5.7).

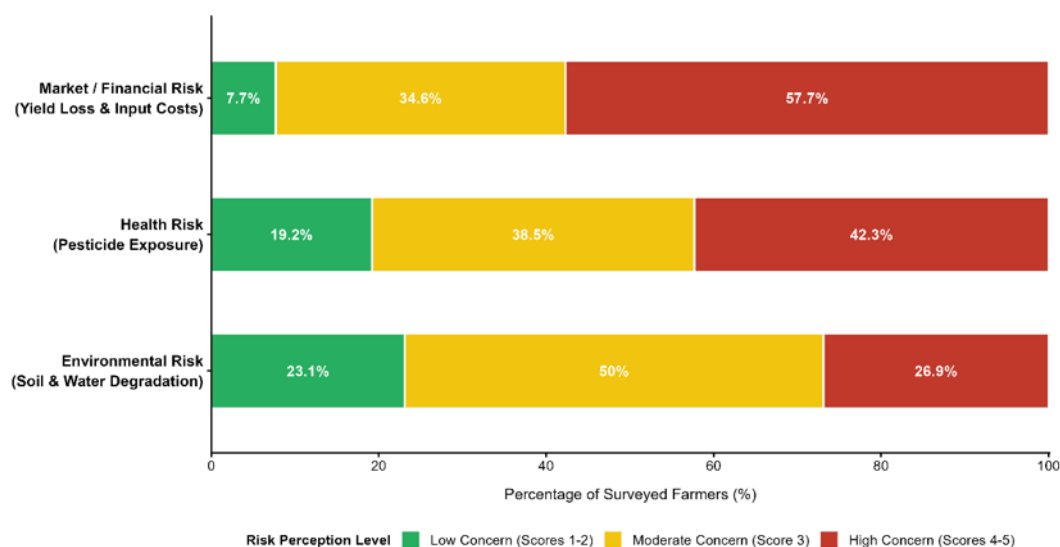


Figure 5.7. Reported Influence of Financial Considerations, Health and Environmental Risks on Farmers' Decisions to Adopt Biological Alternatives (N=26).

Financial risk emerged as the strongest perceived barrier to technology adoption, with 57.7% of respondents expressing great concern about potential yield losses and input costs. Health risk was also highly influential, as 42.3% reported great concern regarding the personal safety implications of continued synthetic pesticide exposure. In contrast, environmental risk had the weakest influence on immediate decision-making: exactly half of the farmers (50.0%) reported only moderate concern about issues such as soil and water degradation, while the strongest concern category was the lowest at 26.9%.

5.5.2 Ability to evaluate biological alternatives

This chart summarizes farmers' comparative evaluations of biological alternatives and synthetic pesticides across four dimensions, rated from "much worse" to "much better," with a distinct "no idea" option for respondents lacking any basis for comparison (Figure 5.8).

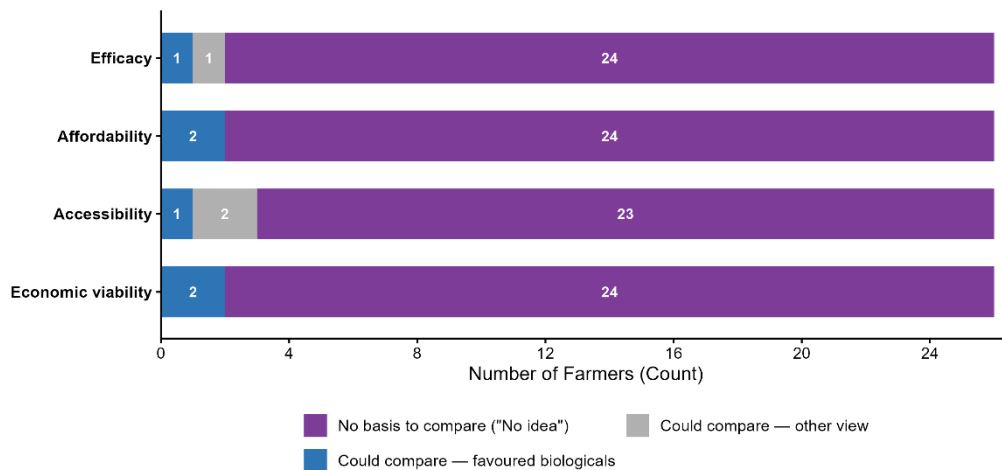


Figure 5.8. Respondents' Basis for Comparing Biological Alternatives with Synthetic Pesticides Across Four Feasibility Dimensions (N=26).

Across all dimensions, the dominant response was an inability to compare: 24 of 26 respondents selected “no idea” for efficacy, affordability, and economic viability, and 23 of 26 for accessibility. Among the few who did offer an assessment, the numbers were too small to indicate any clear directional pattern.

5.6 Factors Influencing Adoption Decisions

5.6.1 Ranking of adoption priorities

Farmers prioritized demonstrated value over training support when considering adoption. Perceived effectiveness and cost were ranked most highly, while training and extension support ranked lowest (Figure 5.9).

Panel (a) shows the mean rank score of each factor among the 19 respondents who ranked all seven factors from most to least important (1 = most important to 7 = least important, with lower scores indicating higher priority). The remaining 7 respondents ranked only some of the factors and so could not be included in the mean rank, which requires a complete ordering. All 26 respondents did, however, indicate their single most important factor, and panel (b) reports this across the full sample.

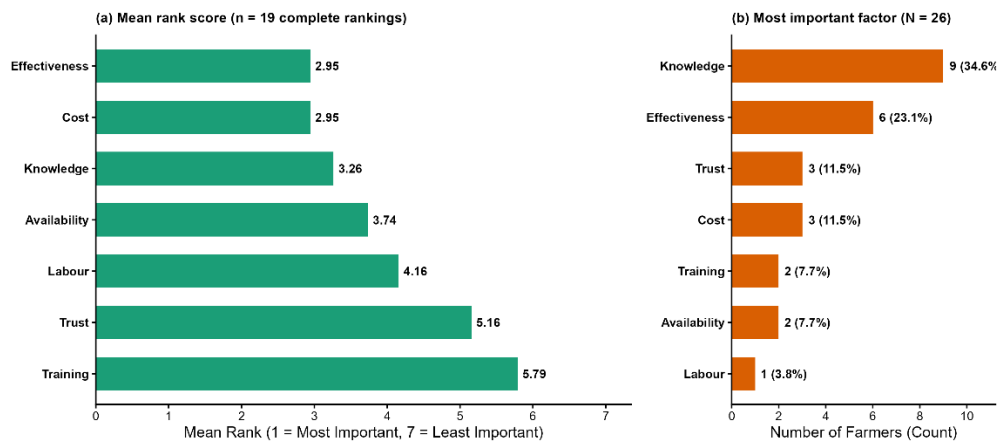


Figure 5.9. Prioritization Profile of Factors Influencing the Adoption of Biological Alternatives: (a) Mean Rank Scores (n=19); (b) Single Most Important Factor (N=26).

Panel (a) shows that perceived effectiveness emerged as the dominant driver influencing adoption, receiving the highest priority with a mean rank of 2.95, jointly with cost/affordability. In contrast, training ranked lowest, with a mean score of 5.79.

Panel (b), which draws on all 26 respondents, shows a related but distinct pattern. When asked to name their single most important factor, the largest group (9 respondents, 34.6%) identified baseline knowledge and awareness, followed by perceived effectiveness (6 respondents, 23.1%). This finding is consistent with the low levels of awareness and the absence of extension training on biological control reported earlier, suggesting that the lack of extension training may have contributed to the limited awareness of biological alternatives observed among respondents.

A clearer picture emerges when the rankings are examined by importance band (Figure 5.10).

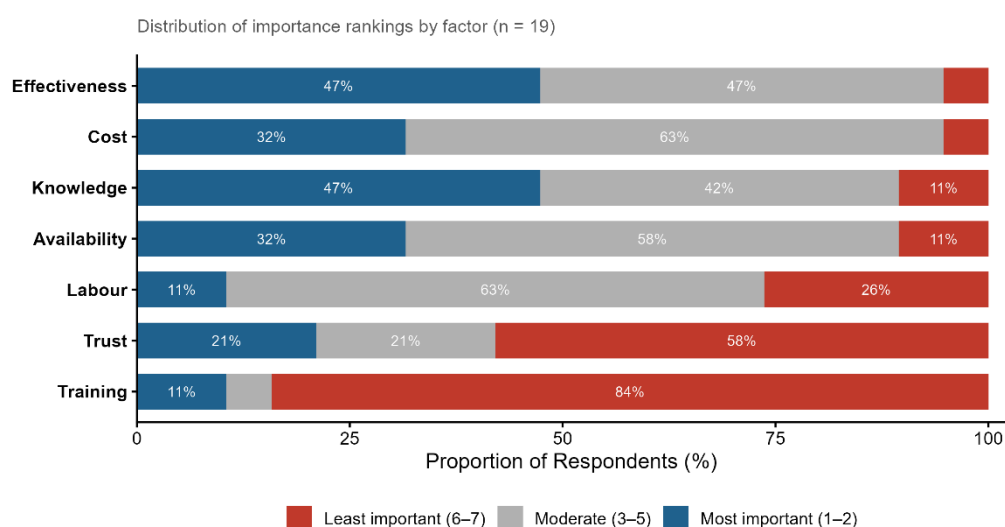


Figure 5.10. Relative Importance Profile Matrix of Farmer Priorities Affecting Bio-Alternatives Adoption, Showing the Spread of Rankings Across Factors (n=19).

Note: Percentage labels are omitted for clarity from segments that each represent a single respondent (approximately 5%); percentages are rounded to the nearest whole number and may not sum to 100%.

Farmers agreed most on effectiveness and knowledge, concentrating both in the higher-importance bands: 94% placed effectiveness in the most-important or moderate bands (only 5% ranked it least important), and knowledge followed at 89%.

Cost and availability clustered in the moderate band (63% and 58% respectively), suggesting that while these factors matter, farmers did not treat them as decisive barriers. Labour intensity was also concentrated in the moderate band (63%), with only a minority (26%) ranking it least important.

Trust in the product and training showed the opposite pattern, dominating the least important band. Trust was the most divided factor: while some ranked it highly, most (58%) placed it least important. Training and extension support showed the highest concentration of responses in the least important category (84%). Despite all respondents reporting no previous extension training on biological control, knowledge and awareness were still ranked among the most important adoption factors.

Overall, the distribution shows broad agreement at the extremes: effectiveness and knowledge were widely ranked as important, while training was almost unanimously ranked as least important. Trust displayed the greatest dispersion across categories, indicating the lowest level of agreement among respondents. This

pattern reinforces the ranking order in Figure 5.9 while also showing the degree of consensus behind it.

Baseline literacy and education was the factor farmers frequently identified as essential for adopting new agricultural technology, cited by 11 of 26 (42.3%) (Figure 5.11).

