



Are biopesticides and integrated pest management feasible for controlling fall armyworm among smallholders in Battambang, Cambodia?

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List of Abbreviations

a.i.	Active ingredient
ANOVA	Analysis of variance
ASEAN	Association of Southeast Asian Nations
ASR	Agriculture System Research Cambodia Company Ltd.
BBCH	Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und Chemische Industrie
Bit	BITADIN WP
BiMe	BITADIN WP and METABE
BRI	Belt and Road Initiative
BT	<i>Bacillus thuringiensis</i>
CFU	Colony Forming Units
CPP	Cambodian People's Party
DAS	Days after sowing
DM	Dry matter with 14 % moisture content
ELCs	Economic land concessions
FAO	Food and Agriculture Organization of the United Nations
FAW	Fall armyworm
FFS	Farmer Field School
FM	Fresh matter
GDA	General Directorate of Agriculture
GDP	Gross domestic product
ha	Hectare
HCD	Human Center Design
HEKS	Hilfswerk der Evangelisch-reformierten Kirche Schweiz
ICM	Integrated Crop Management
IPM	Integrated Pest Management
IU	International Unit
KHR	Khmer Riel
KR	Khmer Rouge
MEM	Marginal estimated mean
Met	METABE
MSD	Market System Development
MAFF	Ministry of Agriculture, Forestry and Fisheries
MSL	Meters above mean sea level
NGO	Non Governmental Organization
Nee	Neem oil
Neg	Negative control
NUBB	National University of Battambang
PDAFF	Provincial Department of Agriculture, Forestry and Fisheries
PIB	Polyhedral inclusion bodies
Pos	Positive control
PPE	Personal protective equipment
SD	Standard deviation
SDC	Swiss Development Cooperation
ToT	Training of Trainers
w/w	Weight by weight

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List of artificial intelligence tools

ChatGPT, OpenAI, version GPT-4-turbo, chatgpt.com

- Assistance to find more accurate wording and to shorten paragraphs (Abstract)
- Assistance to find more accurate wording and to shorten paragraphs (Chapter 1)
- Assistance to find more accurate wording and to shorten paragraphs (Chapter 2)
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Abstract

RAUSER NOAH

The fall armyworm (FAW) is a global, highly invasive pest which affects millions of farmers and their food security in Africa, Asia and the Near East. The FAW has a huge potential for causing yield loss in maize, sorghum, rice and other cash crops. Estimations by Food and Agriculture Organization of the United Nations (FAO) for the risk of annual crop losses reach up to US\$ 18 billion. In the last decade, the pest has started to leave its native range in America and invaded huge areas in Africa, Asia and Australia. In 2019, the FAW was first reported in Cambodia. At this time, approximately 100'000 ha of maize and 3.2 million ha of rice were cultivated within the country, that could be affected by the FAW.

According to Association of Southeast Asian Nations Cambodia (ASEAN), Cambodia is not yet ready to tackle this devastating pest. The main gaps to address are a missing national FAW management strategy, lack of research on how to control the pest in the context of Cambodia, lack of knowledge dissemination about FAW and Integrated Pest Management (IPM) among farmers and other agricultural stakeholders. Furthermore, it is not clear which potential beneficials and parasitoids are currently present in Cambodia. An additional challenge is that farmers primarily rely on synthetic pesticides for pest management.

To narrow these gaps identified by ASEAN and tackle the issue of improper pesticide usage, this study about FAW was implemented under an IPM approach in the upland cropping area in the Battambang province, Cambodia.

To evaluate the efficacy, economic impact and farmers perception about three commercial biopesticides (Neem oil, *Beauveria bassiana* and *Metarhizium anisopliae*, *Bacillus thuringiensis* and different nucleopolyhedroviruses) compared to a positive control (Emamectin benzoate) and a negative control (no spray), both an on-station trial, with four replications, and a participatory on-farm trial, with eight replications, were established.

To examine the current management strategies of the FAW by the farmers, semi-structured interviews with eight farmers were conducted.

To assess the available FAW preventative and intervention management practices in Cambodia, key person interviews were conducted with the head of the ASEAN FAW Action Plan, a deputy director from Provincial Department of Agriculture, Forestry and Fisheries in Battambang and two biopesticide sellers. The findings from the interviews were complemented with scientific literature.

For the on-station trial, we concluded that the positive control and the biopesticides, except Neem oil, significantly reduced the foliar damage. The positive control achieved the highest kernel yield (4277 kg/ha) and the highest gross profit (1088 US\$/ha). The most profitable biopesticide achieved 1009 US\$/ha.

In the on-farm trial, the biopesticides and the positive control showed no effect, due to lack of rainfall and poor crop management. The limitations of the crop management among farmers were lack of knowledge and lack of financial resources.

Regarding the current management of the FAW by the farmers, we found that they consciously rely exclusively on synthetic insecticides and their most important information sources for pest management are input shops, followed by fellow farmers.

The key person interviews revealed that currently only synthetic insecticides are available in rural areas. Biopesticides, such as the ones evaluated in the field trials, play currently no crucial role for the pest management of Cambodian farmers. Furthermore, different bottlenecks on the market level were identified such as lack of monitoring and control by the government, inconsistent quality of products and a low quality of knowledge which is transmitted to the farmers.

Therefore, the recommendations for an improved FAW control management are the usage of synthetic insecticides according to an IPM approach in the short-term. And in the long-term, biopesticides should start to play an ever-increasing critical role in an IPM strategy for FAW management due to their various benefits.

Further gaps to address among smallholder farmers are knowledge dissemination about FAW, IPM, crop management and shifting precipitation patterns by the relevant actors in the agricultural sector.

Keywords: Biopesticides, Cambodia, fall armyworm, Integrated Pest Management, smallholders

1 Introduction

The fall armyworm *Spodoptera frugiperda* (FAW), is a global and highly polyphagous insect pest (Prasanna et al. 2021 cited in Kenis et al. 2022) and the protagonist of this scientific paper. In recent years the FAW became a huge threat to the crops and the food security of millions of farmers (Day et al. 2017; Harrison et al. 2019) in Africa, Asia and the Near East (FAO 2020a).

The FAW became a significant threat, primarily due to the high migration ability and fertility of the female moth, as well as its adaptability as a pest (Kenis et al. 2022). The moth can travel up to 250 km in a single night (Jia et al. 2021 cited in Kenis et al. 2022) and the female moth can lay up to 1500 eggs per life cycle (Huang et al. 2021 cited in Kenis et al. 2022). Its offspring, the larva, feeds primarily on maize, rice, sorghum and other plants belonging to the botanical family of *Poacea* (Montezano et al. 2018). If their preferred host plants are not available, the FAW can switch to over 350 other plant species from different botanical families (Montezano et al. 2018).

FAW primarily causes great economic damage in cereals, forage and grasses, especially maize, rice and sorghum. Other important arable crops which are affected by FAW are soybean and cotton (Barros et al. 2010; Oliveira et al. 2014; Wu et al. 2021).

Estimations by Food and Agriculture Organization of the United Nations (FAO) (2020) for the risk of annual crop losses due to FAW in Africa, Asia and the Near East reach up to US\$ 18 billion. Therefore FAO (2020) considers the FAW as one of the top 10 devastating agricultural plant pests in a global view. The Association of Southeast Asian Nations (ASEAN) (2020) estimates crop losses, due to ineffective FAW control management, worth US\$ 880 million per year for the region.

In recent years, the FAW left its native range in the Americas (Kenis et al. 2022) and invaded Africa, Asia, the Near East and Australia (FAO 2020a). It was first observed in Africa in 2016 (FAO 2020a; CABI 2021), before it was reported for the first time in Cambodia in 2019 (Hadi 2019).

In 2019, almost 100'000 hectares of maize were cultivated in Cambodia (EuroCham 2023b, 13).

According to ASEAN, Cambodia is not yet ready to tackle this devastating pest (ASEAN 2020). A lack of research on how to control FAW and a missing FAW management strategy have been identified as the main gaps to address it properly (ASEAN 2020). Further constraints identified by ASEAN for an effective FAW control are lack of knowledge dissemination about FAW and Integrated Pest Management (IPM) such as Farmer Field Schools (FFS) and Training of Trainer (ToT) programs (ASEAN 2020). Other gaps are lack of FAW monitoring and identification and monitoring of potential beneficials and parasitoids (ASEAN 2020).

Additionally, farmers in Cambodia predominantly rely on synthetic pesticides for pest management (Bureau-Point et al. 2024). Furthermore, farmers frequently receive biased information on pest management from so-called input shops (Bureau-Point et al. 2024). Biopesticides, compared to synthetic pesticides, are often more target-specific and regularly have lower toxicity to humans and the environment (Nuruzzaman et al. 2019, 69), but do not play a vital role in the pesticide market (Pesticide Register Cambodia, 2019) or in pest management practices on Cambodian farms (Bureau-Point et al. 2024).

To narrow the gaps identified by ASEAN and tackle the issue of improper pesticide usage, this study about FAW is conducted under the umbrella of the local Nurture project (see chapter "2.1 Nurture Project").

The overall objective of the study is to assess the available FAW management practices in Cambodia, examine how farmers currently manage FAW, and evaluate the efficacy of commercially available biopesticides. The findings will be used to develop IPM recommendations for improved FAW control management by local smallholders and for future research (for a detailed overview of the objectives and research questions, see chapter "1.1 Study objective and Research Questions").

To investigate the control methods available for FAW in Cambodia, expert interviews are conducted. To assess the efficacy of commercially available biopesticides, both an on-station trial for agronomic data and a participatory on-farm trial to gather farmers perceptions about the treatments are carried out. To explore how farmers currently manage FAW and to assess existing knowledge and knowledge dissemination gaps, semi-structured interviews with farmers are conducted.

Currently, not only FAW but also other pests within the *Spodoptera* genus are threatening the crops of Cambodian farmers (TPPP 2024). Various armyworm species cause damage to cassava, vegetables, rice, and other crops (TPPP 2024; Delatouche 2024, personal communication). Distinguishing between these

armyworm larvae is often challenging due to high intraspecific variability and overlapping morphological characteristics among species (EPPO 2015, 2). Consequently, these pests are sometimes misidentified in the field (Delatouche 2024, personal communication). However, these other species of the *Spodoptera* genus are not included in this study.

Throughout the writing process of the study, artificial intelligence tools were used, particularly ChatGPT. It was used to find more accurate wording and to shorten paragraphs.

1.1 Study objective and Research Questions

1.1.1 Research questions

The main research questions for this study are:

- What preventative and intervention FAW management options are available in Cambodia (with a focus on Northwestern Cambodia) and what is known about the efficacy, strengths and weaknesses of the methods?
- How is the accessibility (awareness, know-how, affordability, cultural) for smallholder farmers for the different available FAW preventative and intervention management options in Cambodia?
- Where do farmers primarily get information for management of insect pest in maize from and how do they evaluate the usefulness of the different information channels?
- What methods are farmers using to manage FAW in maize in the region and how do they evaluate the efficacy, strengths and weaknesses of the different methods?
- How do commercially available biopesticides (BITADIN WP, METABE, Neem oil) perform compared to frequently used synthetic insecticides in terms of yield, vegetative damage and economic impact? How do farmers evaluate them?
- How do smallholders assess the economic impact of FAW on maize production in Northwestern Cambodia?
- What are recommendations to optimize FAW-management of smallholders in Cambodia according to an IPM approach? What are recommendations for further research and capacity building in Cambodia?

1.1.2 Research Objectives

The main objective of this study is:

To give an overview of available FAW management practices in maize in Northwestern Cambodia, to assess current management practices by farmers and to evaluate the efficacy of commercial bio-pesticides, in order to devise IPM recommendations for local smallholders and further research.