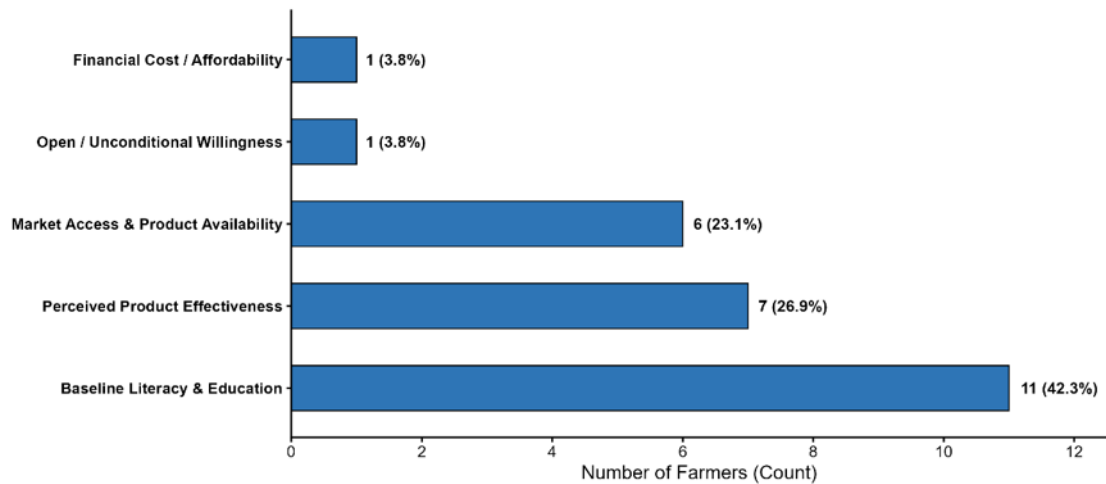


Figure 5.11. Key Socio-economic and Informational Factors Shaping Farmers' Decisions to Adopt Biological Alternatives (N=26).

Perceived product effectiveness followed (26.9%, n = 7), then market access and product availability (23.1%, n = 6). Cost and unconditional willingness were each named by only one respondent (3.8%). These findings broadly align with the mean importance rankings, where effectiveness, cost, and knowledge emerged as key considerations, although the single-factor responses placed greater emphasis on knowledge and effectiveness. Together, the results indicate that farmers view knowledge, confidence in product effectiveness, and affordability as important conditions for potential adoption of biological alternatives.

5.7 Correlations Between Socio-economic Factors and IPM Adoption Willingness

Health-risk perception was the clearest correlate of IPM adoption willingness; no demographic factor showed a significant association (Figure 5.12).

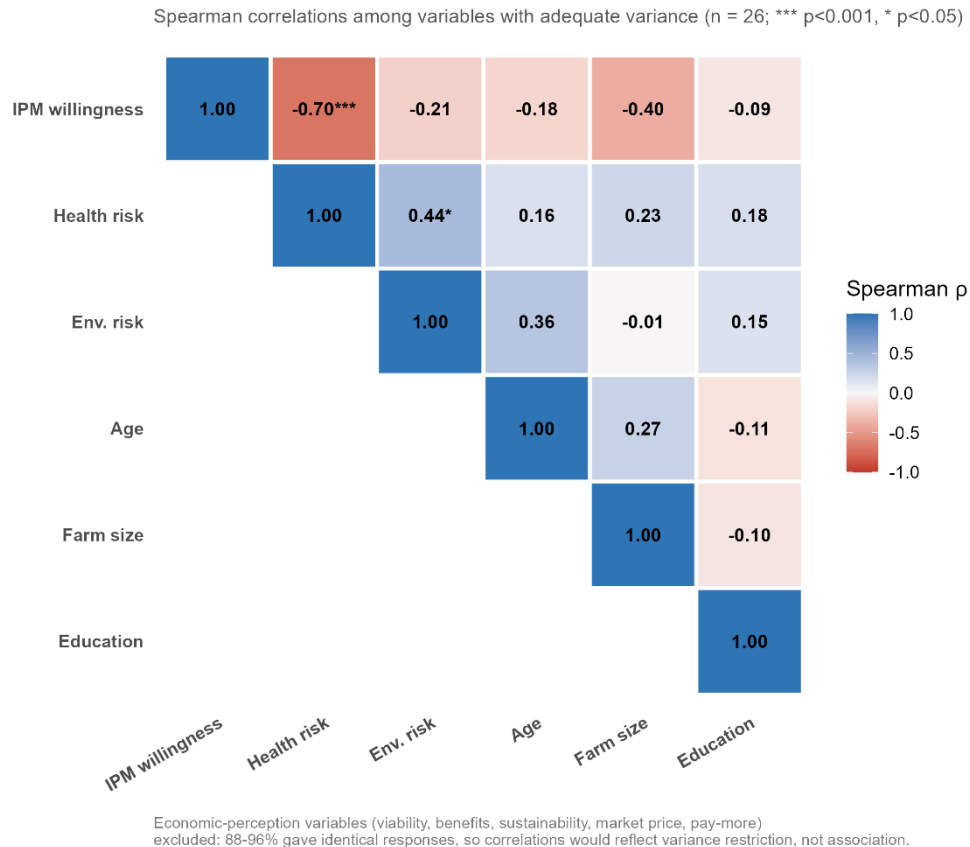


Figure 5.12. Spearman Rank Correlation Matrix of Farmer Demographics, Risk Perceptions, and IPM Willingness (N=26).

The matrix presents Spearman rank correlations among farmer demographics, risk perceptions, and willingness to adopt an integrated approach. Several attitudinal variables – economic viability, perceived benefits, and long-term sustainability– were excluded, as 88–96% of respondents gave the same response, leaving too little variance for meaningful correlation. Colour intensity reflects the strength and direction of each correlation (blue positive, red negative). Two statistically significant correlations emerged. Greater concern about health risks was associated with lower willingness to adopt an IPM approach combining biological alternatives with synthetic pesticides ($\rho = -0.70$, $p < 0.001$). Environmental and health-risk perceptions were moderately correlated ($\rho = 0.44$, $p < 0.05$). No other variable pairs – including age, farm size, and education – showed statistically significant correlations.

Willingness to adopt IPM declined as farmers' perceived health-risk concern rose (Spearman $\rho = -0.699$, $p < 0.001$; Figure 5.13).

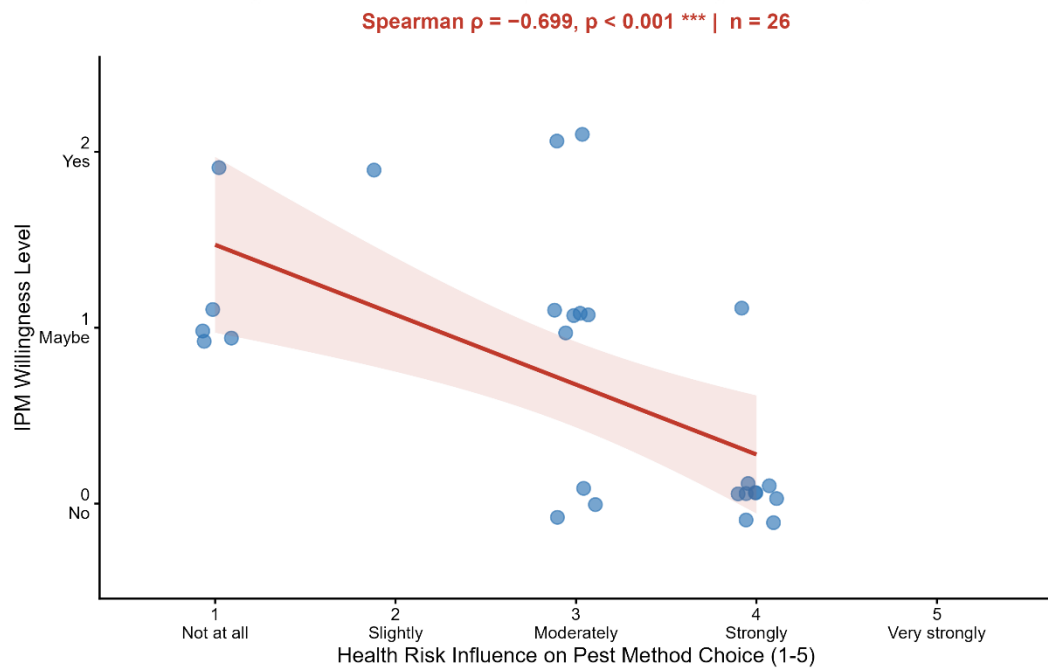


Figure 5.13. Scatter Plot with Fitted Regression Line Showing the Negative Association Between the Influence of Health Risks on Farmers' Pest Management Decisions and Their Willingness to Adopt IPM Combining Biological Alternatives With Synthetic Pesticides (N=26).

Each point represents one respondent, plotting the influence of health-risk perception on pest-management decisions against willingness to adopt IPM, an approach combining biological alternatives with synthetic pesticides. The fitted regression line runs clearly downward: respondents who rated health risks as strongly influential tended to report the lowest willingness to adopt an integrated approach, while those less concerned about health risks were more receptive.

5.8 Summary of key findings

The four-quadrant matrix consolidates the study's core findings on the awareness – adoption gap (Figure 5.14).

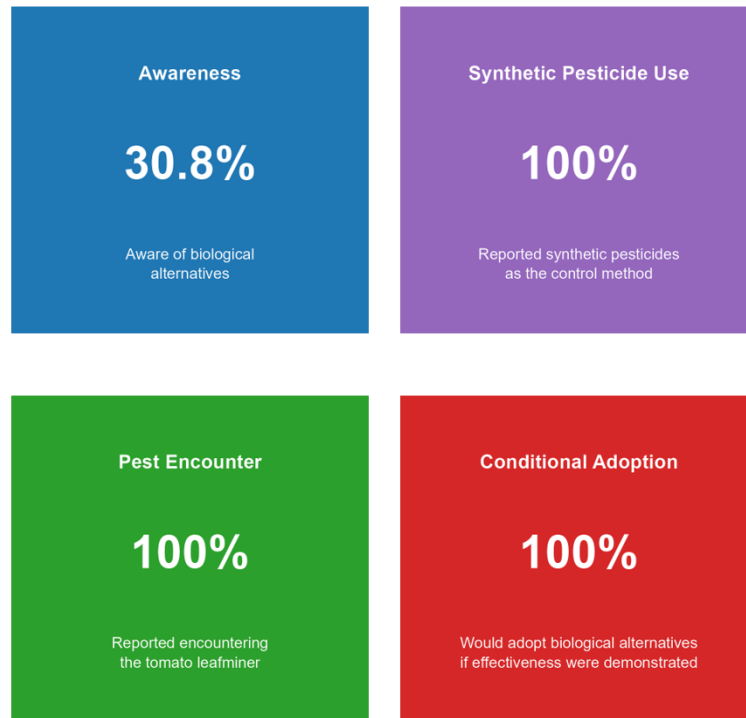


Figure 5.14. Conceptual Dashboard Summarizing Respondent Awareness, Pest Experience, and Willingness to Adopt Biological Alternatives (N=26).

All 26 respondents (100%) had encountered *Tuta absoluta* and relied on synthetic pesticides, establishing a universal baseline of pest pressure and chemical-based management. In contrast, only 30.8% reported prior awareness of biological alternative options, yet all respondents indicated that they would adopt biological alternatives if their effectiveness were demonstrated under field conditions. The matrix therefore highlights the contrast between near-universal pest exposure and chemical dependence, limited awareness of biological options, and strong stated willingness to consider alternative management approaches.

6. Discussion

6.1 Introduction

This chapter interprets the results through the lens of the study's four research questions. First, it examines farmers' awareness and knowledge of biological alternatives for managing *Tuta absoluta*, including semiochemicals and natural biocontrol agents, as well as their previous exposure to these approaches. Second, it evaluates farmers' perceptions of the agronomic and practical benefits of biological alternatives compared with synthetic pesticides, including human safety, plant and environmental health, labour demands, and pest-suppression efficacy. Third, it analyzes farmers' perceptions of the feasibility of adopting biological tools, focusing on affordability, accessibility, perceived effectiveness, and economic viability. Finally, it examines whether selected socio-economic and perception-related factors are linked to farmers' willingness to adopt and integrate semiochemicals and natural biocontrols into their existing pest-management practices. Together, these sections provide an interpretation of the barriers and opportunities shaping the adoption of biological alternatives in smallholder tomato systems.