Secondary objectives are:

- To create an overview of available preventive and intervention strategies for FAW control in Northwestern Cambodia, and summarize the strengths and weaknesses of the methods.
- To evaluate the efficacy of biopesticides and the impact on smallholders profit and to assess possible constraints for their adoption
- To document farmers assessment of the economic impact of FAW, and their main sources of information for insect pest management

2 Current State of Research

2.1 Nurture Project and Context of this study

The Nurture project, to which this internship and study contributes to, wants to increase the climate resilience of smallholder farmers in Cambodia (Suess and Melara 2022, 5). The overall goal is the following: "Vulnerable smallholder farming households and their communities are more resilient to climate change and have increased incomes through climate proofing of agroecological farming systems" (Suess and Melara 2022, 5).

This goal is aimed to be achieved with a systemic approach because building climate resilience among smallholder farmers is multi-dimensional and a highly complex process (Suess and Melara 2022, 47). The applied methods are the Market System Development (MSD) approach and the Human Center Design (HCD) solution development (Suess and Melara 2022, 47). In short, the MSD approach aims at developing markets so that they function more effectively, sustainably, and beneficially for a particular target group.

For the Nurture project this means it will work on a system level with existing actors from the private and public sector to support them to work differently, to help developing new business models, to increase their capacities and to create multi-stakeholder partnerships. The HCD helps thereby to understand the perspective of the target group (Suess and Melara 2022, 47). Especially to assess their difficulties, ambitions and needs (Suess and Melara 2022, 47) and to jointly develop and evaluate solutions (Suess and Melara 2022, 47).

The Nurture project was established in 2023 by the two Swiss Non-Governmental Organizations (NGOs): Hilfswerk der Evangelisch-reformierten Kirche Schweiz (HEKS) and Caritas Switzerland and will be implemented over four years (Suess and Melara 2022, 2). The total project budget amounts to US\$ 9 million, with each of the mentioned NGOs contributing a quarter, and the remaining half funded by the Swiss Development Cooperation (Suess and Melara 2022, 8).

The project target area includes four provinces in the north of Cambodia, with Battambang province being one of them (Suess and Melara 2022, 5). Its primary target group are vulnerable smallholder farmers, especially women involved in agriculture and other disadvantaged groups (Suess and Melara 2022, 39). Further target groups of the project are farmer water user communities and agricultural cooperatives (Suess and Melara 2022, 39).

To achieve its overall goal mentioned at the beginning of this chapter, the Nurture will follow the theory of change described in the strategic framework below (see Figure 1). Within this the three main outcomes are (Suess and Melara 2022, 22):

- Vulnerable smallholder farmers have increased yields and reduced climate risks through better and more stable access to water for irrigation
- Vulnerable smallholder farmers and their communities and the private sector, benefit from greater participation and responsive planning and policies related to climate change adaptation
- Vulnerable smallholder farmers adopt agroecological practices and diversify their sources of income

This internship and the bachelor's thesis contribute to the third outcome of the project. By the examination of the extent to which the pest pressure caused by the fall armyworm can be reduced with integrated pest management and biopesticides, thereby changing the farm's income. The research activities are mainly implemented with Nurture and its local private partner Agricultural Systems Research Co. Ltd. (ASR).

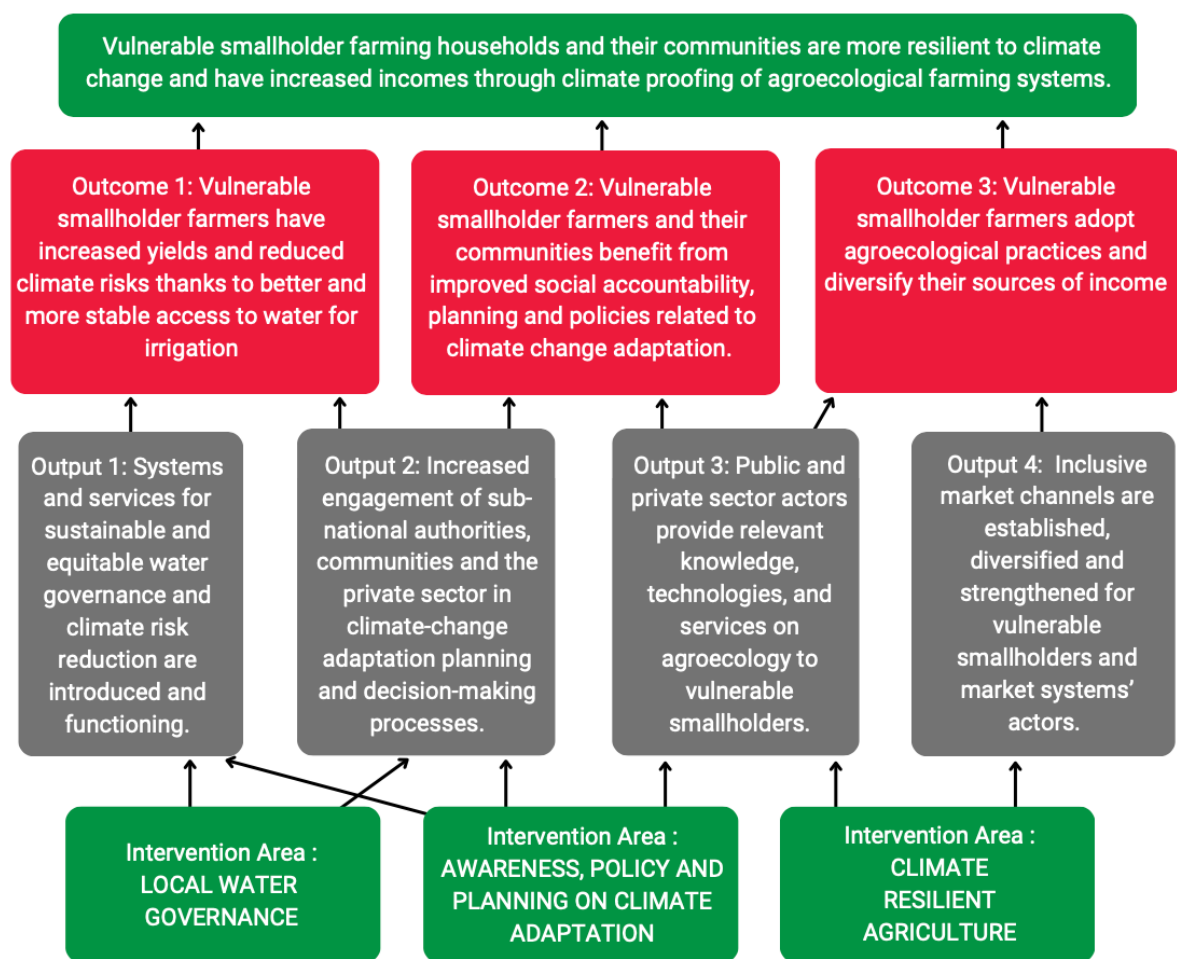


Figure 1: The strategic framework of the Nurture project (Source: Suess and Melara 2022, 23):

2.2 Context of Cambodia

Geography and climate

Cambodia is a parliamentary constitutional monarchy (PRESSOCM 2017) bordering the gulf of Thailand (Britannica 2024).

The country covers an area of 181'035 km² (MFAIC no date) which is approximately four times the size of Switzerland (ARE no date). Cambodia has approximately 17 million inhabitants (WBG no date) from whom approximately 74 % live in rural areas (WBG no date). The largest city in the country is the capital Phnom Penh with estimated 2'352'680 inhabitants (WPR no date). The official language in Cambodia is Khmer, spoken by about 96 % of the population (Britannica 2024). The official currency of Cambodia is the Khmer Riel (KHR) (Im and Dabadie 2007, 2). However, the country's economy is highly influenced by the US dollar (Im and Dabadie 2007, 5).

Education in Cambodia has improved considerably over the past two decades (UNICEF no date). In the 2017/18 school year, 97 % of children were enrolled in primary education (UNICEF no date). Despite this progress, the quality of education remains low (UNICEF no date). At the primary level, 25 % of children in the third Grade are unable to write a single word in a dictation (UNICEF no date). The improvements in education have contributed to an increase in the literacy rate among adults, aged 15 and older (TPPP 2021). In 2019, Cambodia's literacy rate reached 87.7 %, up from 77.6 % a decade earlier (TPPP 2021).

The country's landscape is mainly characterized by a vast low lying central alluvial plain, surrounded by uplands and mountains at the coast, the north and the eastern part of the country (Britannica 2024). In the northwest, the Tonle Sap is located, the largest freshwater lake of Southeast Asia (GNF 2016). A further crucial hydrological feature is the Mekong River, which meanders through the country and plays an important role in Cambodia's water supply (Britannica 2024).

Except for the coastal region, Cambodia is bordered by neighboring countries Thailand, Laos, and Vietnam (Britannica 2024).

Cambodia experiences two distinct seasons driven by the monsoon winds. The wet season occurs from May to October, while the dry season extends from November to April (Britannica 2024; WBG and ADB 2021, 5). Annual precipitation across the country varies highly, ranging from 1'270 mm in the central plain to 5'000 mm in the southern highlands (Britannica 2024). The mean annual temperature in Cambodia is 28 °C (Thoeun 2015). The maximum temperature is reached in April with 38 °C on average, while the coolest temperatures are usually recorded in January or December, dropping to 14 °C on average (UNDP no date).

Overall, the country is perceived as very vulnerable to climate change and is ranked 130th out of 187 countries by the Notre Dame Global Adaptation Initiative (2022). It seems highly vulnerable and not yet ready to cope with climate change (ND-GAIN 2022). The incidence of heatwaves and other adverse weather events with grave repercussions on agricultural yields is likely to continue under all different emission pathway scenarios for Cambodia (WBG and ADB 2021, 13).

Economy, public institutions and Khmer rouge

From 2016 to 2019, Cambodia has experienced an average annual gross domestic product (GDP) growth rate of 7.1 % (ADB 2021), like in the previous two decades (ADB 2021). Cambodia is globally one of the fastest rising economies (ADB 2021). Garment sector, tourism, agriculture and recently construction and real estate sector had been the drivers of the economic growth since the turn of the millennium (ADB 2021). In 2023, Cambodia's GDP reached approximately US\$31.77 billion, while Switzerland's GDP during the same period was US\$884.94 billion for comparison. The GDP in Cambodia in 2022 was composed of contributions from agriculture at 22.2 %, industry at 37.9 %, and services at 33.8 %. (Statista 2024).

Within the agricultural sector, crop production had the highest contribution to the national GDP with 13.0 %, followed by fisheries with 5.5 % and livestock at 2.6 % (ADB 2021).

According to estimations of the International Labour Organization, about 37 % of total workforce population of 9.1 million people (TE no date) in Cambodia was occupied in the agricultural sector in 2022 (WBG no date).

This economic growth significantly reduced the proportion of Cambodians living in poverty (Karamba and Tong 2022). In 2009, 33.8 % of the population was below the poverty line (Karamba and Tong 2022). Over the span of a decade, this number was nearly halved, dropping to 17.8 % in 2019 (Karamba and Tong 2022), resulting in almost 2 million Cambodians escaping poverty. The national poverty line, as defined by the government, is set at 10'951 KHR per person per day (Karamba and Tong 2022), approximately equivalent to US\$ 2.7 per day.

In recent years, China was a top investor in Cambodia and thereby an important driver of its economic growth, followed by Singapore and South Korea (ASEAN Briefing 2022; Leng 2019). In 2021, China had a share of 48 % of the total Foreign Direct Investment in Cambodia (ASEAN Briefing 2022). Between 2012 and 2017, China invested under the Belt and Road Initiative (BRI) more than US\$ 15 billion in Cambodia for infrastructure, such as roads, ports and airports, and invested another US\$ 11 billion in the energy sector alone (ASEAN Briefing 2022).

This high influx of Chinese capital and local and national governmental support led to a speculative land market with a new phase of dispossession (Goldman 2020). Under this system, the Cambodian government has allocated land to foreign investors, often using forceful evictions, repressive laws, and questionable policy reforms (Beban et al. 2017; Loughlin and Milne 2021). The primary victims of this systematic land grabbing were often smallholder farmers and indigenous people (Hak et al. 2018). By 2012, more than 2 million ha of rural land had been annexed and given to investors through economic land concessions (ELCs) (Hak et al. 2018). These ELCs, which were often allocated for agro-industrial development (Hak et al. 2018), were frequently accompanied by forest clearing and significant land degradation. According to Rudel (2015), such land acquisitions have been a driving factor behind the deforestation in Cambodia.

This all happens under an atmosphere of political fear and corruption, which was created during the last few decades by the former prime minister Hun Sen and the elites in Cambodian People's Party (CPP) (Loughlin 2023). These favored elites are establishing a system of political and economic control in the hands of the CPP (Loughlin and Milne 2021). Therefore, it is not surprising that Cambodia is ranked 158th out of 180 countries on the Corruption Perception Index (TI 2024). The lower the ranking the less is the country's public sector perceived as corrupt (TI 2024).

The current situation is heavily influenced by Cambodia's history over the past decades (BTI 2024). Persistent violence since the 1960s, which lasted for 30 years and culminated in the Khmer Rouge (KR) genocide, left deep traumas in society that have yet to be fully addressed (BTI 2024). Nearly two million people are believed to have died under the Khmer Rouge regime from 1975 to 1979 due to overwork, malnutrition, and execution (Naron 2011, cited in Hill and Menon 2013). During the KR regime, which lasted from 1975 until 1979, many of the country's institutions were destroyed or overturned (Naron 2011 cited in Hill and Menon 2013).

2.3 Agriculture in Battambang

The northwest of Cambodia, including the Battambang province, served as a stronghold for the KR, where they organized resistance against governmental forces during the 1980s and 1990s (Kong et al. 2019). To finance their guerrilla war against the Cambodian government, the KR exploited Cambodia's natural resources, especially through extensive logging in the region. Between 1990 and 1998, the KR exported a total of 2.5 million m³ of logs (Kong et al. 2019). Following the peace agreement with the government, the reintegration policy allowed former KR members to settle in these areas and assume responsibility for land management (Kong et al. 2019). The allocation of forest land to demobilize soldiers opened the agricultural frontier, which spurred further migration to the region (Diepart and Dupuis 2014 cited in Kong et al. 2019; Montgomery et al. 2017a). The peak of the migration flow was from 1998 to 2000 (Kong et al. 2019). This led to an immense forest loss in the western part of the Battambang province between 2006 and 2016 (Sourn et al. 2021). Nowadays, 25 % of the province remain covered with forest (Sourn et al. 2021) while roughly 59 % of the total provincial area are used for crop cultivation (Kong et al. 2019) (see Figure 2). Over the whole country, the forest cover went down from 13.3 Mha in 1960 to 8.6 Mha in 2016 (Tsujino and Yumoto 2019). After clearing the forest, the soil fertility was high and thus maize production very profitable (Brown and Johnstone 2012 cited in Montgomery et al. 2017a). Maize and later cassava dominated the upland farming system, reducing crop diversity in the region (Brown and Johnstone 2012 cited in Montgomery et al. 2017a).

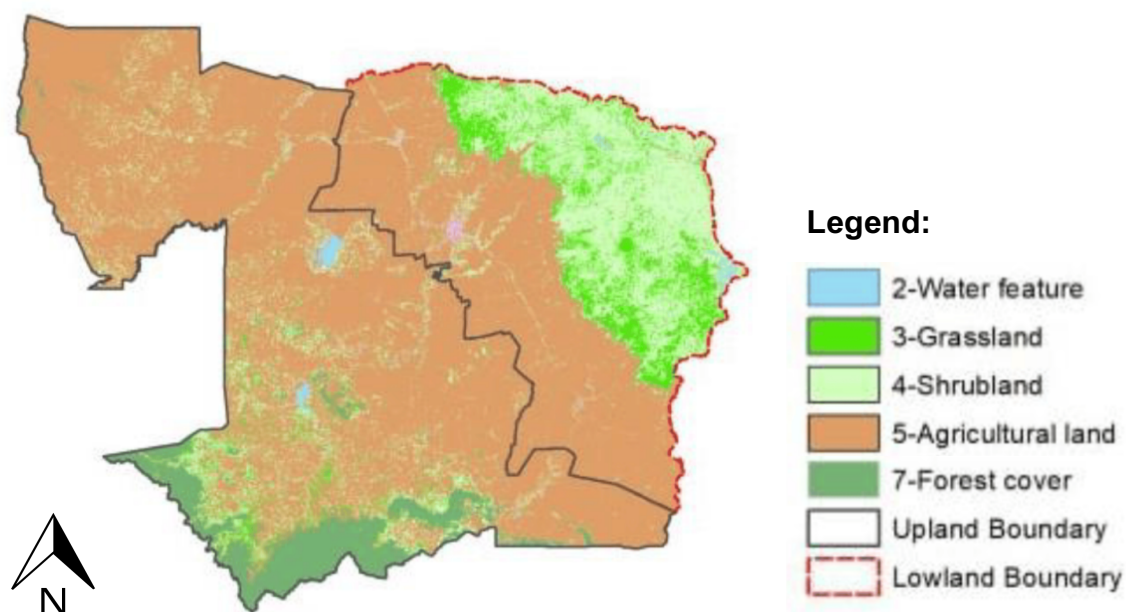


Figure 2: Land use pattern in Battambang province in 2018 with the upland and lowland cropping area (Source : Adapted from Sourn et al. 2022)

The traditional rotational and diversified cropping systems which included soybean, peanut and mung beans in the upland cropping area were substituted by cassava and maize (Kong et al. 2021; Montgomery et al. 2017a). Rice remains the main crop in Battambang's farming systems, alongside upland crops (maize and cassava) (EuroCham 2023a, 12). In addition, most smallholder household's income in the Battambang province is diversified through livestock (i.e. cattle, water buffalo, pigs, chicken and ducks) (Ecker and Diao 2011 cited in Gill et al. 2020; Dany et al. 2016 cited in Gill et al. 2020). Cattle and water buffalos are particularly important to smallholders as a source of wealth accumulation like a bank account (Olmo et al. 2016 cited in Gill et al. 2020). These ruminants are mainly fed with rice straw, native grasses collected at roadsides (cut and carry) or the ruminants are brought to communal grazing areas (Gill et al. 2020).

The Battambang province is known for its fertile soils and is called the rice chamber of Cambodia (Nesbitt 1997, 15 - 31). The conditions in the Battambang province are very favorable for rice cultivation, due to its flat terrain and the very fertile soils for Cambodian conditions (Nesbitt 1997, 31). This soil fertility is due to long-term deposition from the mountains within Cambodia and the sediments from the regularly flooding of the plains by the Tonle Sap (Nesbitt 1997, 15). Depending on access and availability of water, rice farmers can harvest rice between two or three times per year (Nesbitt 1997, 71). Nowadays, Battambang is the leading rice production area in Cambodia with a total harvest of 339'600 tons in the season 2018/19 (EuroCham 2023a, 12). For maize production, the Battambang province is the leading producer as well (EuroCham 2023b, 12). Of the total annual maize production in Cambodia with 350'000 tons in 2019, more than half of it was contributed by the Battambang province with 185'700 tons (EuroCham 2023b, 12). In 2019, the total maize cropping area in Cambodia was 99'000 ha with an average yield of 4.8 tons/ha (EuroCham 2023b, 13). The average maize yield in the Battambang province in 2013 was 5.4 tons/ha, exceeding the national average of 4.3 tons/ha (Pheakdey 2014). The region, where the on-farm trial takes place (Montgomery et al. 2017b), reported an average maize yield of 3.4 tons/ha. The maize in Cambodia is mainly cultivated by smallholder farmers. The average maize area per farm is 1.5 ha (Pheakdey 2014). Most farmers in the area are paying less attention to practicing mixed cropping. They tend to practice mono cropping to increase their income by cultivating maize, cassava and other cash crops (Pheakdey 2014).

The farmers in the upland cropping area try to attempt two crop cycles per year (Montgomery et al. 2017b). The farmers plant the first maize cycle "dam dai" (Nget 2024, personal communication) in the wet season in April if the rainfall conditions allow (Montgomery et al. 2017b). Sometimes the first planting fails due to erratic rainfall during this time of the year (Chan et al. 2009 cited in Montgomery et al. 2017b). The second planting "jiang dai" (Nget 2024, personal communication) starts in July/August after the harvest and the burning or incorporation of the crop residues (Montgomery et al. 2017b). Most farmers extensively plough the fields before planting (Montgomery et al. 2017b). Most farmers in Cambodia apply chemical pesticides for the maize production. They use insecticides, herbicides, fungicides and other chemicals to enhance crop development (Pheakdey 2014). In recent years, the farmers faced several challenges and constraints in the maize value chain. The market price of maize is fluctuating due to the unstable markets. For instance, in August 2012, the cob maize price in the North-West of Cambodia was 0.125 US\$/kg and decreased to 0.1 US\$/kg in August 2013, due to the reducing number of traders involved in this sector (Pheakdey 2014). This unstable price makes smallholder farmers suffer from debt of the bank. Farmers also have very limited access to market information. Farmers normally make distress sales of their crops immediately after the harvest, since they need to repay their loans, pay for their daily living expenses and meet other financial obligations, particularly field operation costs for the next crop after the harvest (Pheakdey 2014). As a result, farmers are often obliged to sell their crops immediately after the harvest despite low prices offered by traders. Almost the whole yield in Cambodia is sold within the first three months after the harvest. Also due to poor post-harvest techniques and storing facilities (Pheakdey 2014). The main part of the harvest is processed to livestock feed in domestic feed mills according to official sources (EuroCham 2023b, 16). Other sources state that the majority of the harvest is exported to neighboring countries like Thailand and Vietnam through informal channels (Pheakdey 2014; Belfield and Brown 2009). Edible maize has as long history in Cambodia since the 17th century (EuroCham 2023b, 9), and nowadays edible maize is only produced on a small scale for local consumption as boiled or roasted maize cobs (EuroCham 2023b, 16). Other challenges besides the high volatility of market price are low intensive agricultural practices due to lack of knowledge at the farm level (Pheakdey 2014). Furthermore, farmers often face crop loss and failure due to increasing rainfall variability (Montgomery et al. 2016). Almost 70 % of the farmers interviewed in the upland cropping area report drought as the major constraint for their production (Montgomery et al. 2016). Additionally, soil fertility is diminishing due to erosion and monocropping, which further reduces yields (Montgomery et al. 2016; Kong et al. 2021).

2.4 Fall armyworm *Spodoptera frugiperda*

The fall armyworm (FAW) is a highly invasive, polyphagous and nocturnal lepidopteran pest (Prasanna et al. 2021 cited in Kenis et al. 2022) which originates in tropical and subtropical areas of North, Central and South America (Kenis et al. 2022).

Since its first observation in 2016 in Africa, it has now invaded all tropical and parts of sub-tropical Africa, Near-East, Asia and Australia, mainly targeting maize and other food crops (FAO 2020a; CABI 2021). For Cambodia, FAW was first reported in 2019 (Hadi 2019).