6.2 Awareness, Knowledge and Experience of Biological Alternatives

The empirical baseline compiled in this study to address Research Question 1 reveals a profound awareness and conceptual deficit surrounding agricultural biological alternatives within the target smallholder community. As shown in Table 5.3, more than two-thirds of respondents reported no prior familiarity with biological alternatives in any general sense. This quantitative pattern was strongly reinforced by the interview data, where most farmers stated that they had never heard of alternative pest-control mechanisms and described synthetic chemicals as the only practical option within their experience.

These findings align with existing literature documenting substantial awareness and knowledge gaps regarding biological pest management options. A related study in the Ruaha River Basin of Tanzania found that 88.8% of surveyed tomato farmers were unaware of alternative strategies for managing *Tuta absoluta* beyond synthetic pesticides, while only 11% were aware of pheromone traps (Kombe et al., 2022). However, awareness of biological pest-management options does not necessarily translate into use. In a KAP study among 150 smallholder farmers in the Chole district of Ethiopia, none reported using biological alternatives for plant protection, despite some conceptual understanding of biologicals (Mulugeta et al., 2024).

This prevalent lack of awareness appears rooted in a structural deficit within the agricultural knowledge system. Knowledge about pest management is typically disseminated through extension services, agro-dealers, and peer networks (Leta et al., 2018), yet in the present study, all three channels failed to deliver information on biological alternatives. This is consistent with Alwang et al. (2019), who identify weak institutional support as a key barrier to IPM diffusion, and Chilipweli et al. (2025), who attribute dependence on synthetic pesticides to institutional and informational constraints.

Among the minority who reported some general awareness (30.8%, $n = 8$), conceptual understanding declined sharply when they were asked to explain the term in greater detail; in other words, their understanding of the distinction between biological control methods and other non-chemical approaches was limited. Several respondents confused biological alternatives with mechanical tools such as yellow sticky traps, while only one interviewee gave a partly accurate explanation by describing biological solutions as “insects that chase other insects away.” This pattern indicates that functional knowledge of targeted biological pest-management mechanisms remains extremely limited, representing a major barrier to independent adoption (Table 5.3; Figure 5.4).

Beyond awareness, a deeper knowledge deficit emerged in relation to natural enemies and field-based ecological observation. Table 5.3 shows that 88.5% ($n = 23$) of farmers were unable to identify beneficial organisms or distinguish them from crop pests in the field. However, the qualitative narratives suggest that some farmers do possess relevant field experience, even if they lack the knowledge to interpret it as biological control. As reported in Section 5.3, two of the three farmers who had observed natural enemies described brown ants and native birds attacking *Tuta absoluta* larvae and noted that pest damage appeared to decrease when these natural enemies were more active on their farms.

Despite recognising these local benefits, neither farmer identified these organisms as natural enemies nor linked them to biological alternative strategies. This disconnect suggests that while some farmers possess relevant field experience through direct observation, they lack the formal knowledge needed to translate these observations into management decisions (Figure 5.3). As a result, naturally occurring biological control agents remain unnamed, unrecognized, and vulnerable to destruction under the frequent synthetic pesticide regimes documented in Table 5.2 (see also Figure 5.3).

The frequent synthetic pesticide applications reported by farmers may also help explain the limited observations of natural enemies (Table 5.2). Insecticides can adversely affect beneficial arthropods involved in controlling *T. absoluta* (Biondi

et al., 2018). Frequent spraying could therefore reduce opportunities for farmers to observe these organisms, alongside difficulties in recognizing them. However, natural enemy abundance and synthetic pesticide effects were not measured in this study, so this remains an inference.

This situation is not unique to this research project. In a study conducted by Bonhof et al., (2001) among 240 maize farmers on the Kenyan coast, 33% of them had observed the cocoons of the parasitoids *Cotesia flavipes* and the indigenous *Cotesia sesamiae*, but none could identify what they were. Similarly, Martínez-Sastre et al. (2020), in Asturias (Northern Spain), revealed that 42.3% of respondents visually encountered many natural enemies in their orchards but lacked the knowledge to identify them or recognize their role in biological control. The present findings mirror this pattern: farmers observed ants and birds suppressing *Tuta absoluta* but lacked the knowledge basis to interpret these observations as biological control.

As noted by Gross (2016) and Thomas & Tabanca (2025), bio-pesticides and semiochemical systems are not “plug-and-play” technologies; they require hands-on, context-specific training, often delivered through intensive approaches such as Farmer Field Schools (FFS). The awareness deficit documented in Mapinduzi village is therefore better understood as a failure of information delivery than as farmer indifference.

First, the institutional channel through public extension services, is largely absent. Despite reporting no previous extension training, farmers ranked knowledge and awareness among the most important adoption factors while placing formal training last (Figure 5.10). This apparent contradiction may reflect farmers’ experience of extension services as absent or ineffective; they recognize the value of information but have little confidence that formal training channels will deliver it. Although extension officers are expected to provide technical guidance, diagnostic support, and training on biological control, the survey and interview data suggest that such support is either extremely limited or unavailable.

This is consistent with national evidence: only 6.9% of Tanzania’s 7,677,291 crop-growing households received crop extension advice during the 2019/20 agricultural year. Of the Mainland Tanzanian households that reported receiving such advice, 4.8% were located in Iringa Region (National Bureau of Statistics, 2021). This may reflect understaffing, inadequate transport and logistical resources, or gaps in the technical training of extension personnel themselves, which reduce their ability to communicate approaches such as semiochemical use or natural enemy conservation. Without training, farmers may be less able to recognize the natural enemies already present in their fields, limiting the potential for biological control.

Second, agro-dealers, who often serve as an important fallback source of advice, also appear constrained by limited knowledge of biological alternatives. This finding is consistent with Constantine et al. (2020), who reported a similar knowledge and supply disconnect among agro-dealers in Kenya (see Section 6.4). Because many dealers focus primarily on selling conventional inputs and may not be trained in biological control, they are unlikely to recommend, stock, or explain safer alternatives. As a result, the commercial advice channel reinforces dependence on synthetic pesticides rather than expanding access to new technologies.

Semi-structured interviews with 20 agro-dealers in Iringa Town, conducted as part of a parallel study (Manda, unpublished data, 2026), further emphasize this information gap. Across the twenty dealers, biological products were rarely stocked: two sold only bio-fertilizers rather than pest-management tools, and a single dealer stocked a semiochemical product – the only biological pest-control tool found.

Notably, the one dealer who demonstrated clear knowledge of semiochemicals or natural biocontrol agents did not stock or sell them, while the dealer who did stock the semiochemical was a different respondent. This suggests that agro-dealers – who often serve as key intermediaries between farmers and new technologies – are themselves constrained by limited awareness, training, and product availability.

Third, peer-to-peer communication has become the dominant source of information, with 46.2% (n = 12) of respondents identifying fellow farmers as their primary source of agricultural advice (Figure 5.2), which can be effective when accurate knowledge is circulating. In this case, however, because most farmers have little or no exposure to biological alternatives, the peer network simply reproduces the same limited knowledge and understanding. This creates an information echo chamber in which the community continues to rely on frequent synthetic pesticide spraying as the default response to *Tuta absoluta*. This pattern is consistent with broader evidence that peer networks, while effective when accurate knowledge circulates, tend to fortify existing practices in the absence of external technical input (Bonabana-Wabbi, 2002; Leta et al., 2018).

This broader information vacuum is further evidenced by the fact that none of the respondents had received the training necessary to develop functional knowledge of natural enemies or beneficial insects (Figure 5.3). Taken together, the weak extension system, the limited technical capacity of agro-dealers, and the closed nature of peer learning have left farmers without reliable guidance, training, or exposure to biological control concepts. Consequently, awareness of biological alternatives has not emerged through the community's normal channels of knowledge exchange.

6.3 Perceived Agronomic Benefits of Biological Alternatives

To address Research Question 2, this section examines how smallholders perceive the performance of biological alternatives relative to conventional synthetic pesticides across four main dimensions: human safety, plant and environmental health, labour demands, and pest-suppression efficacy. These dimensions were informed by the comparative assessment in the questionnaire, which asked farmers to rate biological alternatives against synthetic pesticides in terms of efficacy, plant health, safety, and ease of use in relation to labour and application, while environmental risks were assessed separately as a factor influencing pest-management decisions. Overall, the findings show that farmers view biological alternatives positively in principle, but their perceptions are shaped by both their experiences with the risks associated with synthetic pesticide use and their limited awareness and experience of biological alternatives.

Safety concerns emerged strongly, though from farmers' experience of synthetic pesticides rather than direct comparison. In the comparative survey item, respondents had no basis to judge biological alternatives; farmers' safety preference instead surfaced through their accounts of chemical harm. A notable minority of farmers reported health-related difficulties with chemical use, including irritation during or after spraying (Figure 5.1).

Interview accounts further described coping practices such as drinking milk, bathing immediately after spraying, and consuming large amounts of water in response to perceived pesticide toxicity. Farmers also described crop damage associated with pesticide use, providing further evidence of the negative experiences through which chemical control was evaluated.

These experiences appear to contribute to what might be described as a “least-worst” logic: even when farmers had limited understanding or direct experience of biological alternatives, they tended to perceive an alternative to synthetic chemicals as potentially less harmful to human health and the environment. This interpretation is reflected in the 88.5% of respondents who indicated that they would be willing to pay more for biological alternatives if these offered clear health or environmental benefits (Figure 5.5). This tendency aligns with the ‘natural-is-better’ bias documented in risk-perception research, where people judge natural or non-synthetic options as inherently safer than synthetic ones, even in the absence of supporting technical evidence (Rozin et al., 2004; Meier & Lappas, 2016).

The affect heuristic – the tendency to rely on emotional impressions when technical knowledge is limited – provides a plausible explanation for this pattern (Slovic et

al., 2002). When individuals lack the technical knowledge needed for a full risk assessment, they substitute an intuitive “good/bad” judgment. In this case, farmers’ negative experiences with synthetic pesticides shape a strong negative affect, making biological alternatives feel inherently safer despite limited familiarity with how they work. This perception is further supported by the moderate to high concern levels for environmental and health risks shown in Figure 5.7.

Farmers’ accounts of chemical damage also point to a possible perception that biological alternatives may be gentler on crops. During interviews, respondents described synthetic pesticides as “harsh” and reported that they sometimes scorch tomato foliage, leading to plant death in some cases. These experiences may influence how farmers perceive biological alternatives, even where direct knowledge of biological alternatives remains limited, though this was not explicitly reported by respondents.

These reports are consistent with evidence that excessive or inappropriate pesticide use can negatively affect crop growth while also creating environmental and health risks. Beyond controlling pests, repeated applications of synthetic pesticides may disrupt beneficial organisms, contaminate soil and water, and contribute to pest resistance, ultimately reducing the sustainability of tomato production (Pimentel, 2005; Biondi et al., 2018). Thus, the field-level indicators farmers already rely on – scorched leaves, plant death – align with documented agronomic consequences of chemical-intensive management.

In relation to labour demands, although most respondents had little or no direct experience with commercial biological products, a small number described encounters with naturally occurring biological agents such as brown ants and birds, as well as the use of rabbit urine. These farmers reported visible reductions in *Tuta absoluta* pressure, improved yields, and fewer synthetic pesticide sprays during such periods. In these cases, biological control appears to have been relatively easy to use, since the organisms were naturally present or the inputs locally available – though this was inferred rather than explicitly stated by respondents.