In the regions of origin and in the recently invaded areas, the FAW causes great economic damage (Day et al. 2017; Mitchell 1979). Alone for Sub Saharan Africa, the annual loss for major food crops is estimated at US\$ 13 billion (Day et al. 2017). For Africa, Asia and Near East FAO (2020) estimates a risk for annual crop losses due to FAW worth US\$ 18 billion and thereby a huge threat to the food security of millions of farmers (Day et al. 2017; Harrison et al. 2019).

FAO (2020) considers the FAW as one of the top ten devastating agricultural plant pests in a global view.

The FAW belongs to the *Spodoptera* genus (Pogue 2002 cited in Kenis et al. 2022). In this genus, there are about 15 lepidopteran pest species which cause economic damage to agricultural crops (Pogue 2022 cited in Kenis et al. 2022). The FAW looks similar and is often misidentified with the beet armyworm *Spodoptera exigua*, the cotton leaf worm *Spodoptera litura* and African cotton leaf worm *Spodoptera littoralis* (Goergen et al. 2016 cited in Kenis et al. 2022).

In North America, one of its native ranges, FAW survives year-round only in southern Florida and some regions of Texas (Tessnow et al. 2023). This is because FAW becomes inactive at low temperatures (Keosentse et al. 2021 cited in Kenis et al. 2022) and cannot survive temperatures below 0°C (Tessnow et al. 2023; Meagher and Nagoshi 2004 cited in Kenis et al. 2022).

The FAW must develop new immature life stages year-round to stay at certain locations (Tessnow et al. 2023) because it cannot diapause (Keosentse et al. 2021 cited in Kenis et al. 2022).

After overwintering, the FAW can invade and colonize huge areas (Tessnow et al. 2023) due to its high migration ability and its high fertility (Kenis et al. 2022). In northern America, seasonal migration occurs over thousands of kilometers from southern Texas up to Canada (Nagoshi et al. 2012 cited in Kenis et al. 2022). It has been shown that the FAW moth can migrate up to 250 km in one night (Jia et al. 2021 cited in Kenis et al. 2022) and that under optimal conditions, a female moth can lay up to 1500 eggs per life cycle (Huang et al. 2021 cited in Kenis et al. 2022).

At first a female moth (see Figure 3) deposits grey, brown or whitish colored eggs masses (see Figure 4) with a hairy cover on the underside of the leaves (FAO and CABI 2019, 8).

When there is a high abundance of FAW in the area, the moths may lay its eggs on top of the leaves or plant stems (FAO and CABI 2019, 8).



Figure 3: The male fall armyworm moth is shown on the left, displaying its characteristic whitish spots at the center and near the tips of the wings. On the right is the female fall armyworm moth (Source: Adapted from UF 2020).



Figure 4: Whitish colored fall armyworm egg mass with a hairy cover on maize.



Figure 5: Newly hatched larva of the fall armyworm with spines on the body (Source: UF 2020)



Figure 6: Fall armyworm larva with four dark spots forming a square on the second last body segment.

At optimal temperatures ($\approx 30^{\circ}\text{C}$), the larvae hatch already after two days (du Plessis et al. 2020 cited in Kenis et al. 2022). On maize plants, after hatching the larvae move quickly to the funnel (FAO and CABI 2019, 9). At this stage the larvae are approximately 2 mm with a green colored body and a black head (see Figure 5) (UF 2020). Then the larvae begin their development, typically going through six instar levels (Kenis et al. 2022). On less suitable host plants and with lower temperatures, there are usually more than six instar levels (Montezano et al. 2019 cited in Kenis et al. 2022). In the higher larval stages, the larvae are up to 35 mm long of brownish, green color with bright dorsal lines (UF 2020). On the reddish-brown head there is a typical inverted “Y” visible and on the body the larvae have dark colored dots with small spines (UF 2020). On the second last body segment the larvae have four dark spots forming a square (see Figure 6) (UF 2020). The larval stages last from 10 days at approximately 32°C to more than 30 days when the temperature is below 20°C (du Plessis et al. 2020 cited in Kenis et al. 2022). Larvae exhibit the highest survival rates between 26 and 30°C (Kenis et al. 2022).

The pupation usually happens in the soil (Kenis et al. 2022), 2 to 8 cm below the surface (UF 2020).



Figure 7: Reddish brown fall armyworm pupa (Source: NC STATE no date).



Figure 8: On the left is the female fall armyworm pupa, characterized by the larger distance between the genitalia and the anal slit, while on the right is the male fall armyworm pupa. (Source: Adapted from Navasero and Navasero 2020).

When the soil is too compact the larvae pupate also in the plant litter or in the maize cob (FAO and CABI 2019, 10). The pupae are red and brown colored (see Figure 7) (FAO and CABI 2019, 10) and normally between 20 and 30 mm long. One can visually determine the sex at this development stage (Sharanabasappa et al. 2021; Odhiambo and Ondasi 2020, 5). For the female pupae, the distance between the genital opening and the anal opening is larger as for the male pupae (Sharanabasappa et al. 2021; Odhiambo and Ondasi 2020, 5). Furthermore, the ninth and tenth segments of the pupa curves strongly

to the genital opening of the female which is not the case for the male (see Figure 8) (Odhiambo and Ondasi 2020, 5).

At approximately 30°C, the pupal stage lasts about eight to nine days (Kenis et al. 2022). At 18°C, the pupal stage can last up to thirty days (Kenis et al. 2022).

After hatching, it takes few days for the female moth before initiating oviposition (Habib et al. 1982). During their entire lifespan, which is approximately between two and three weeks (Kenis et al. 2022), female moths mate with different male moth (Simmons and Marti 1992).

The life cycle and the reproductive parameters of the FAW are generally impacted by the temperature (Ramirez-Garcia et al. 1987). The development rate of the FAW depends highly on the temperature (du Plessis et al. 2020 cited in Kenis et al. 2022) and their diet (Gergs and Baden 2021 cited in Kenis et al. 2022).

Between 18 and 30°C, the development rate increases linearly with rising temperatures (du Plessis et al. 2020 cited in Kenis et al. 2022). The optimal range for egg-to-adult development is between 26 and 30°C, while a plateau occurs at slightly higher temperatures (du Plessis et al. 2020 cited in Kenis et al. 2022). Consequently, the life cycle is completed in approximately 30 days under optimal conditions at 28°C and can extend up to 90 days at lower temperatures (Kenis et al. 2022).

It appears that the FAW exists in two closely related strains (Pashley et al. 1985; Pashley 1986). The rice strain and the maize strain which differ in their host plant distribution (Pashley 1986). The rice strain seems to occur mainly in pasture habitats with grass species and millet (Pashley 1986) whereas the maize strain is associated with maize and sorghum (Pashley 1986).

However, recently it was demonstrated in the laboratory that both strains preferred maize plants for oviposition (Ingber et al. 2021). Furthermore, it was reported that both strains feed well on both maize and rice plants, though they gained more weight when fed on maize (Ingber et al. 2021).

Besides maize and rice, Montezano et al. (2018) reported that FAW can feed on more than 350 host plants. Most of the reported host plants belong to the botanical family of *Poaceae* followed by *Asteraceae* and *Fabaceae* (Montezano et al. 2018). However, one has to consider that a lot of these records of host plants might be made due to the ballooning and not by real maternal oviposition on these plants (Prasanna et al. 2021, 144). Ballooning refers to the ability of newly hatched FAW larvae to secrete a silk thread, allowing them to be carried by air currents to nearby plants (Li et al. 2023). This behavior may serve as a strategy to avoid competition and cannibalism, which frequently starts to occur between larvae two to four days after hatching (Li et al. 2023).

Primarily FAW causes economic damage in cereals, forage and grasses, especially maize, rice and sorghum. Other important arable crops which are affected by FAW are soybean and cotton (Barros et al. 2010; Oliveira et al. 2014; Wu et al. 2021).

In maize, FAW damage occurs through the destruction of seedlings, consumption of leaves that reduces the photosynthetic area, and direct feeding on the ear, which directly decreases kernel yield (Capinera 2008; Vilarinho et al. 2011). Moreover, ear feeding can create entry points for infestations by saprotrophic and pathogenic fungi on the cob (Farias et al. 2014).

FAW larvae feed on all crop stages and all aerial plant parts in maize (Prasanna et al. 2021). But primarily they feed on the plant whorl (Prasanna et al. 2021). Depending on the severity of infestation and on the crop stage the plant can recover from the damage especially when the plants are growing fast (Midega et al. 2023, 2). The impact of FAW on yield will be greatest if the growing point is damaged or if there is huge defoliation around flowering and tasseling (Prasanna et al. 2021).

Midega et al. (2023, 2) investigated the relation between observed plant damage and reduced yield of data from Africa. They reported no significance but with increased observed severity of plant damage the yield tended to decrease (Midega et al. 2023, 6).

According to Midega et al. (2023, 2), there exists almost no data about quantified yield loss due to FAW for Asia.

For the ASEAN region, the estimated annual crop loss is 10 % due to ineffective FAW control (ASEAN 2020). This results in costs of over US\$ 880 million per year for the region (ASEAN 2020). Regarding the FAW control in Cambodia, ASEAN (2020) identified various important gaps to address. They reported there is lack of research on how to control FAW and a missing FAW management strategy (ASEAN 2020). Furthermore, they identified as constraints knowledge dissemination for FAW and IPM lack of Farmer Field Schools and Training of Trainer programmes (ASEAN 2020). Other gaps are lack of FAW monitoring and identification and monitoring of potential beneficials and parasitoids (ASEAN 2020).

2.5 Integrated Pest Management

There are more than a hundred different definitions for Integrated Pest Management (IPM) (Deguine et al. 2021). In this paper we are using the definition of Food and Agriculture Organization of the United Nations (FAO). FAO defines IPM as an ecosystem approach for crop protection and a production that combines different pest management strategies and methods to grow healthy crops and reduces the use of pesticides (FAO 2024). IPM considers all the local available pest control methods (FAO 2024). Every intervention is applied based on economically justified thresholds (FAO 2024). IPM considers the economic, ecological and toxicological properties of an applied method or technology and gives priority to control methods with minimized risk to human health, environment and the lowest possible disruption of the agroecosystem (FAO 2024).

According to ECHO Staff (2022), IPM focuses on the long-term pest control management using a combination of prevention and suppressive methods. IPM approaches should always be adapted to a specific context (ECHO Staff 2022), such as the ecosystem and the scale of operation, from smallholder farmers up to very large businesses (ECHO Staff 2022).

IPM considers only one or few pests occurring in a field and not all the pests at once of a particular crop (Coll and Wajnberg 2017). IPM is a less holistic approach as Integrated Crop Management (ICM) which considers the interdependence of soil health, pest management, water management and crop nutrition for producing crops in a sustainable way (CABI 2024). But within ICM, IPM has a core function (CABI 2024).

Barzman et al. (2015) recommend to apply eight key principles of the IPM approach. One should use them in a dynamic and flexible manner considering the context (Barzman et al. 2015). The eight principles are built upon each other in a sequential rationale. This structure requires that each principle is considered in order (Barzman et al. 2015).

In the following, the eight IPM principles are described in detail.

1. Prevention and suppression

Pest prevention is the minimization of the potential for pests to be present in a field and to cause damage (ECHO Staff 2022). Preventative methods create conditions which are not favorable for pests. For example, plant varieties with toxic compounds for pests or soil cultivation when the pests reproduce in the soil (ECHO Staff 2022). According to Barzman et al. (2015), suppressive methods complement the preventative methods by decreasing the incidence and the severity of pests. There are four preventative methods that can be applied in an escalating manner, CULTURAL, MECHANICAL, BIOLOGICAL and CHEMICAL preventative methods (ECHO Staff 2022).