While formal biological tools such as semiochemical lures or traps may require more technical deployment, the farmers’ responses suggest that labour intensity is not a major obstacle: most respondents placed labour in the moderate importance band (Figures 5.9 and 5.10), likely because tomato farming is already highly labour-intensive and farmers are accustomed to demanding field work. This is consistent with the broader adoption literature, where labour demands are rarely identified as a primary barrier to biological control; instead, awareness, cost, and access to products consistently emerge as the dominant constraints (Alwang et al., 2019; Mulugeta et al., 2024).

Although farmers tended to regard biological alternatives as potentially safer and less harmful to plant health, most had no basis for comparing their pest-suppression efficacy with synthetic pesticides (Figure 5.8). This uncertainty appears to be driven mainly by unfamiliarity rather than direct failure of the technologies. Studies in Africa have demonstrated the potential of biological control and semiochemical-based approaches for managing *T. absoluta*, although their performance varies with the method and growing conditions (Goda et al., 2015; Zekeya et al., 2022).

Semiochemical-based approaches, including pheromone trapping and mating disruption, can reduce reliance on synthetic insecticides and help conserve beneficial insects. When integrated with biological control, they can contribute to effective suppression of *Tuta absoluta* and reduced crop damage within an IPM programme (Witzgall et al., 2010; PURE, 2015; Desneux et al., 2022).

Since most farmers had never used commercial biological alternatives and had no basis for comparing their effectiveness with synthetic pesticides, their familiarity with the fast, visible action of pesticide sprays may have contributed to concerns that biological methods would be too slow or insufficiently effective against a pest such as *Tuta absoluta*. This finding is consistent with Mulugeta et al. (2024), who reported that limited knowledge and experience with biological alternatives influenced how farmers perceived and evaluated these technologies.

This perception is understandable given how differently the two approaches actually work. Synthetic pesticides act rapidly, and farmers often observe dead larvae shortly after application. Biological control options, by contrast, generally act more gradually because they rely on ecological processes rather than immediate toxicity: microbial biopesticides require time to infect and kill target pests, while pheromone-based technologies such as mating disruption reduce pest populations by interfering with reproduction rather than causing immediate mortality. The benefits of these approaches therefore become evident over successive pest generations rather than within hours or days (Witzgall, Kirsch & Cork, 2010; Komala, Manda & Seram, 2021).

Because farmers are accustomed to quick, visible results, this slower and more indirect mode of action can easily be misread as biological tools being ineffective. Yet this view is not shared by the few farmers who had observed natural suppression in the field. Their experiences suggested biological interactions can be effective when present – pointing to an information deficit rather than an inherent rejection of biological control.

This same uncertainty was evident in how farmers evaluated the long-term sustainability of biological control. When asked whether natural enemies could provide long-term, sustainable pest control compared with chemicals, the majority

responded neutrally rather than negatively (88.5%). This pattern suggests that farmers did not reject the idea of biological sustainability outright; rather, their responses reflected limited knowledge and experience with natural enemies, strengthening the pattern already seen in the efficacy findings above.

Importantly, this knowledge gap appears conditional rather than fixed. When asked whether they would conserve natural enemies if shown that these could effectively control *Tuta absoluta*, nearly two-thirds of respondents expressed willingness to do so, with only 19.2% opposed. This suggests that a majority of the farmers are open to ecological pest management, but that their willingness may be closely tied to confidence in demonstrated effectiveness. The small “No” group (19.2%) indicates that some farmers may remain unwilling to adopt biological alternatives even under a proof-of-efficacy scenario. The reasons for this are not fully understood and may relate to factors beyond the scope of this study, such as trust in familiar practices or scepticism toward unfamiliar technologies.

In sum, these findings show that farmers are generally receptive to biological alternatives, especially when safety and health benefits are emphasised. Their hesitation appears linked mainly to doubts about efficacy and limited exposure to proven biological tools, rather than outright rejection of biological control. This pattern highlights the importance of practical demonstrations, training, and local evidence of performance to improve farmers’ understanding of biological pest management.

6.4 Perceived Feasibility of Adoption

Research Question 3 examines the practical feasibility of adopting biological alternatives by assessing farmers’ views on affordability, accessibility, perceived effectiveness, and economic viability, particularly relative to the chemical management practices currently in use.

Most farmers had no basis to judge the affordability of biological alternatives, having never encountered them (Figure 5.8). Among the few who did respond, biological alternatives were perceived as less expensive than synthetic pesticides. These responses may reflect the perceptions of the few farmers who had previously observed natural enemies, such as brown ants and birds, providing natural pest suppression in their fields. Although respondents did not explicitly identify these organisms as biological control agents, such experiences may have shaped their views of biological alternatives. However, market observations indicated that the biological products available were more expensive than conventional synthetic pesticides.

Although a minority of farmers identified cost as a challenge associated with chemical pesticides (Figure 5.1), interview data suggested that synthetic pesticides remained the more affordable option in practice. During the interviews, several farmers reported using pesticide mixtures because they considered the recommended label dosages insufficient to achieve effective control. While respondents attributed this to poor product performance, it is plausible that financial constraints also contributed, leading some farmers to dilute pesticides beyond the recommended rate in order to cover larger plot sizes. If so, this practice may itself have reduced product efficacy and partly explain the frequent spraying reported by many farmers. However, this interpretation is inferential, as respondents did not explicitly state that cost was the reason for dilution.

Although effectiveness and cost ranked as the highest mean decision factors, knowledge emerged as the single most important factor for over a third of respondents (Figure 5.9a, b), yet most had no basis to compare the affordability of biological alternatives with synthetic pesticides (Figure 5.8). Cost sensitivity is therefore evident, but it currently operates without reference to the actual cost of biological options, which farmers have limited experience evaluating.

Market observations further supported this affordability disparity. Indicative Tanzanian market prices for some commonly used synthetic pesticides include Profecron at TZS 7,000 – 23,000 for 100 – 500 ml packs and Duduba at TZS 6,000 for a 120 ml pack (Joack Agrovat, n.d.). In comparison, Malex (its formulation was labelled for false codling moth rather than *T. absoluta*), the only semiochemical-based product reported to be stocked by the interviewed agro-dealer, cost approximately TZS 160,000 per 150 g pack (Manda, unpublished data, 2026). These figures represent purchase prices rather than equivalent treatment costs. This higher upfront purchase price is consistent with previous studies reporting that biological pest-management tools are often more expensive and less widely available in smallholder markets (Deguine et al., 2021; Mulugeta et al., 2024; Fenibo & Matambo, 2025).

Accessibility presents a further feasibility constraint, though most respondents had no basis to judge it, having never encountered biological alternatives (Figure 5.8). Those who did respond noted that synthetic pesticides were readily available in multiple brands while biological products were absent from local retail channels (Figure 5.11), a supply-side shortfall consistent with the agro-dealer constraints discussed in Section 6.2. Agro-dealer interviews supported this observation: only one of twenty dealers stocked a semiochemical product, indicating very limited local availability.

This pattern is not unique to Tanzania. Similar findings have been reported in Kenya, where smallholders rarely have access to biological products and agro-dealers seldom stock them. Farmers in that context assumed biological alternatives were unavailable simply because they had never encountered them in retail outlets, while agro-dealers refrained from procuring biological inputs because they believed farmers lacked interest (Constantine et al., 2020). This reciprocal misunderstanding reflects a breakdown in the agricultural knowledge and supply system: farmers cannot express demand for products they have never seen or know about, and agro-dealers cannot justify stocking products for which there is no apparent demand. As a result, both parties, despite their intentions, help entrench the conditions that limit access to biological alternatives and impede their broader market uptake.

As stated earlier, market observations showed that biological alternatives were rarely available through local agro-dealers, in contrast to synthetic pesticides, which were readily obtainable. This restricted availability likely reflects wider institutional and market barriers, rather than low farmer demand alone. Registration procedures developed around conventional synthetic pesticides can raise the difficulty and cost of bringing microbial, botanical, and semiochemical products to market (Mawcha et al., 2025; Malek et al., 2026).

The East African Community sought to address these regulatory barriers through its 2019 Harmonized Guidelines for the Registration of Biopesticides and Biocontrol Agents (EAC, 2019), but most Partner States, including Tanzania, have yet to adopt them fully. Although Tanzania's Plant Health Act (2020) provided a national legal framework for pesticide and biopesticide registration, biopesticides and conventional pesticides continue to be regulated under the same registration procedures unless otherwise specified (Mawcha et al., 2025).

This slow translation from regional guidance to enforceable national practice, administered in Tanzania by the Tanzania Plant Health and Pesticides Authority (TPHPA), remains a key bottleneck restricting market presence. The regulatory gap is consistent with the near-absence of biological products observed in agro-dealer shops in this study (ICGEB, 2025).

Perceived effectiveness is another important dimension of the feasibility of biological alternatives. However, most farmers in this study had no basis on which to evaluate the efficacy of biological pest-management tools (Figure 5.8). The lack of informed comparisons is itself revealing. Rather than indicating negative perceptions of biological alternatives, it reflects the absence of practical experience on which farmers could evaluate their effectiveness.

Two conclusions follow. First, unfamiliarity rather than rejection is the dominant pattern, strengthening the broader finding that limited exposure, not entrenched

scepticism, is the main constraint to evaluating the feasibility of biological alternatives. Second, because so few farmers had sufficient experience to assess biological effectiveness, current evaluations of the effectiveness remain largely unformed. This suggests that practical demonstrations and firsthand experience could play an important role in shaping more informed evaluations of biological pest-management options.

This is supported by the three respondents who had encountered naturally occurring or farmer-derived biological practices: brown ants, birds, and rabbit urine, all of whom reported positive outcomes, with two expressing a desire for more natural enemies and the third recommending her rabbit-urine practice to other farmers. Although she was a proxy observer rather than a user of commercial biological products, her three-year experience with the practice provides a reasonable basis for her perception of its efficacy.

This aligns with evidence that farmers' evaluations of pest-management technologies are strongly shaped by direct experience and observation. Participatory, discovery-based approaches such as Farmer Field Schools have been shown to improve understanding and acceptance of biological approaches because farmers are more likely to trust technologies whose benefits they observe under their own farming conditions (Rejesus & Jones, 2020). Taken as a whole, these insights indicate that farmers' perceptions of biological effectiveness are not fixed but may evolve through practical exposure, demonstration, and locally relevant evidence.

Regarding economic viability, as with the other feasibility components, most farmers lacked sufficient exposure to biological inputs to assess their economic value, with the majority unable to form an opinion (Figure 5.8). The few respondents who viewed biological alternatives more favourably may reflect farmers' observations of natural pest suppression on their farms, particularly by brown ants and birds. Although these experiences did not involve commercial biological products, they illustrate how naturally occurring biological control may be perceived as providing pest-management benefits without additional input costs (Bale et al., 2008; Jahnke & Da Silva, 2021).

However, this perceived advantage applies primarily to conservation biocontrol rather than purchased biological inputs such as semiochemicals, which require financial investment and were observed in this study to be considerably more expensive than synthetic pesticides. The predominance of "no idea" responses therefore suggests that farmers currently have limited capacity to judge the economic viability of commercial biological alternatives, including their

consistency, management requirements, and potential returns relative to conventional chemical approaches.

Although biological methods are natural, they are not necessarily simple; their success often depends on appropriate timing, ecological conditions, and knowledge of how they function. Limited familiarity therefore restricts farmers' ability to assess both their practical and economic value. Nevertheless, when biological control is effective, its benefits may extend beyond yield outcomes to include improved plant health, reduced farmer exposure to pesticides, and environmental gains (Bale et al., 2008; Deguine et al., 2021). This suggests that the potential economic value of biological approaches may currently be underestimated simply because farmers have had little opportunity to observe them firsthand.

6.5 Factors Influencing Willingness to Adopt

To answer Research Question 4, several factors influence farmers' decisions regarding the adoption of new technologies, particularly when these involve unfamiliar practices and financial commitments. In this context, knowledge/awareness is important because farmers may be reluctant to invest in technologies they do not understand or have not observed in practice. Knowledge and demonstrated effectiveness consistently emerged as the most important factors shaping farmers' willingness to consider biological alternatives (Figures 5.9–5.11). Limited familiarity may therefore increase the perceived risk associated with adopting new pest-management approaches, particularly among farmers operating under financial constraints (Rogers, 2003; Kassie et al., 2015).

Cost is a central consideration in farmers' adoption decisions, ranking joint-highest with effectiveness in mean importance (Figure 5.9a) and tying with trust as the third most frequently cited single factor after knowledge and effectiveness (Figure 5.9b). This emphasis is consistent with the broader financial risk perceptions in the study: nearly all the respondents expressed moderate to high concern about market and financial risks associated with pest management (Figure 5.7), further explaining their reluctance to invest in unfamiliar technologies.

At the same time, the cost of synthetic pesticides was also identified as one of the main challenges in current practice (Figure 5.1). Together, these findings indicate that farmers are highly sensitive to the financial implications of pest-management decisions. Consequently, although most respondents had no basis on which to compare the affordability of biological alternatives, cost is likely to remain an important consideration once these technologies become more widely available and familiar (Feder et al., 1985).

The correlation matrix revealed two significant associations (Figure 5.12). First, health-risk perception was strongly and negatively correlated with willingness to adopt IPM (Figure 5.13), signifying that farmers who expressed greater concern about pesticide-related health risks were less willing to adopt an integrated approach that retains some synthetic pesticide use. One possible explanation is that these farmers may perceive IPM approaches that retain synthetic pesticide use as insufficient to address their health concerns, although the present study did not directly investigate the reasons underlying this relationship.

Second, health and environmental risk perceptions were moderately and positively correlated ($\rho = 0.44$, $p < 0.05$), suggesting that concerns about human health and environmental impacts tend to occur together. Collectively, these findings denote that heightened concern about pesticide-related risks may reduce acceptance of IPM approaches involving continued synthetic pesticide use. However, this does not imply rejection of alternative pest-management approaches: all respondents indicated willingness to adopt biological alternatives if their effectiveness were demonstrated (Figure 5.5). This suggests that farmers' concerns about synthetic pesticides can coexist with openness to biological alternatives, provided demonstrations directly address these health worries while clearly showing the effectiveness of biological alternatives, enabling farmers to assess both the benefits and the remaining risks of an IPM approach.

6.6 Integration: Toward an IPM Adoption Pathway

Collectively, the findings indicate that important barriers to sustainable IPM integration include limited knowledge and exposure to biological pest-management options, as well as restricted local access to these alternatives, rather than outright rejection of alternative pest-management approaches. Farmers appear to rely heavily on synthetic pesticides because these remain the most familiar, accessible, and established pest-management options available to them. If extension systems and agro-dealer networks can address the knowledge gap and provide locally demonstrated biological alternatives, farmers may become more willing to consider sustainable pest-management approaches.

Although biological control is formally a component of IPM, respondents in this study appeared to associate IPM primarily with continued use of synthetic pesticides. Among farmers with greater concerns about pesticide-related health and environmental risks, this association may reduce the acceptability of IPM approaches that retain chemical inputs. However, the willingness of all respondents to adopt biological alternatives if their effectiveness were demonstrated suggests that farmers are not opposed to sustainable pest-management approaches. Rather, acceptance may depend on demonstrating that biological tools are effective,

practical, affordable, and compatible with farmers' expectations of reducing chemical dependence.

7. Conclusion

This study investigated farmers' awareness, perceptions, feasibility, and adoption potential of biological alternatives for *Tuta absoluta* management in smallholder tomato production systems in Iringa, Tanzania.

Regarding awareness and experience (RQ1), the findings reveal a steep knowledge gradient: while all 26 respondents were familiar with *Tuta absoluta* itself, only 30.8% had heard of biological alternatives in any general sense, and just 7.7% had ever used one. None had received extension training on natural enemies/biological control. Farmers' knowledge was confined almost entirely to synthetic pesticides, which remain the most familiar, accessible, and trusted pest-management option available.

Regarding perceived agronomic benefits (RQ2), farmers had almost no direct experience with biological alternatives and could not evaluate their performance across standard dimensions. However, negative experiences with synthetic pesticides, including health effects, crop damage, and inconsistent efficacy, created a favourable disposition toward biological alternatives, contributing to a perception that biological alternatives could offer safer outcomes for both human and plant health, despite limited direct experience with these technologies.

Regarding feasibility (RQ3), cost and effectiveness were jointly ranked as the most important considerations. However, most farmers lacked sufficient experience with commercial biological inputs to evaluate their affordability, accessibility, effectiveness, or economic viability in comparison with synthetic pesticides. Agro-dealer interviews nevertheless showed that biological products were virtually absent from local retail channels: only one of twenty agro-dealers stocked a semiochemical product, at roughly five times the price of an average synthetic pesticide. Farmers' limited ability to evaluate biological alternatives therefore echoes not only low awareness and exposure, but also genuine supply-side constraints, compounded by regulatory bottlenecks in the national registration of biopesticides.

With respect to adoption drivers (RQ4), socio-economic factors, including education level, age, and farm size, showed no significant association with adoption willingness, although the small sample size ($N = 26$) limits the strength of this conclusion. Health-risk perception was the strongest correlate of adoption willingness ($\rho = -0.70$, $p < 0.001$): farmers who expressed greater concern about pesticide-related health risks were less willing to adopt IPM approaches that retain synthetic pesticide use. Health and environmental risk perceptions were also positively correlated ($\rho = 0.44$, $p < 0.05$), indicating that these concerns tend to co-

occur. However, the findings also suggest that this reluctance may relate more to the continued use of synthetic pesticides within IPM than to biological alternatives themselves, as all respondents stated that they would adopt biological alternatives if their effectiveness were demonstrated.

The central finding is that limited information, access, and demonstrated performance are more important barriers to adoption than outright resistance to biological alternatives. Although awareness of pesticide-related risks was near-universal and willingness to adopt biological alternatives was strong, these options remain largely unknown, unavailable, and undemonstrated in the study area. For biological pest management to become a viable component of sustainable tomato production in Tanzania, a coordinated approach involving farmers, extension services, agro-dealers, researchers, and regulatory institutions is needed. Farmer-centred demonstrations, strengthened extension capacity, improved product availability, supportive regulatory frameworks, and promotion of conservation biological control will be necessary for building confidence and enabling adoption.

7.1 Practical and Policy Implications

7.1.1 Demonstration-based introduction of biological alternatives

Throughout the interviews, farmers consistently emphasized the importance of seeing and testing new technologies before considering their use (Figure 5.9b). Respondents repeatedly called for demonstrations and field trials that would allow them to observe how biological alternatives perform under their own farming conditions.

Without such practical evidence, acceptance of unfamiliar technologies is likely to remain limited. This pattern is also reflected in how farmers may prefer to acquire knowledge: despite valuing knowledge highly, they ranked formal training lowest among adoption factors (Figure 5.10). This suggests that practical demonstrations should be considered alongside conventional training methods.

A suitable approach for facilitating this experiential learning is the Farmer Field School (FFS) model, which enables farmers to learn through observation, experimentation, and collective evaluation (Rejesus & Jones, 2020). However, demonstrations should go beyond simply showing pest-control efficacy. For biological alternatives to gain farmer confidence and achieve wider acceptance, demonstrations should provide evidence of their overall performance, including effective pest suppression, compatibility with crop health, personal health and environmental safety, economic viability, and practicality under smallholder conditions. Farmers need to understand not only whether a product controls the

target pest, but also whether it provides broader benefits without creating new environmental or production challenges.

Furthermore, biological alternatives must be competitive with existing chemical options in terms of cost and accessibility (Figure 5.9a). Demonstration programmes should therefore include realistic comparisons of input costs, application requirements, availability, and expected benefits. Products that perform well but are difficult to obtain, expensive, or unsupported by technical guidance may be unlikely to achieve sustained adoption. Establishing reliable supply channels and providing follow-up support after introduction will therefore be essential.

Given the importance of farmer-to-farmer knowledge exchange observed in this study, respected and trusted farmers within communities should be actively involved in designing and hosting demonstrations (Figure 5.2). Such peer-based approaches may enhance credibility, reduce uncertainty, and improve the likelihood that successful biological alternatives are accepted and adopted by other farmers.

7.1.2 Training and strengthening of agro-dealer and extension officers' networks

Effective communication and dissemination of biological pest-management approaches will require strengthening the capacity of both agro-dealers and extension officers. This study showed that, after fellow farmers, extension officers and agro-dealers were among the most cited sources of pest-management information (Figure 5.2). Therefore, these actors represent critical links between research institutions, regulatory agencies, input suppliers, and farming communities.

To effectively support farmers, extension officers and agro-dealers should receive comprehensive training not only on the characteristics and application of available pest-management options, but also on the specific information farmers require when evaluating new technologies. Training should cover the appropriate use of synthetic pesticides, biological alternatives, identification and conservation of natural enemies, and the principles of integrated pest management (Figure 5.3).

This would enable them to provide accurate, practical, and context-specific advice rather than simply promoting individual products. However, priority should be given to training agro-dealers, who, after fellow farmers, were identified as the most frequently consulted source of agricultural advice (Figure 5.2). Because farmers already visit agro-dealers regularly to purchase inputs, this existing relationship offers the most immediate and practical channel for disseminating information about biological alternatives.

In addition to technical knowledge, agro-dealers and extension officers require adequate resources and institutional support to effectively perform their roles. This includes access to updated technical materials, demonstration tools, and reliable information on registered biological products and their suppliers. Strengthening these networks will be essential for addressing the knowledge shortfalls identified in this study and building farmer confidence in alternative pest-management approaches.

Lastly, agro-dealers should be supported through appropriate market incentives and supply-chain strengthening measures to ensure that biological products are available through the same channels farmers already rely on for pest-management inputs. Encouraging agro-dealers to stock biological alternatives without addressing supply constraints, profitability concerns, and product availability may limit their ability to provide the technologies that farmers are being encouraged to adopt.

7.1.3 Improvement of product availability and regulatory support

For biological alternatives to become practical options for farmers, improvements in regulatory support and product availability are important. Although farmers in this study showed willingness to consider biological approaches when their effectiveness could be demonstrated (Figure 5.5), their adoption potential may remain limited if appropriate products are not available through established agricultural input channels. Therefore, government institutions and regulatory bodies must ensure that registration processes, guidelines, and implementation frameworks for biological products are effectively established and communicated to relevant stakeholders.

A coordinated approach is required across the entire implementation pathway: from regulatory approval and product suppliers, through agro-dealers, to the farmers who ultimately use these technologies. Delays or gaps at the institutional level can restrict product availability, weaken market development, and prevent farmers from accessing alternatives they are willing to consider. Specifically, regulatory authorities should establish clear timeframes for registration and licensing decisions and define explicit criteria for provisional licensing to enable faster market entry (Mawcha et al., 2025).

On the supply chain side, agro-dealers should be supported through targeted training and certification programmes that build their capacity to stock and advise on biological products, while policy incentives such as redirecting existing input subsidies toward biopesticides can improve both availability and affordability at the retail level (Tambo et al., 2024).