CULTURAL preventative methods are the use of certified seeds which are free from pathogen and weeds (Barzman et al. 2015). One should use seeds which germinate quickly and grow well (Barzman et al. 2015; ECHO Staff 2022). Furthermore, plant varieties that are not preferred by pests. Pest tolerant or resistant plant varieties (ECHO Staff 2022). Crop rotations belong to the cultural preventative methods too. One should implement in a cropping system plant species from different families, because often plants from the same family are susceptible to similar pests and diseases (Barzman et al. 2015; ECHO Staff 2022). Additionally, one can alternate winter and spring-summer crops to break the life cycle of pests, particularly of weeds (Barzman et al. 2015). If possible, applying spatial diversification of plant species within the field (Barzman et al. 2015; ECHO Staff 2022) and around the field (Barzman et al. 2015).

MECHANICAL preventative methods physically exclude pests from the crop (ECHO Staff 2022). This can involve using nets, fences, row covers, and various types of mulches (ECHO Staff 2022).

BIOLOGICAL preventative methods primarily focus on habitat management and increasing biodiversity of both animal and plant species (ECHO Staff 2022). Conserving native areas, such as hedgerows around crops, can support populations of beneficial insects that prey on pests (ECHO Staff 2022). Additionally, planting trap crops around the field can divert and attract specific pests away from the primary crop (ECHO Staff 2022). Trap crops belong to the host range of these pests, and in some cases, pests are unable to complete their life cycle on the trap crops (ECHO Staff 2022).

The last preventative methods are the CHEMICAL one (ECHO Staff 2022). Based on experience from previous cropping seasons or on a set schedule which keeps pests from entering an area one can apply preventative sprays (ECHO Staff 2022). But the preventative sprays are not recommended because they may lead to pesticide resistance (ECHO Staff 2022).

2. Monitoring

To determine which pests are abundant in a crop, regular monitoring in a systematic pattern is required (Barzman et al. 2015). Monitoring can occur at the field level, the regional level, or even across multiple countries, as seen with *Phytophthora infestans* in the European Union (Barzman et al. 2015). This data is then provided to decision-makers through plant protection advisory and recommendation systems (Barzman et al. 2015).

Monitoring helps identify the pests present in a field, estimate their density, and assess their developmental stage, which is critical for the next principle, decision-making (Barzman et al. 2015; ECHO Staff 2022). The monitoring includes the sampling of pests in the field (ECHO Staff 2022). For insect pests, this means active sampling or sampling by traps, such as pheromone lures or yellow sticky-traps (ECHO Staff 2022). For both methods, it is eminent to know where to sample and how to sample (ECHO Staff 2022). Otherwise, it could lead to an over- or underestimation of the actual pest population in a crop, because the insect pests are not always evenly distributed in a field (ECHO Staff 2022).

3. Decision making based on monitoring and threshold

Thresholds play a crucial role in deciding whether to apply intervention pest control methods (Barzman et al. 2015). However, these thresholds are often unavailable or inapplicable (Barzman et al. 2015). For instance, thresholds frequently do not exist for weeds (Sattin et al. 1992) or pathogens (Underwood et al. 2007). When thresholds are unavailable, it may be more effective to emphasize the importance of monitoring, establish clear decision-making rules, and consider the full set of IPM principles (Barzman et al. 2015).

The intervention threshold usually depends on several factors such as crop stage, potential value of the crop, type of insect, where on the crop the damage happens and other factors (ECHO Staff 2022). Normally, with increased financial value of the crop, the damage boundaries decrease (ECHO Staff 2022). As shown in Figure 9, different damage boundaries exist, depending on the size of the pest population (ECHO Staff 2022). The economic threshold is the point at which, if no intervention occurs and the pest population continues to grow, profit loss will result from the damage (ECHO Staff 2022). It is generally recommended to apply control methods when the economic threshold is reached. Below this damage boundary, spraying is not economically justified (ECHO Staff 2022). The upper damage boundary is the economic injury level, where the value of crop loss due to the pest exceeds the cost of the intervention (ECHO Staff 2022).

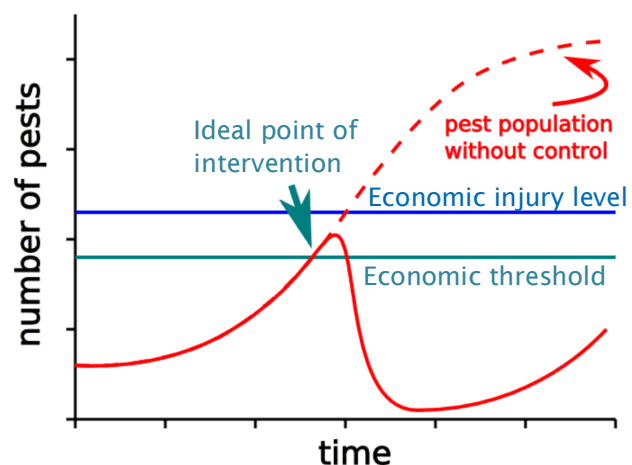


Figure 9: The red dashed line represents the pest population without control. The red solid line illustrates the population trend when an intervention is applied after reaching the economic threshold. (Source: Adapted from eOrganic 2009).

4. Non-chemical intervention methods

Non chemical intervention methods are categorized in the same order as the preventative methods.

CULTURAL intervention methods for example are the removal of alternative host plants to reduce the pest population (ECHO Staff 2022). By removing some plant parts of the main crop, one can increase the airflow between the plants and thus reduce the relative humidity and the population of diseases (ECHO Staff 2022).

MECHANICAL intervention methods can be distinguished in passive and active methods. Passive methods are applied and then impact the pest. For example, the application of kaolin clay on plants which hinders pests from feeding on plant tissue or diatomaceous earth which is spread on plant whorls as a feeding deterrent for larvae (ECHO Staff 2022). The active methods immediately impact the pest such as pre-emergence soil cultivation, mechanical weeding with hoes for intra-row weeding (Barzman et al. 2015), manually collection of caterpillars or the application of hot water on weeds (ECHO Staff 2022).

BIOLOGICAL intervention methods are living organisms that are chosen based on the targeted species (ECHO Staff 2022).

Biological control methods are for example predators which are reintroduced in a region, the introduction of parasitoids which are not native to a region or the application of entomopathogenic fungi and viruses (ECHO Staff 2022).

Biological control methods often must be applied in combination with other control methods to be effective and in view of a long term IPM strategy and investment in the agroecosystem (Barzman et al. 2015; ECHO Staff 2022), because individually they may be less efficient or convenient than synthetic pesticides (Barzman et al. 2015).

5. Pesticide selection

When prevention and alternative control methods alone do not achieve satisfactory results, selective pesticides are also used. In such cases, Principles 5, 6, and 7, which assume the use of pesticides, become relevant (Barzman et al. 2015). The rational selection of pesticides that minimize risks to human health and the environment is crucial (Barzman et al. 2015). It is important to choose pesticides that minimize disruption of the agroecosystem (Barzman et al. 2015). This means choosing pesticides which have an impact on the targeted organisms but not on non-targeted species, i.e. to avoid collateral damage (ECHO Staff 2022).

In addition to selecting the appropriate pesticide, other factors should be considered when using pesticides (ECHO Staff 2022). One should always use adequate personal protective equipment (PPE) during preparing, mixing, applying and disposal of pesticides (ECHO Staff 2022). Before spraying, it is essential to check air temperature, wind speed, rainfall, and plant physiology (ECHO Staff 2022). Spraying should be done early in the morning or late in the evening when temperatures are lower (ECHO Staff 2022). Spraying pesticides should be avoided when wind speeds exceed 3 m/s (Ramseier 2022, personal communication) or immediately before, during, or after rainfall (ECHO Staff 2022).

6. Reduced pesticide use

The volume of applied pesticides should be reduced, whenever possible, to contribute to the IPM goal of minimizing risks to human health and the environment (Barzman et al. 2015). In fact, national pesticide plans have adopted reduced use as a key goal for pesticide application (Barzman et al. 2015; Admin 2024). Strategies for reducing pesticide use include methods such as spot spraying, band spraying, and lowering the frequency of application by using resistant crop varieties (Barzman et al. 2015).

7. Non-resistance strategies

In an IPM approach, implementing an anti-resistance strategy for target species is crucial (Barzman et al. 2015). The occurrence of resistance in the targeted pest species can be reduced by fully utilizing preventative measures before using the pesticide (Barzman et al. 2015). Additionally, alternating the mode of action of pesticides decreases the risk of resistance (Barzman et al. 2015). This is particularly

important when considering that past cropping systems in tendency often became over-simplified, relying on monocultures and only few crop protection measures, which has contributed to resistance, especially in weeds (Barzman et al. 2015).

8. Evaluation

The last principle is the evaluation of the applied methods. Thereby it is important to monitor the preventative methods as well as the intervention methods (Barzman et al. 2015; ECHO Staff 2022). It is important to not only assess the efficacy of methods by using criteria such as absolute yield per hectare and the absolute absence of pests such as weeds in a field (Barzman et al. 2015) because this can hinder the adoption of IPM (Barzman et al. 2015). Additionally, many methods within an IPM approach take weeks, months, or even years to fully unfold their effects, and often benefit not just a single crop but multiple crops over time (Barzman et al. 2015; ECHO Staff 2022).

IPM for FAW

In managing any pest through an IPM approach, emphasis should be placed on long-term control fitting the specific context (Barzman et al. 2015; ECHO Staff 2022). Therefore, the IPM principles and steps outlined above should be integrated into a comprehensive, long-term FAW control strategy. Various factors and criteria must be considered, such as local climate, as FAW abundance often decreases during the peak rainy season (Niassy et al. 2021). For instance, young larvae can be washed off leaves during heavy rainfall, while older larvae may drown in the plant whorl (Varella et al. 2015).

Additionally, factors such as landscape structure and elevation, which impact the local climate and the abundance of FAW (Groote et al. 2020), current local crop management practices, existing natural enemies of FAW (Prasanna et al. 2021, 115), action thresholds that indicate intervention differ between regions (Prasanna et al. 2021, 11), as well as locally available and accessible biopesticides and synthetic insecticides (Prasanna et al. 2021, 66), should all be considered. These elements, among others, are critical to developing a context-specific IPM approach for effective FAW management.

In the table below (see Table 1) a brief overview of existing preventative and intervention based IPM methods for controlling FAW is provided based on scientific literature. The table is not intended to be complete or cover all globally and commercially available methods. Rather, it aims to give the reader an understanding of different methods to control FAW.

Table 1: In the table an overview of existing preventative and intervention based integrated pest management methods for controlling fall armyworm are provided.