7.1.4 Promotion of conservation biological control and farmer awareness of natural enemies

The experiences of the two farmers who had observed natural enemies of *Tuta absoluta* provide important insights into the potential role of naturally occurring biological control within smallholder farming systems. Their observations demonstrate that beneficial organisms already present in the farming environment can contribute to pest suppression when they are recognized and conserved. Rather than relying solely on external inputs, farmers can be supported to work with existing conservation processes that provide pest-management benefits.

Therefore, farmer education should extend beyond commercial biological products to include awareness of natural enemies, their identification, and practices that support their survival and activity. Simple conservation measures, such as maintaining flowering plants, reducing unnecessary broad-spectrum pesticide applications, and creating habitats that support beneficial organisms, can help strengthen ecological pest regulation. By promoting conservation biological control, farmers may reduce reliance on synthetic pesticides while improving the sustainability of their production systems, even before commercial biological alternatives become widely available.

7.2 Study Limitations and Future Research

The sample size and geographic coverage constitute the main limitations of this study. Twenty-six participants drawn from a single locality (Mapinduzi, Mgera village, Kiwere Ward) limit the spatial representativeness of the data and reduce the extent to which the findings can be generalized beyond this community. Although participants provided rich, context-specific narratives, the study lacks a comparative baseline across neighbouring districts, which may differ in market structures, institutional support, and localized pest pressures.

The findings should therefore be understood as characterizing this community rather than as a complete representation of Iringa Region or of Tanzanian smallholder tomato production more broadly. Future studies should include larger samples across multiple locations to assess whether the patterns identified in this study are consistent across different smallholder tomato-producing communities.

These constraints reflect the conditions under which the fieldwork was conducted. Permit procedures, travel distances, and financial limitations narrowed the feasible study area, and a later-than-planned start reduced the time available for recruitment, inter-site travel, and follow-up probing. Recruitment relied on voluntary participation and was accordingly limited by the number of farmers available and willing to engage within the fieldwork timeframe. There should therefore be greater

time and resource allocation for future fieldwork to support more comprehensive data collection.

Another limitation relates to physical accessibility and the absence of direct field observation. Many cultivation plots were located at considerable distances from the central interview area and could not be visited within the available time and transport constraints. As a result, data collection was restricted to face-to-face interviews, without on-farm visits. While the semi-structured format allowed farmers to describe their management practices in detail, the inability to conduct field inspections reduced opportunities to directly observe pest pressure, input use and crop conditions, and to triangulate these observations with self-reported practices. Future studies should therefore incorporate on-farm visits and direct field observation to validate self-reported practices against actual pest pressure, input use, and crop conditions.

A further limitation is the pronounced gender imbalance in the sample, with 24 male and only 2 female respondents, and, notably, no women at all among the 22 active tomato cultivators, as both female participants were proxy observers. In this rural context, community interactions are strongly shaped by traditional cultural norms and social roles, and local feedback indicated that men typically speak on behalf of households in public or centralized forums, while women are less visible in such spaces. It is therefore highly likely that women contribute substantially to local tomato production and hold distinct perspectives on labour demands, pest impacts and risk, but were under-represented in the study. The combination of limited fieldwork time and these entrenched cultural dynamics created an unintended barrier to achieving a more gender-balanced and inclusive set of farmer experiences. Also, there is another possibility that because the crop was tomatoes, it might be more male-dominated in terms of cultivation, but the study did not ask or test this possibility. Future research should, thus, feature gender-sensitive recruitment strategies, such as conducting interviews within household settings or through women-only focus groups, to capture the perspectives and contributions of female farmers.

A further consideration relates to the interpretation of willingness-to-adopt scores. Because farmers had limited prior experience with biological alternatives, their responses may have been influenced by how the technologies were introduced during the interviews. The interpreters had also previously participated in a semiochemical attract-and-kill trial in the same locality and were therefore familiar with the technologies discussed, which may have influenced how biological alternatives were described. Additionally, one respondent had participated in an earlier semiochemical trial and was therefore not entirely new to these tools. These factors suggest that the willingness-to-adopt findings should be interpreted with

some caution. Future studies should consider using follow-up visits or post-demonstration assessments to measure willingness after farmers have gained direct experience with the technologies.

In practice, there were moments when the translator appeared to struggle with capturing the precise nuances or intent of certain questions, raising the possibility that some meaning or reasoning may have been lost, overemphasized or diluted before reaching the respondent. Moreover, interpreting is cognitively demanding and becomes increasingly taxing over long interview days; as fatigue sets in, the consistency and precision of translations may have declined. Taken together, these factors introduce an additional layer of interpretive noise into the dataset, which should be considered when assessing the depth and accuracy of the qualitative findings. Where possible, future research should employ bilingual enumerators with technical training in the subject matter to reduce interpreter-related variability.

Lastly, the broad objectives required some related concepts, such as awareness, knowledge, and experience with biological alternatives, to be considered together. Future studies could examine these and other dimensions separately to provide a more detailed understanding of their individual roles in farmers' adoption decisions.

7.3 Study contribution

Despite the stated limitations, this study contributes to the growing literature on biological pest-management adoption in smallholder farming systems in three ways. First, it moves beyond measuring awareness of biological products to highlight a deeper deficit in ecological understanding: farmers may observe naturally occurring pest-control agents such as ants and birds without recognizing them as forms of biological control. Second, the findings underscore the importance of agro-dealers and other agricultural information channels in shaping farmers' exposure to biological alternatives, while also revealing constraints in the information provided through these channels, particularly regarding the availability, use, and effectiveness of biological pest-management options. Third, the study provides farmer-level evidence from the Iringa region on perceptions, experiences, and willingness to adopt biological alternatives for *Tuta absoluta* management, contributing to the limited empirical understanding of how these approaches are perceived within smallholder tomato production systems.

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Popular science summary

Farmers want safer pest control - but no one has shown them the alternatives

Tomatoes are the most important horticultural crop in Tanzania for smallholder farmers. The crop, however, is constantly ravaged by a pest: *Tuta absoluta*, commonly known as the South American tomato leafminer, a moth that destroys harvests. Since its arrival in the country in 2014, it has spread to almost all the major tomato-growing regions, boring into leaves and fruits and causing significant financial losses to farmers.

To try to manage this situation as best as possible, farmers resort to using chemical pesticides, because that is what most of them know as a solution to the pest problem. So they spray more often than not because the pests are hard to get rid of. Unfortunately, the pesticides do not work as well as the farmers would like, leaving them frustrated but unable to stop. Farmers also experience side effects from the spraying - breathing difficulties, skin irritation, and crop damage from the chemicals themselves.

There are, nonetheless, other alternatives that can be used to address this problem: biological pest control methods. These include scent-based tools that mimic the moth's natural chemical signals to disrupt its mating behaviour, as well as natural enemies of the insect such as parasitic wasps and predatory insects. These help to reduce the infestation rate of the moth without causing environmental or health harm to the farmers. However, the question is: are farmers aware that these methods exist? If so, what do they know about them? Would they be willing to try them? And even if they are, can they have access to them, and are they affordable?

This study set out to answer those questions. Twenty-six farmers in Mapinduzi village, Iringa Rural District, were interviewed about their knowledge and experiences with biological pest control methods. They also shared what they thought about these methods, especially when comparing them to the chemical pesticides they already know and use, and what it would take for them to consider switching.

The problem is not simply resistance - it is limited awareness

The results were compelling. Every single farmer who took part in the interview knew about the pest - *Tuta absoluta* - and the damage it causes, all of them reporting severe losses. In contrast, about 70% of them had not even heard about biological pest control. In addition, none of the farmers had ever had any form of training on

the natural enemies of the insect from extension officers or other agricultural advisors.

Interestingly, two of the interviewed farmers had unknowingly observed nature doing its work on their own farms by way of natural enemies of the pest: brown ants and birds, both attacking the larvae of the moth. They observed that when these natural enemies were in full swing, the pest infestation rate was lower and yields were consequently higher. Yet, they had no idea that these were natural enemies of the pest or that what they were witnessing was a form of biological control. The awareness gap thus goes beyond not knowing which products exist; farmers lack the basic ecological understanding to recognize natural allies already active in their own fields.

Willing to change, but with nothing to change to

Even though most of the interviewed farmers knew very little about biological alternatives, they were not against them. When asked if they would be willing to adopt a method if it showed that it worked effectively in controlling the pest, all of them said yes. That means they are not opposed to new technology; they simply lack the information, practical demonstrations, and access needed to make the switch.

The study also found that farmers who were most worried about the health risks of synthetic pesticides were less likely to accept pest-management approaches that involve both synthetic pesticides and biological alternatives. These farmers also tended to be more concerned about the environmental effects of these pesticides. This suggests that adding biological control methods to existing chemical spraying methods may not be attractive to the farmers who are most concerned about their health and the environment.

On the supply side, the situation is equally grim. Interviews with 20 local agro-dealers, conducted as part of a parallel study, revealed that only one stocked a single biological product, priced at roughly five times the cost of a typical synthetic pesticide. Most dealers also lacked any form of training on biological pest control and may not be of help to farmers, even if they came to them for advice on such matters. The result is a closed loop: farmers cannot ask about products they are not aware of, while dealers are unlikely to stock products for which there is little demand.

What needs to happen

The study recommends several practical steps to address this issue. First, farmers need to be made aware of biological pest control methods and shown that they work.

In addition, the demonstrations should show farmers how these methods can reduce risks to their health and the environment, helping to address their worries. These practical sessions should take place on farms in their own communities under similar conditions, ideally led by trusted local farmers, to build confidence in the technology.

Second, agro-dealers and extension officers, who are important sources of information for farmers, should be well trained in biological pest control methods so they can provide farmers with reliable information and advice, while agro-dealers should also be supported to stock these products. Third, Tanzania's regulatory system needs to make it faster and easier for biological products to reach the market, with clear timeframes for registration and licensing decisions.

Finally, farmers should be helped to recognize and protect the natural enemies already present in their fields. Simple practices - such as reducing unnecessary spraying and maintaining natural habitats for beneficial insects - can strengthen natural pest control even before commercial biological products become widely available.

The central message of this study is clear: the main obstacle to adopting biological pest control among the farmers studied was not outright resistance to these alternatives. Rather, the alternatives remained largely unknown, undemonstrated, unavailable and, where available, expensive. Closing that gap requires action not just from farmers, but even more importantly from the institutions, supply chain participants, and knowledge systems around them.

Appendix 1

Sensitivity Analysis: Pooled Sample (N = 26) versus Active Tomato Cultivators Only (n = 22)

All main analyses were repeated using only the 22 respondents who reported an active tomato cultivation area, thereby excluding the four proxy observers. None of the findings reported in Chapter 5 change when the proxy observers are excluded.

Table A1.1: Spearman Rank Correlations with Willingness to Adopt an IPM Approach.

Predictor	N = 26 (p)	p	n = 22 (p)	p
Health-risk perception	−0.699	0.0001	−0.664	0.0007
Farm size	−0.404	0.0619	−0.404	0.0619
Environmental-risk perception	−0.210	0.3038	−0.223	0.3187
Market/income influence	−0.203	0.3190	−0.244	0.2730
Age	−0.179	0.3809	−0.374	0.0865

The observed association - a strong negative association between health-risk perception and willingness to adopt an integrated, chemical-inclusive approach - is unchanged in direction, magnitude and significance. No other predictor reaches significance in either sample. Farm size is identical across both columns because proxy observers, by definition, have no recorded tomato cultivation area and are excluded from this correlation in both samples.

Table A1.2: Key Categorical Outcomes.