		Method:	Source:
Preventative	Cultural	Planting date: Ensure that all farmers in an area plant the maize within the same time frame, otherwise, staggered planting provides a continuous food source of young maize plants for FAW larvae.	(FAO 2018, 14)
		Soil fertility and soil moisture: Improved soil fertility and soil moisture are critical to grow healthy and resilient maize plants.	(FAO 2018, 14)
		Crop rotation: Implement crop rotation patterns in the cropping system. This can include plants which are less preferred by FAW or non-host plants. Although FAW may reproduce on host plants around the field this method often reduces the population.	(FAO 2020c, 3)
		Soil cultivation: Different studies have found that maize fields prepared with reduced tillage, or zero tillage had less damage than maize fields prepared with conventional tillage. This may be primarily due to an increased layer of crop residues on the soil surface, which leads to a higher density of general predators and natural enemies of the FAW larvae and pupae.	(Baudron et al. 2019; Mutyambai et al. 2022; FAO 2020b)

		Use of tolerant maize varieties: The International Maize and Wheat Improvement Center (CIMMYT) is screening and breeding maize varieties that are tolerant to FAW. Since 2018, these tolerant varieties have been distributed to national research and breeding institutes for further development. Use tolerant maize varieties if they are available locally.	(Prasanna et al. 2021, 102)
		Plant diversity in the field: Increase plant diversity in the maize field through intercropping or other systems. This may help distract adult moths, reduce the availability of preferred host plants for the larvae and increase the abundance of natural enemies such as parasitoids and predators.	(FAO 2018, 14)
		Fertilizer management: Implement a well-balanced fertilizer strategy to ensure vigorous and healthy plants. Inappropriate use of inorganic fertilizer can attract more pests resulting in higher plant damage	(Morales et al. 2001; Harrison et al. 2019)
	Mechanical	Apply ash, sand, sawdust, or soil into the plant whorl: This can help prevent larvae from feeding on maize plants. Additionally, the soil may contain entomopathogenic nematodes, viruses or bacteria that can infect the larvae.	(FAO 2018, 20)
		Frequent weeding: Frequent weeding tends to decrease the damage by FAW. This might be mainly due to the removal of other host plants in the field and due to that pupae are not covered by weeds and therefore exposed to the environment.	(Baudron et al. 2019; Mengesha et al. 2023)
	Biological	Push-pull technology: Plant Napier grass, or in drier areas, the <i>Brachiaria</i> hybrid cultivar Mulato II, around the maize field to attract moths for egg-laying on the grass. Due to its poor nutritional value, only a few larvae survive on the grass. Within the field, intercrop with <i>Desmodium</i> , which emits volatiles that repel FAW and enriches the soil with nitrogen.	(FAO 2018, 18)
		Spray fish soup and sugar: Some farmers in Central America and Africa reported to spray fish soup, sugary sprays and other things on the maize plants to attract ants and wasps. The predatory ants are attracted by the smell and once on the maize plants, they also find and eat FAW larvae.	(FAO 2018, 20)
		Augment the population of beneficials: Plant hedgerows around the field and use target-specific insecticides with minimal impact on beneficial organisms like parasitoids and predators. This approach supports the population growth of naturally occurring beneficials, such as <i>Telenomus remus</i> , <i>Trichogramma</i> species, ladybird beetles, and others.	(FAO 2018, 26)
	Chemical	Pheromone-based mating disruption technology: Use synthetic sex pheromones, which are normally emitted by female moths to attract male moths for mating. When these pheromones are released in the field, the air becomes saturated with the pheromone. This pheromone cloud confuses the male moths, preventing them from locating females to mate with.	(Prasanna et al. 2021, 73)
	Mechanical	Crush egg masses and young larvae: Visit the maize field at least twice a week and crush the visible egg masses and larvae by hand.	(FAO 2018, 20)
Intervention	Biological	Application of biopesticides: Apply biopesticides to the plant whorl, including entomopathogenic bacteria, fungi, viruses, and plant extracts. Examples include <i>Bacillus</i>	(Prasanna et al. 2021, 15)

		<i>thuringiensis</i> (BT), baculovirus, <i>Beauveria bassiana</i> , <i>Metarhizium anisopliae</i> , neem oil (Azadirachtin) and others. Often biopesticides are more target specific as synthetic insecticides and less harmful for humans and the environment.	
		Collection of entomopathogens in the field: Some farmers recycle naturally occurring entomopathogens by collecting larvae killed by viruses or fungi, grinding them, straining out the body parts (leaving only the fungal spores or viroid particles), mixing the filtrate with water, and spraying it back into the whorls of the maize plants.	(FAO 2018, 20)
		Mass rearing and releasing of beneficials: Parasitoids and predators for FAW have been mass-reared and released on a large scale in the past. For example, the egg parasitoid <i>Telenomus remus</i> was used in the 1990s in Venezuela, and <i>Trichogramma</i> species were mass-reared and released in various countries affected by FAW. When mass-releasing beneficials, an IPM approach should be considered, and broad-spectrum insecticides should be avoided in release fields.	(Colmenarez et al. 2022; Navik et al. 2023)
	Chemical	Application of target specific synthetic insecticides: When the economic threshold is reached, it is recommended to use target-specific synthetic insecticides with the least possible impact on human health, the environment, and other organisms. Selecting a synthetic insecticide requires balancing efficacy, cost, safety, environmental risk, and availability. Today, there are several modern, low-toxicity, low-environmental-risk insecticides, including both synthetic options and biopesticides, that are highly effective against FAW. However, these insecticides are typically more expensive than older products, and some are not widely available in many developing countries. Some synthetic insecticides that could potentially be recommended for an IPM approach include: Chlorantraniliprole, Cyantraniliprole, Methoxyfenozide, Spinetoram and Spinosad.	(Prasanna et al. 2021, 69)

3 Material and Methods

3.1 Secondary data collection

The literature review was conducted alongside primary data collection by using Web of Science, Ovid and Google Scholar. The supervising lecturer provided additional scientific articles. The main key words which were used for secondary data collection are the following: Fall armyworm, *Spodoptera frugiperda*, Cambodia, biopesticides, IPM and Integrated Pest Management.

The following scientific papers were pivotal to my comprehension of the FAW, IPM approaches, and served as key references throughout the research and thesis-writing process:

- Invasiveness, biology, ecology, and management of the fall armyworm, *Spodoptera frugiperda* (Kenis et al. 2022)
- The Efficacy of Alternative, Environmentally Friendly Plant Protection Measures for Control of Fall Armyworm, *Spodoptera Frugiperda*, in Maize (Babendreier et al. 2020)
- Fall Armyworm Field Handbook: Identification and Management (FAO and CABI 2019)
- Eight principles of integrated pest management (Barzman et al. 2015)
- Integrated Pest Management (ECHO Staff 2022)

3.2 Primary data collection

Primary data collection involved two field trials, a farmer evaluation of one trial, and semi-structured interviews with both farmers and experts on FAW in Cambodia.

The following subchapters describe the different material and methods used.

3.2.1 On-station trial

Research site and crop management

The field trial was established on the farm of the apostolic prefecture in Battambang (13.07855, 103.26403). The field measures approximately 0.7 ha (Ratt 2024, personal communication) and is situated 14 meters above mean sea level (MSL) (Google Earth 2023a). The region has an unimodal rainfall pattern with a peak between August and October (Vance et al. 2004, 10 cited in Belfield and Brown

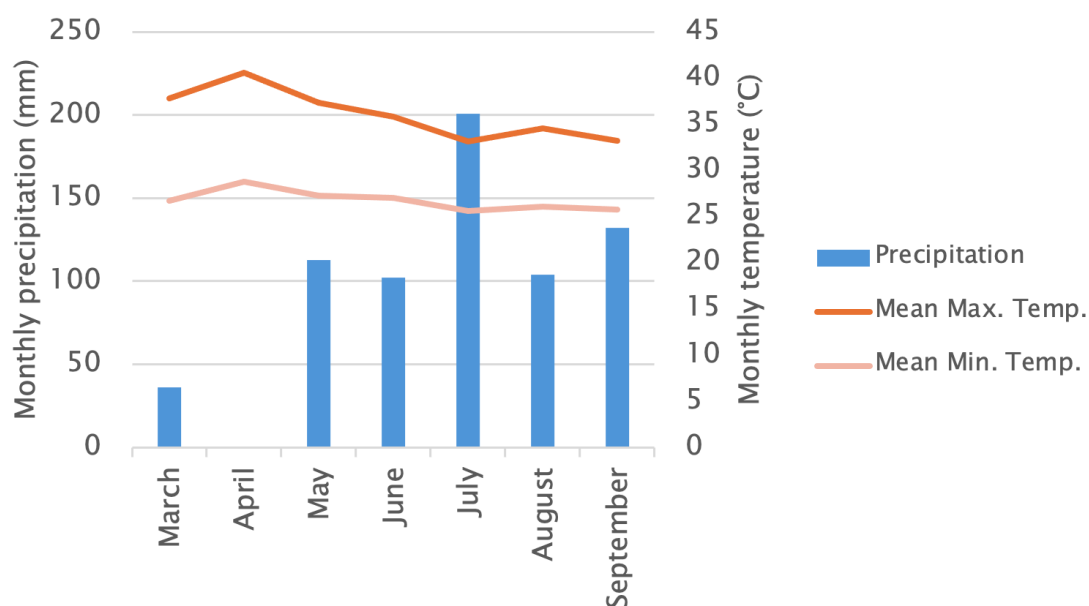


Figure 10: Weather data during the trial phase of the on station trial, measured at the PDWRAM weather station in Battambang, 13.09040, 103.21412. (Source: Adapted from PDWRAM 2024)

2009) and a mean annual rainfall of about 1350 mm (Vance et al. 2004, 5). The mean annual temperature in this region is 27.7°C (ClimateData no date). During the main 14 weeks of the trial implementation, rain of 499 mm were observed in total with a weekly mean of 35.6 mm (PDWRAM 2024). During the first three weeks of August there were in total 60 mm of precipitation (PDWRAM 2024). During the trial period, the mean maximum temperature was 34 °C, and the mean minimum was 26 °C (see Figure 10) (PDWRAM 2024).

The soil is determined as sandy loam with a pH-value of 5 according to the methods of Burgos et al. (20, 2022) and Bühler (1, 2024). The mungbeans, the previous crop, were harvested in October 2023 (Ratt 2024, personal communication). Before planting the whole field was ploughed with a disk harrow and rotovated (Ratt 2024, personal communication). After the soil cultivation and before planting the whole field was treated with Glyphosate with 360g active ingredient (a.i.)/ha. The maize variety used in the trial was KWS 7304 with a thousand grain weight of 249.3 g (Roggenbach 2024, personal communication). The maize was planted on 19.06.2024 in adequate moist soil with a KID planting machine installed on a common four-wheel tractor.

The disc seeding machine with four rows and a row distance of 70 cm placed the seeds approximately 8 cm below the surface. The seeding rate was 18 kg/ha respectively approximately 72200 grains/ha with a germination rate of 95% (Martin 2024a, personal communication). Basal fertilizer application of 50kg/ha with NPK (20-20-15 &TE) was done during planting. While top dressing with 50 kg/ha urea (46% N) was done 34 days after sowing (DAS).

Weed control was done 23 DAS manually with a knapsack-sprayer. 1.8 L/ha of the product ANIME 30 OD (Nicosulfuron 3 % weight by weight (w/w), Mesotrione 7 % w/w, Atrazine 20 %) with a total spray mixture of 200 L/ha was sprayed.

General experimental design

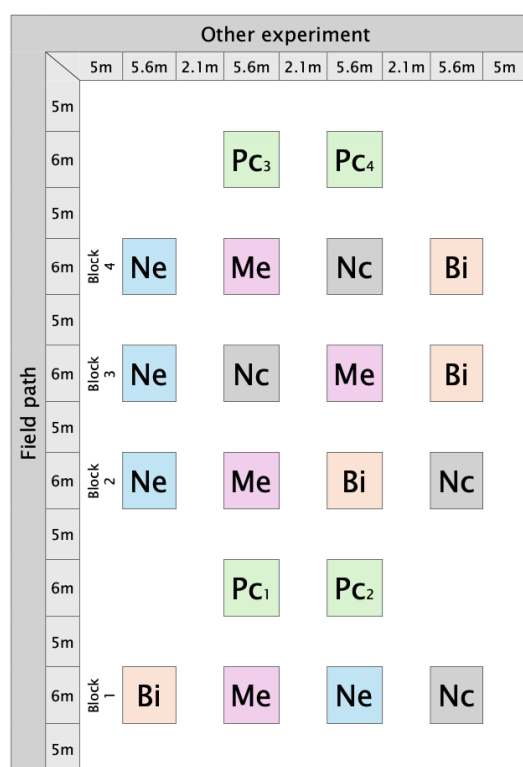
The experimental design used to test biopesticide efficacy was a completely randomized block design. Positive control plots were placed outside the blocks due to limited space (see Figure 11) due to limited space. The distribution of the plots was conducted as recommended by Scheidegger (2024, personal communication), with each plot's treatment being randomly drawn from a concealed hat.

In total the trial had five treatments, three biopesticides, a positive control and a negative control.

The products in table 2 were evaluated. The products were compared with M-T 57 EC - Emamectin benzoate EC 57 g a.i./L as a positive control and no application of insecticides as a negative control.

Table 2: Products and their active ingredients evaluated in the on-station trial

Product name	Active ingredients
Nimbecidine (Stanes no date)	• Neem oil with azadirachtin 0.03 % w/w
BITADIN WP (UNIFI 2022a)	• <i>Bacillus thuringiensis</i> var. <i>kurstaki</i> 16'000 International Unit (IU)
	• <i>Helicoverpa armigera</i> nucleopolyhedrovirus 60 * 10 ⁹ Polyhedral inclusion bodies (PIB)/g
	• <i>Spodoptera exigua</i> nucleopolyhedrovirus 30 * 10 ⁹ PIB/g
	• <i>Spodoptera litura</i> nucleopolyhedrovirus 20 * 10 ⁹ PIB /g
METABE (UNIFI 2022b)	• <i>Beauveria bassiana</i> BA01 1.6 * 10 ⁸ Colony Forming Units (CFU)/g
	• <i>Metarhizium anisopliae</i> MA01 5 * 10 ⁸ CFU/g



Bi: Bitadin
 Me: Metabe
 Ne: Neem oil
 Nc: Negative control
 Pc: Positive control

Figure 11: Experimental design of the on-station trial: Three treatments, two Controls, and four replications (Block)

The products and 20 L of water were mixed with a whisk for one minute. After mixing, the author of this bachelor thesis waited for five minutes until spraying, following the recommendations of a biopesticide company (Keo 2024a, personal communication)



The treatments were applied between 6AM and 8AM with windless conditions. The products were applied on the gross-plot with an electric knapsack sprayer (BUSTAR BS-20D) of 20 L and a spray bar (see Figure 12). The spray bar had seven nozzles and an effective spray width of 2.1 m. with the lowest possible rotational frequency of the engine. The knapsack sprayer was always thoroughly cleaned between each treatment. The application rate for all treatments was 400 L/ha. The dosage of the products is visible in table 3. Producers recommendations were followed (Bio-Agritech no date; Stanes no date; UNIFI 2022b).

Figure 12: The electric knapsack sprayer BUSTAR BS-20D 20 L with the spraying bar which was used in the on station trial as well as in the on farm trial

The gross-plots were measuring 5.6 * 6 m (8 rows) and were separated from each other by 2.1 m (3 rows) alleys as buffer zones for drift. The net-plots were measuring 4.2 * 5 m (6 rows). The corners of the net plots were marked with bamboo sticks.

The trial was marked after crop emergence 9 DAS. For the four blocks the author of this paper selected locations with homogenous gradients for the plots considering crop emergence, soil type, edge effects, distance to trees, water logging and abundance of weeds. Monitoring of the whole trial site was carried out regularly immediately after crop emergence visually and with two PHEROCON[®] bucket traps which contained pheromone lures to attract and catch male FAW moths (TRÉCÉ 2024).

The first treatments were imposed when more than 10 % of 100 randomly selected plant whorls on the site were showing infestation signs by FAW. The other applications were done when the infestation rate by FAW of plant whorls increased further after the application of the products.

The first application took place on 30th of June 2024. Two more applications were done on 13th of July and 27th of July.

The application of the three products Nimbecidine, BITADIN WP and METABE was repeated four days after the first application. Following producers recommendation (Bio-Agritech no date; Stanes no date).

For weighing the powdery products, a digital pocket scale of PESOLA AG (MS1000, 1000g; d=0.2g) was used. For the liquid products a syringe with 50 mL volume was used for Nimbecidine respectively one with 30 mL volume for M-T 57 EC.

Table 3: Applied dosages of the three treatments and the positive control in the on-station trial

Product	Volume or mass applied per treatment/ ha
Nimbecidine	2.5 L
BITADIN WP	400 g
MetaBe	800 g
M-T 57 EC	0.5 L

During the vegetative crop stage, data was generally collected one day before treatments were applied and seven days after the repeated application of the three products Nimbecidine, BITADIN WP and METABE. Resulting in three assessments. The data was collected within the net-plot. On each assessment 15 plants were sampled per net-plot. The assessed plants were distributed in a “W” shaped pattern. On each of the five corners of the “W” the author labelled one plant to simplify the assessment process. Per corner always three consecutive plants in a row were assessed carefully. On each of the three assessment dates different plants were assessed (Allen 2024a, personal communication). The assessed target variables are visible in table 4.

Table 4: Assessed target variables, data type, time of the assessment and the assessed plant part in the on-station trial

Target variable	Data type	Time of assessment	Assessed part	Source of methodology
Number of larvae/ plant	Numeric	One day before application	Whole plant	(Babendreier et al. 2020)
Number of larvae/ plant	Numeric	Seven days after application	Whole plant	(Babendreier et al. 2020)
Damage of plants according to simplified day independent Davis scale	Numeric (0 – 9)	Seven days after application	Whorl, the three newest leaves	(Toepfer et al. 2021)
Whorl damage	Logical (Yes/ No)	Seven days after treatment	Whorl, the three newest leaves	
Number of plants/ plot	Numeric	Seven days after treatment		

During harvest, the yield (kg/ha) of dehusked cobs per net-plot in fresh matter (FM) was measured with a digital hanging scale of PESOLA AG (PHS040, 40kg; d=10g). Additionally, the number of plants per net-plot which were at least in the Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundesortenamt und Chemische Industrie (BBCH) Stage 85 was assessed.

For assessing the kernel yield (kg/ha) in dry matter (DM) with a corrected moisture content at 14 % a subsample of 20 randomly chosen cobs per net-plot was collected due to limited resources. The subsample was processed immediately after the harvest.

Therefore, the subsample was weighted with a digital pocket scale of PESOLA AG (MS1000, 1000g; d=0.2g). Then the cobs were manually threshed. The kernels were weighted with a digital pocket scale of PESOLA AG (MS1000, 1000g; d=0.2g).

After drying the kernels in a portable oven for three hours at 180° Celsius the kernels were weighted with a digital pocket scale of PESOLA AG (MS1000, 1000g; d=0.2g) and the moisture content of the kernels was assessed with a Kett Grain Moisture Meter PM-650. The moisture content of each sample was measured twice and the average of the two values was taken for the calculation. The adapted formula of Karki et al. (2023) was used for calculating the kernel yield (kg/ha) with a moisture content at 14 % (see Figure 13).

$$KY = \frac{FY * \text{Ratio 1} * \text{Ratio 2} * (100 - \text{moisture content after drying})}{(100 - 14)}$$

FY: Fresh yield of dehusked cobs (kg/ha)

KY: Kernel yield (kg/ha) at 14% moisture content

Ratio 1: Fresh kernel (g)/ total sample weight (g)

Ratio 2: Dried kernel (g)/ fresh kernel (g)

Figure 13: Formula for calculating the kernel yield (kg/ha) at 14% moisture content out of the yield of fresh cobs (Source: Adapted from Karki et al. 2023).

Data analysis

Quantitative trial data were analyzed using descriptive and inferential statistics with R (version 4.4.1, June 14, 2024) and RStudio (version 2024.4.2.764). For the specific script see Annex 4 and Annex 5. In table 5, the different target variables, the tests for assessing the assumptions for the statistical analysis, and the specific post hoc test are shown.

Table 5: Target variables, the tests of the assumptions and the post hoc test for each assessed target variable

Target variable	Test of the assumptions		Post hoc test
Number of larvae before application	The model assumptions were checked using diagnostic plots (Burren 2024, personal communication).		Marginal estimated means
Number of larvae after application	The model assumptions were checked using diagnostic plots (Burren 2024, personal communication).		Marginal estimated means
Damage of plants according to simplified day independent Davis scale	The model assumptions were checked using diagnostic plots (Burren 2024, personal communication).		Marginal estimated means
Whorl damage	The model assumptions were checked using diagnostic plots (Burren 2024, personal communication).		Marginal estimated means
Kernel yield (kg/ha)	Levene Test	Shapiro Test	Marginal estimated means
Kernel yield (g/plant)	Levene Test	Shapiro Test	Marginal estimated means

For analyzing the impact on profitability of the different treatments, the tool of partial budgeting was used. The partial budgeting analysis is very appropriate to analyze partial changes of a farming business (ISU 2018). Partial budgeting analysis considers only the costs and benefits that change. Costs and benefits which are left unchanged are not considered (ISU 2018). Therefore, the relevant economic factors for each treatment were the economic value of the mean maize harvest per treatment, the insecticide and biopesticide costs per treatment and the additional labor cost per treatment over the whole trial period.

The costs for seed, fertilizer and other things were not considered. All the costs, yield, and income were expressed on a per hectare basis. All the values for the costs and income are expressed in regular font in US\$ and in *italics* in KHR. I used an exchange rate of 1 US\$ = 4,000 KHR. Furthermore, I made the following assumptions and definitions which are valid for the

partial budgeting analysis of the on-farm trial too. With exceptions for the on-farm trial regarding the income per treatment, the costs of the products and number of applications which are defined in chapter “3.2.2 On-farm trial”.

- I calculated the income per treatment based on the mean FM cob yield, multiplied by the mean price for fresh dehusked cobs per ton from the results of the farmer survey (see chapter “4.3.3 Economics about FAW and maize”) as the eight farmers sell their harvest as fresh dehusked cobs. The mean price was US\$ 159.5/ton. I crosschecked the price with the silo owner in the Sarteh which stated that he pays in average a price of US\$ 156.25/ton for fresh dehusked cobs (Yurn 2024, personal communication).
- I calculated the mean hourly wage of a smallholder farmer based on the informal interviews with five smallholder farmers, which I conducted on 07.06.2024 in Koas Krala district. The daily income ranged from US\$ 12 to US\$ 10, and the daily working hours varied from 9 to 7. The mean hourly wage is US\$ 1.4.
- Based on my data collection from 10.08.2024, I determined that the time required to spray one hectare of corn, including preparation, mixing, and application of the products, is 1.25 hours.
- I defined the cost of products for the biopesticides respectively synthetic insecticide based on the producers recommendation and the price of purchasing them. The price for a single application of Emmamectin benzoate M-T 57 EC is US\$ 14.5/ha. For Nimbecidine it is US\$ 30/ha, for Bitadin it is US\$ 16.4/ha and for Metabe it is US\$ 28.8/ha.
- The synthetic insecticide for the positive control was applied a total of three times, while all biopesticides were applied a total of six times.

3.2.2 On-farm trial

Research sites and crop management

The participatory field trial was conducted on eight farms in Koas Krala and Samlout districts, located in the southwest of Battambang province (see Figure 14). The participatory part of the field trial is explained later in this chapter.

The participating farmers were preselected by ASR employee Penny Kimhoun, who considered the Nurture project’s target area and target group, primarily consisting of smallholders. (Suess and Melara 2022, 5).



Figure 14: Location of the eight farms participated in the on-farm-trial on a 2D map (Source : Adapted from Google Maps 2024).