Outcome	Response	N = 26	n = 22
Heard of biological alternatives	Yes	8 (30.8%)	6 (27.3%)
Aware of specific alternative tools	Yes	5 (19.2%)	4 (18.2%)
Would integrate with chemicals (IPM)	No	12 (46.2%)	9 (40.9%)
Willing to conserve natural enemies	Yes	17 (65.4%)	15 (68.2%)
	Maybe	4 (15.4%)	4 (18.2%)
	No	5 (19.2%)	3 (13.6%)

No outcome shifts materially between the two samples.

Table A1.3: Additional Group Comparisons Supplementing Table A1.5.

Variable	Test	Statistic	p	Direction
Gender	Fisher's exact	OR = 0	0.0185	0 of 22 cultivators were female
Environmental risk (1–5)	Kruskal–Wallis	$\chi^2 = 4.295$, df = 1	0.0382	Proxies rate higher
Health risk (1–5)	Kruskal–Wallis	$\chi^2 = 2.777$, df = 1	0.0957	Not significant

The gender difference arises because both female respondents in the study are proxy observers. Excluding the proxy observers would therefore have produced an entirely male sample, which constitutes a further reason for retaining them.

Table A1.4: Tomato Cultivation Area (Active Cultivators Only, $n=22$).

Statistic	Value
Median	3.0 acres
Mean	3.57 acres
Mean excluding largest holding	2.64 acres
Range	0.5 – 23.0 acres
Upper outlier fence ($Q3 + 1.5 \times IQR$)	7.56 acres

One respondent (aged 59, with 45 years of tomato cultivation experience) reported a farm size of 23 acres, placing the holding beyond the identified outlier fence and substantially above the other reported farm sizes. This respondent was retained in the analysis because he met the study eligibility criteria, and his responses on the main outcome variables were not notably different from those of the other respondents.

Table A1.5: Baseline Homogeneity and Methodological Validation of Survey Response Groups ($N=26$).

Statistical Test	Variables Analyzed (Between Active Tomato Cultivators and Proxy Observers)	Test Statistic / Parameters	p-value
Kruskal-Wallis Rank Sum Test	Age	$X^2 = 0.4112$ df = 1	0.5214

Statistical Test	Variables Analyzed (Between Active Tomato Cultivators and Proxy Observers)	Test Statistic / Parameters	p-value
	Farming experience	$X^2 = 0.0223$ df = 1	0.8813
Fisher's Exact Test	Education level	Exact Hypergeometric (Two-sided)	0.0987
	Awareness of biological alternatives	Exact Hypergeometric (Two-sided)	0.5633

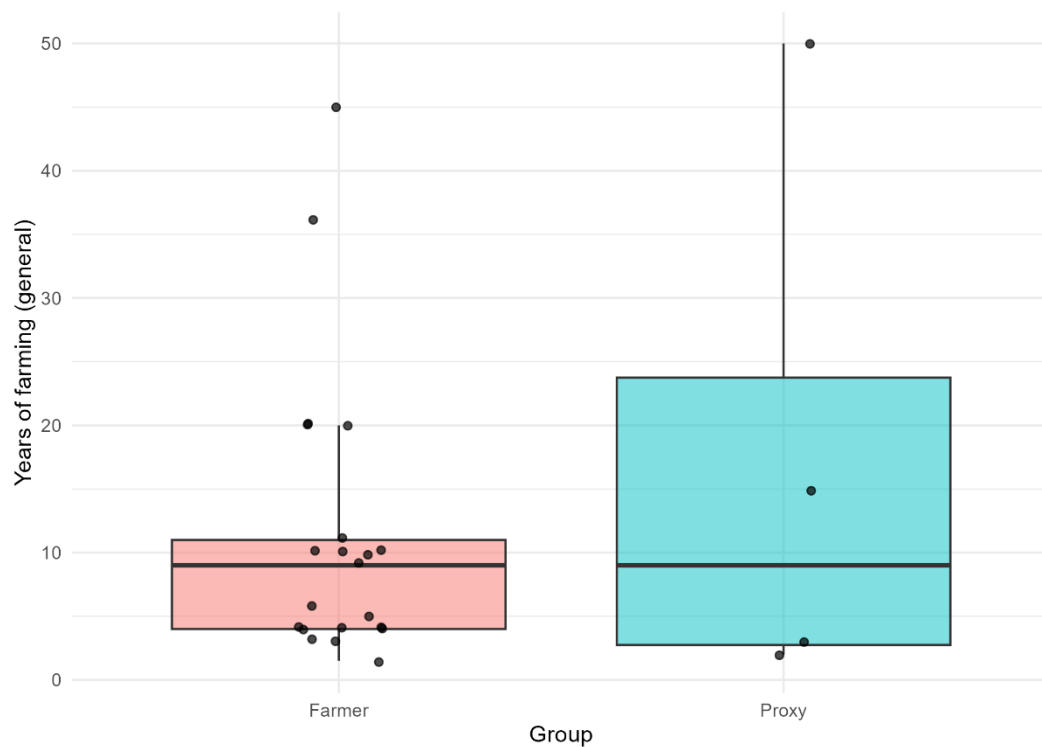


Figure A1.1. Boxplot Comparison with Jittered Data Points of General Farming Experience Longevity Between Active Farmers and Proxy Observers.

To verify that the general farming experience profiles of the two cohorts were statistically comparable, a Kruskal–Wallis test was conducted and visualized using a boxplot. Both the empirical test results ($X^2 = 0.02$, $p = 0.88$) and the graphical illustration - which displays identical median lines despite a wider interquartile

range for the proxy group - confirm that there is no statistically significant difference in farming experience between the active farmers and the proxy observers, as the p-value falls well above the standard $p = 0.05$ cutoff.

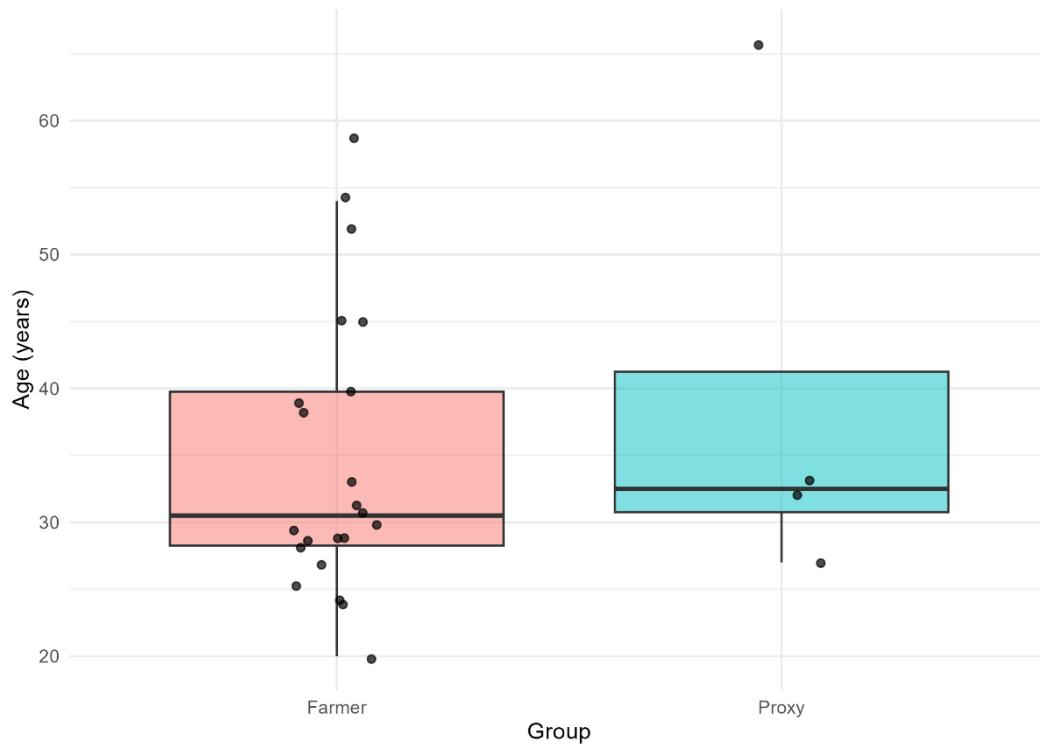


Figure A1.2. Boxplot Comparison with Jittered Data Points of Biological Age Distribution Between Active Farmers and Proxy Observers.

To verify that the age distributions of the two cohorts were statistically comparable, a Kruskal–Wallis test was conducted and visualized using a boxplot. Both the empirical test results ($X^2 = 0.41$, $p = 0.52$) and the graphical illustration - which displays nearly identical median lines and strongly overlapping interquartile ranges - confirm that there is no statistically significant difference in age between the active farmers and the proxy observers at the standard $p = 0.05$ significance threshold.

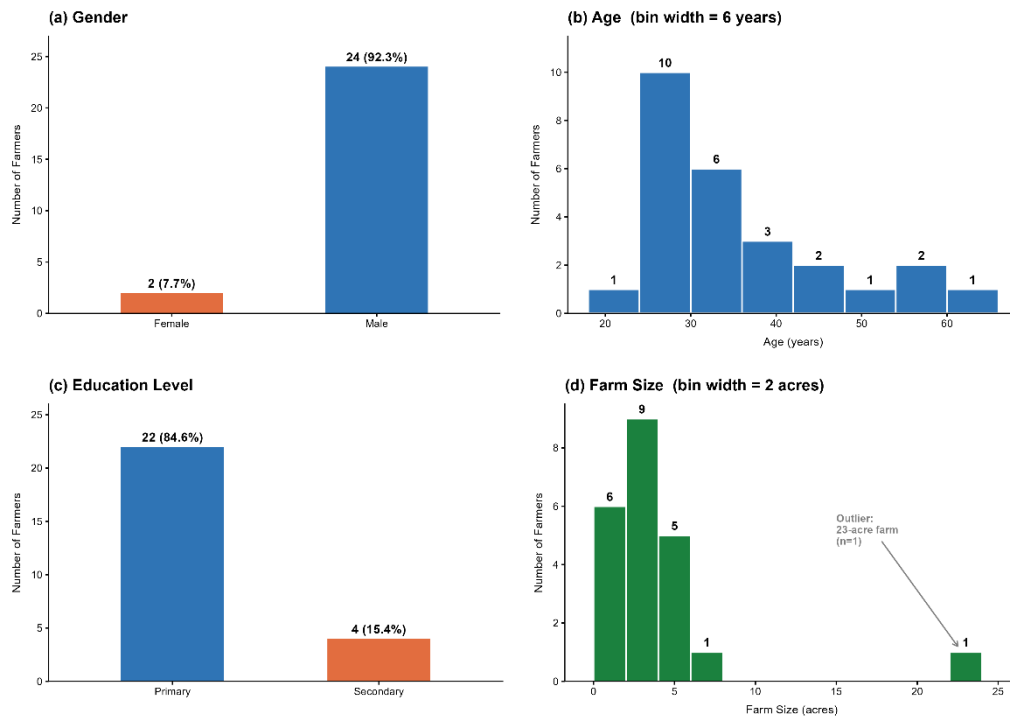


Figure A1.3. Demographic Profile of Surveyed Farmers in Mapinduzi Village (N=26).

This figure summarizes the demographic baseline of all pooled respondents, encompassing both active tomato farmers ($n = 22$) and proxy observers ($n = 4$). Panel A illustrates the gender distribution across the sample pool. Panel B shows the biological age distribution, with respondents ranging from 20 to 66 years. Panel C outlines formal education levels, indicating that the majority of participants completed primary school. Finally, Panel D groups agricultural land holdings, demonstrating that most respondents cultivate relatively small, smallholder plots.

Appendix 2

This appendix contains the full survey instrument used during data collection. The instrument also served as the interview guide for the semi-structured interviews, providing the exact questions and response categories used with all respondents.

Farmer Awareness & Socio-Economic Feasibility Questionnaire

Study Focus: Adoption of agricultural biological alternatives (semiochemicals and natural enemies) for *Tuta absoluta* management in Tanzanian tomato systems.

Interviewer: Naomi Korsah - MSc Plant Biology for Sustainable Production, Swedish University of Agricultural Sciences (SLU).

Project Title: Investigating the synergistic effects of semiochemicals and biocontrol on tomato yield and its socioeconomic benefit for smallholder farmers in Tanzania.

Introduction

My name is Naomi, and I am conducting research for my Master's studies at the Swedish University of Agricultural Sciences (SLU). My thesis explores safer, more effective ways to protect tomato crops from *Tuta absoluta*. Instead of relying only on synthetic pesticides, I am testing natural methods such as pheromone traps (semiochemicals) and beneficial insects (biocontrol). The study examines how these approaches can reduce crop damage, improve yields, and lower costs and labour for smallholder farmers in Tanzania.

Many farmers rely mainly on synthetic pesticides to fight this pest. While pesticides can help, they are expensive, can harm health, and sometimes stop working because the pest develops resistance. For these reasons, researchers (like me) are looking at safer and more sustainable methods. These include semiochemicals (pheromones used for trapping and disrupting the pest) and natural biological controls such as beneficial insects (natural enemies of the pest). These methods are already used successfully in other countries, but in Tanzania, we still need more information about how farmers view them and whether they are practical and affordable.

This survey will help us understand farmers' current practices, awareness of biological alternatives, and opinions about their safety, cost, and effectiveness. The results will provide evidence to guide extension officers, policymakers, and researchers in promoting better pest management strategies. By taking part, you are contributing to research that aims to reduce dependence on harmful pesticides,

improve farmer incomes, and build a more sustainable tomato production system in Tanzania.

Consent statement

You are being asked to take part in this survey about tomato farming and pest control. The survey will ask about your farming practices and your thoughts on new methods for controlling pests. Taking part is your choice. Your answers will be kept anonymous and will only be used for research. You can skip any question you do not want to answer, and you can stop at any time. By agreeing to answer the questions, you give your consent to take part in this study.

Do you agree to take part in this survey?

- ☐ Yes, I agree to participate
☐ No, I do not wish to participate

Section A: Background Information

1. Village/Location: _____
2. Age: ____
3. Gender: ☐ Male ☐ Female
4. Education level: ☐ None ☐ Primary ☐ Secondary ☐ College/University
5. Years of farming (general): ____ years
6. Years of tomato farming: ____ years
7. Farm size under tomato cultivation: ____ acres

Section B: Current Pest Management Practices

1. Do you use pesticides in your cropping system? ☐ Yes ☐ No
- If No, why not? _____
- If Yes, which types? ☐ Insecticides ☐ Herbicides ☐ Fungicides ☐

Nematacides ☐ Other (please specify): _____

2. For what purpose do you use pesticides? _____
3. How often do you apply pesticides during a tomato season?
☐ Weekly ☐ Twice per week ☐ Monthly ☐ Other (please specify): _____

4. What challenges do you face with synthetic pesticide use?
☐ High cost ☐ Limited availability ☐ Health risks ☐ Environmental concerns ☐ Pests becoming resistant to pesticides ☐ Other (please specify): _____

5. Please list and rank the top three (3) most serious pests, diseases, or weeds currently affecting your tomato yield.

Priority	Problem Name (e.g., Tuta absoluta, Blight) etc
1 (Most Serious)	

2 (serious)	
3 (least serious)	

6. Have you ever encountered the tomato leafminer (*Tuta absoluta*) on your farm?

☐ Yes, frequently ☐ Yes, occasionally ☐ No, never ☐ Not sure

- If yes:

a. What kind of damage did you observe on your tomato plants?

b. How severe was the damage?

☐ Mild (small leaf mines, limited crop loss) ☐ Moderate (noticeable leaf and fruit damage, some yield loss) ☐ Severe (widespread damage, major yield loss) ☐ Other (please specify): _____

7. Where do you usually get information or advice about *Tuta absoluta* and its management?

☐ Extension officers ☐ Fellow farmers ☐ Agro-dealers ☐ Radio/TV ☐ Farmer groups/cooperatives ☐ NGOs/projects ☐ Other (please specify): _____

8. Which of these sources do you trust the most, and how does it influence your decisions about adopting new pest management practices?

9. In your opinion, which socio-economic factors most affect farmers' willingness to adopt new pest management technologies?

☐ Income level ☐ Market access ☐ Education ☐ Extension services ☐ Cultural beliefs ☐ Other (please specify): _____

Section C: Biological Control Awareness

1. Have you heard of agricultural biological alternatives in general? ☐ Yes ☐ No

2. How would you define agricultural biological alternatives?

3. Are you aware of specific agricultural biological alternatives such as semiochemicals or natural enemies? ☐ Yes ☐ No

4. If yes, have you ever used any of these biological alternatives? ☐ Yes ☐ No

5. If you have used agricultural biological alternatives, how effective were they compared to synthetic pesticides? ☐ More effective ☐ Same effectiveness ☐ Less effective ☐ Not effective at all ☐ No idea
6. Do you use agricultural biological alternatives? ☐ Yes ☐ No
- i. If yes, which of the agricultural biological alternatives did you use?
- ii. How many years ago did you adopt any of the agricultural biological alternatives?
- iii. If No, why not? ☐ Availability ☐ Cost ☐ Access ☐ Low benefits ☐ Not aware ☐ No idea ☐ Other (please specify):

7. What factors influenced your decision to adopt or not adopt agricultural biological control? Please rank the following factors from most important (1) to least important (7) by writing the number in the box next to each factor.

Factor	Rank (1 = most important, 7 = least important)
Knowledge/awareness of biological control methods	
Perceived effectiveness in controlling pests	
Cost/affordability of biological control methods	
Availability/accessibility of products in local markets	
Labour intensity	
Trust in the product	
Training or extension support received	
Other (please specify):	

Section D: Objective III – Socio-Economic Feasibility

1. On a scale of 1 to 5, how much do environmental risks influence your decision on which pest control method to use? ☐ 1 = Not at all ☐ 2 = Slightly ☐ 3 = Moderately ☐ 4 = Strongly ☐ 5 = Very strongly
2. On a scale of 1 to 5, how much do health risks influence your decision on which pest control method to use? ☐ 1 = Not at all ☐ 2 = Slightly ☐ 3 = Moderately ☐ 4 = Strongly ☐ 5 = Very strongly
3. How accessible are agricultural biological alternatives in your area?
- ☐ Easily available ☐ Sometimes available ☐ Rarely available ☐ Not available ☐ No idea

4. How affordable are agricultural biological alternatives compared to synthetic pesticides?

☐ More affordable ☐ Same ☐ Less affordable ☐ No idea

5. On a scale of 1 to 5, how much do market prices/income influence your decision on which pest control method to use? ☐ 1 = Not at all ☐ 2 = Slightly ☐ 3 = Moderately ☐ 4 = Strongly ☐ 5 = Very strongly

6. Would you be willing to pay more for agricultural biological alternatives if they reduce health/environmental risks?

☐ Yes ☐ No ☐ Maybe

7. Do you agree that agricultural biological alternatives are economically viable for smallholder farmers?

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree.

8. On a scale of 1 (Much Worse) to 5 (Much Better), how do you compare Biological Alternatives to Synthetic Chemicals?

Feature	1 (Much Worse)	2 (worse)	3 (about the same)	4 (better)	5 (Much Better)	No idea
Efficacy (Pest-killing power)						
Plant Health (Leaf & fruit quality)						
Affordability (Total cost)						
Safety (For the farmer/family)						
Ease of Use (Labour/Application)						
Accessibility (Availability in shops)						

Section E: Objective IV – Perceptions & Adoption Factors

1. Would you integrate agricultural biological alternatives with synthetic pesticides (IPM approach)?

☐ Yes ☐ No ☐ Maybe

- If No/Maybe, what is the main reason?

2. Would you be willing to adopt agricultural biological alternatives if its effectiveness was proven?

☐ Yes ☐ No ☐ Maybe

Section F: Cost–Benefit Analysis of Biological Alternatives

1. Considering both costs and benefits (including health, environment, yield, and labour), how do you view biological alternatives compared to synthetic pesticides overall?

☐ Much better ☐ Better ☐ Same ☐ Worse ☐ Much worse ☐ No idea

2. How do biological alternatives compare to synthetic pesticides in terms of labour requirements (time and effort for preparation and application)?

☐ Requires much less labour ☐ Requires slightly less labour ☐ No difference

☐ Requires more labour ☐ No idea

3. Have biological alternatives affected your tomato yields or income compared to synthetic pesticides?

☐ Increased ☐ Stayed the same ☐ Decreased ☐ Not sure ☐ No idea

4. Do you feel the benefits of biological alternatives (e.g., safer for health, less resistance, environmental protection, labour costs) outweigh their costs?

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

5. If you have used biological alternatives, what drawbacks or challenges did you experience?

☐ Limited effectiveness ☐ Higher cost ☐ Difficult to access ☐ More training needed ☐ No idea ☐ Other (please specify): _____

Section G: Natural Enemies (Beneficial Insects) - Awareness, perceptions, and willingness to conserve natural enemies.

1. Have you ever observed natural enemies (e.g., lady beetles, lacewings, parasitoid wasps) in your tomato fields?

☐ Yes ☐ No ☐ Not sure

2. Which natural enemies do you recognize or can identify?

☐ Lady beetles ☐ Lacewings ☐ Parasitic wasps ☐ Predatory bugs ☐ No idea

☐ Other (please specify): _____

3. Can you distinguish between beneficial insects and harmful pest insects in your tomato fields?

☐ Yes, I can clearly identify them ☐ Sometimes, but I am not always sure ☐

No, I cannot distinguish between them ☐ If I had the knowledge, yes I would ☐ No idea

4. If you answered “Yes” or “Sometimes,” please give examples of insects you consider beneficial and those you consider harmful:

Beneficial: _____

Harmful: _____

5. How do you usually respond when you see beneficial insects in your field?

☐ Leave them ☐ Spray pesticides ☐ Encourage them (e.g., by reducing pesticide use, planting flowers) ☐ No idea ☐ Other (please specify):

6. Have extension officers or farmer groups ever trained you on identifying or conserving beneficial insects?

☐ Yes ☐ No ☐ Not sure

7. Would you be willing to conserve natural enemies (e.g., reduce pesticide use, plant flowering strips) if shown they effectively control *Tuta absoluta*?

☐ Yes ☐ No ☐ Maybe

8. If you have tried biological alternatives (e.g., pheromones or natural enemies), how has it affected your synthetic pesticide spraying frequency?

☐ Reduced synthetic pesticide sprays significantly ☐ Reduced synthetic pesticide sprays slightly ☐ No change in synthetic pesticide spraying ☐ Increased synthetic pesticide spraying ☐ No idea ☐ Other (please specify):

9. What challenges do you foresee in using natural enemies for pest control?

☐ Lack of knowledge ☐ Fear of ineffectiveness ☐ Difficulty accessing biological agents ☐ No idea ☐ Other (please specify):

10. Do you think natural enemies can provide long-term, sustainable pest control compared to chemicals?

☐ Strongly agree ☐ Agree ☐ Neutral ☐ Disagree ☐ Strongly disagree

11. Do you have any suggestions for improving pest management in tomato farming?

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