The climate in the trial area is similar to that described in chapter “3.2.1 On-station trial” for Battambang City. Annual rainfall is slightly higher for the sites of the on-farm-trial through the impact of the nearby mountains (Martin 2024a, personal communication).

The altitude ranges from 77 MSL (Farm 4) to 127 meters (Farm 3) (Google Earth 2023b).

The soil type on the farms is determined as sandy loam with pH-values ranging from 5 to 7 according to the methods of Burgos et al. (20, 2022) and Bühler (1, 2024).

Previous crops included maize (five sites), cassava (two sites), and rice (one site). The soil was cultivated two to three times with a disc harrow mounted on a four-wheel tractor, either by the farmers or, in some cases, a service provider. Planting took place after the first rainfall of the rainy season between 3rd and 22nd of May. The eight farmers used six different maize varieties. The planting was done with a simple four row seed drill machine installed on a common four-wheel tractor. The row to row distance was 70 cm. The seeding rate on four farms was 20kg/ha. The highest seeding rate was 25kg/ha. Except the farmer with the highest seeding rate, who did basal fertilizer application of 50kg/ha with NPK (20-20-15 &TE) none of the other farmers did a fertilizer application close to the planting date. Later four other farmers did once a foliar fertilizer application of approximately 2 L/ha between 29 DAS to 42 DAS. Three farmers did not apply fertilizer during the whole trial phase.

Six farmers applied once a herbicide during the trial phase at 4 DAS up to 42 DAS. Two farmers did not apply any herbicide or other weed control methods during the trial.

All decisions and activities about crop management for the trial sites were done by the farmers how they do it normally. Except spraying insecticide which was not allowed within the area where we evaluated the biopesticides.

More detailed information about the location of the sites and crop management are visible in Annex 8 and Annex 10.

General experimental design

The field trial tested the efficacy of the following treatments (see Table 6) under real farming conditions.

Table 6: Products and their active ingredients evaluated in the on-farm trial

Product name	Active ingredients
BITADIN WP (UNIFI 2022a)	• <i>Bacillus thuringiensis</i> var. <i>kurstaki</i> 16'000 IU • <i>Helicoverpa armigera</i> nucleopolyhedrovirus 60 * 10⁹ PIB/g • <i>Spodoptera exigua</i> nucleopolyhedrovirus 30 * 10⁹ PIB/g • <i>Spodoptera litura</i> nucleopolyhedrovirus 20 * 10⁹ PIB /g
METABE (UNIFI 2022b)	• <i>Beauveria bassiana</i> BA01 1.6 * 10⁸ CFU/g • <i>Metarhizium anisopliae</i> MA01 5 * 10⁸ CFU/g
METABE (UNIFI 2022b) in combination with BITADIN WP (UNIFI 2022a)	

The products were compared with the actual use of synthetic chemical insecticides by the farmers as a positive control and no application of insecticides as a negative control.

The treatment “METABE in combination with BITADIN WP” means in detail, when farmers made the first insecticide application METABE was applied in this treatment. When farmers made the second insecticide application one changed to BITADIN WP.

The trial was established after crop emergence on eight farms (farm = block) between 25th and 31st May 2024 with a complete block design. Within the maize field I selected together with the farmers a location with homogenous gradients for the plots considering crop emergence, soil type, edge effects, distance to trees, water logging and abundance of weeds.

The arrangement of the treatments within one block was not completely randomized due to the spraying of synthetic chemical insecticides by the farmers. Furthermore, there were some changes in the evaluated treatments during the marking phase of the trial. Thus, I decided to arrange the positive control at one end of the block and the treatment “METABE in combination with BITADIN WP” at the other end. The remaining three plots were arranged randomly (see Figure 15), following the recommendations of Scheidegger (2024, personal communication) to draw the treatment for each plot from a concealed hat.

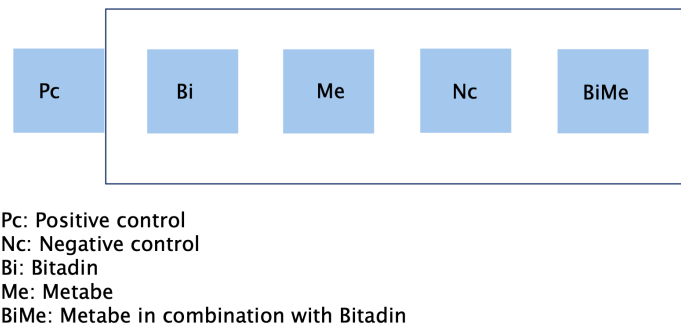


Figure 15: Experimental design of the on-farm trial: Three treatments and two controls.

The gross-plots were measuring 5.6 * 6m (8 rows) and were separated from each other by 2.1 m (3 rows) alleys as buffer zones for drift. Around the whole trial area, except the positive control plot, a buffer zone of 2 m was established. The buffer zone was marked with a blue string to ease the insecticide application for farmers (see Figure 15). The net-plots were measuring 4.2 * 5m (6 rows). Each corner of the net-plot was marked with a bamboo stick.

The treatments were imposed on the same day when farmers applied insecticides. The application of the two products BITADIN WP and METABE was repeated four days after the first application. Following producer recommendation (Bio-Agritech no date).

For weighing the powdery products, an electronic compact scale (SF 400, 500g; accuracy = 0.01g) was used.

The products were mixed with 20L of water using a whisk for one minute. Afterward, the ASR staff waited five minutes before spraying, per the biopesticide company's recommendations (Keo 2024a, personal communication).

Treatments were applied either early in the morning or late in the afternoon. The products were applied on the gross-plot. The responsible ASR-staff used an electric knapsack sprayer (BUSTAR BS-20D) of 20L and a spray bar. The spray bar had seven nozzles and an effective spray width of 2.1m. The knapsack sprayer was operated with the lowest possible rotational frequency of the engine. The knapsack sprayer was always thoroughly cleaned between each treatment.

The application rate for all treatments was 400L/ha.

Table 7: Applied dosages of the three treatments in the on-farm trial

Product	Volume or mass applied per treatment/ha
BITADIN WP	400 g
METABE	800 g

During the growth stage of maize, data was collected on the 27th of June 2024 and on 1st of August 2024.

Data was collected within the net-plots. On each assessment 15 plants per plot were sampled. The assessed plants were distributed in a diagonal pattern (see Figure 16). In five of the six rows, always three consecutive plants in a row were assessed carefully. For the assessment on 27th of June 2024 from the left side (red color in Figure 16) and the one on 1st of August 2024 from the right side (blue color in Figure 16).

The target variables visible in Table 8 were assessed within the two assessments. The maize was in the reproductive stage on the second assessment date, therefore the damage of tassel and ear was collected additionally.

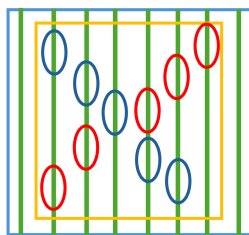


Figure 16: Pattern of the assessment of plants per treatment in the on-farm trial within the net-plot (yellow frame). The red color for the the first assessment date and the blue color for the second assessment

Table 8: Assessed target variables, data type and the assessed plant part in the on-farm trial

Target variable	Data type	Assessed part	Source of methodology
Number of larvae/ plant	Numeric	Whole plant	(Babendreier et al. 2020)
Damage of plants according to simple 1 to 5 damage scale for the fall armyworm	Numeric (1-5)	Whorl, the three newest leaves	(Toepfer et al. 2021)
Whorl damage	Logical (Yes/ No)	Whorl, the three newest leaves	
Tassel damage	Logical (Yes/ No)	Tassel	
Ear damage	Logical (Yes/ No)	Ear	
Number of plants/ plot	Numeric		

For the assessment of the target variables five persons were involved. To ensure congruent data collection between the five person an instruction about the data collection was hold. Followed by an exercise and in the morning and after lunch. For the exercise each person assessed independently the same plants until everybody had the same values for five plants in a row.

During the harvest, the yield (kg/ha) of dehusked cobs per net-plot in FM was measured with a digital hanging scale of PESOLA AG (PHS040, 40kg; d=10g). Additionally, the number of plants per net-plot which were at least in BBCH Stage 85 was assessed.

For assessing the kernel yield (kg/ha) in DM with a corrected moisture content at 14 % a subsample of 20 randomly chosen cobs per net-plot was collected due to limited resources. The subsample was processed immediately after the harvest.

Therefore, the subsample was weighted with a digital pocket scale of PESOLA AG (MS1000, 1000g; d=0.2g). Then the cobs were manually threshed. The kernels were weighted with a digital pocket scale of PESOLA AG (MS1000, 1000g; d=0.2g).

After drying the kernels in a portable oven for three hours at 180° Celsius the kernels were weighted with a digital pocket scale of PESOLA AG (MS1000, 1000g; d=0.2g) and the moisture content of the kernels was assessed with a Kett Grain Moisture Meter PM-650. The moisture content of each sample was measured twice and the average of the two values was taken for the calculation. The adapted formula of Karki et al. (2023) was used for calculating the kernel yield (kg/ha) with a moisture content at 14 % (see Figure 17).

$$KY = \frac{FY * \text{Ratio 1} * \text{Ratio 2} * (100 - \text{moisture content after drying})}{(100 - 14)}$$

FY: Fresh yield of dehusked cobs (kg/ha)

KY: Kernel yield (kg/ha) at 14% moisture content

Ratio 1: Fresh kernel (g)/ total sample weight (g)

Ratio 2: Dried kernel (g)/ fresh kernel (g)

Figure 17: Formula for calculating the kernel yield (kg/ha) at 14% moisture content out of the yield of fresh cobs (Source: Adapted from Karki et al. 2023).

Farmers evaluation of the trial

In a participatory field trial, it is crucial to assess, beside the agronomic target variables (Allen 2024b; Ashby 1990), the opinion and perspective of the farmers. Thereby scientists, who often are specialists in their field of research, and other professionals can gather all the problems which a farming household is facing (Ashby 1990). As well as all the criteria which the farmers use to evaluate and to decide about adopting or rejecting new technologies (Ashby 1990).

For the on-farm trial, each farmer was therefore individually interviewed a few weeks before harvest. For the evaluation (see Appendix 2) farmers were asked open questions, the main objective was to understand their perception of the different treatments of the field trial. Additionally, the evaluation aimed to determine the criteria farmers consider when deciding whether to use insecticides and identify their primary information sources for pest management. The questionnaire was based on the handbook "Evaluating technologies with farmers" by Ashby (1990).

Data analysis

The trial's quantitative data, specifically the yield data, were analyzed using descriptive and inferential statistics with R (version 4.4.1, June 14, 2024) and RStudio (version 2024.4.2.764). For the specific script see Annex 7. In Table 9, the different target variables, the tests for assessing the assumptions for the statistical analysis, and the specific post hoc test are shown. The reasons for analyzing only the yield data are detailed in chapter "5.3 Limitations of the study".

Table 9: Target variables, the tests of the assumptions and the post hoc test for each assessed target variable in the on-farm trial

Target variable	Test of the assumptions		Post hoc test
Kernel yield (kg/ha)	Levene Test	Shapiro Test	Marginal estimated means
Kernel yield per plant (g/plant)	Levene Test	Shapiro Test	Marginal estimated means

For analyzing the impact on profitability, the partial budgeting tool was used in the same way as for the on-station trial, with exceptions made for the income per treatment, costs of the products and the number of applications. The exceptions for the on-farm trial are defined below.

- I calculated the income per treatment based on the mean FM cob yield (n=5), multiplied by the mean price for fresh dehusked cobs per ton from the results of the farmer survey (see chapter "4.3.3 Economics about FAW and maize") as the eight farmers sell their harvest as fresh dehusked cobs. The mean price was US\$ 159.5/ton.
- The number of insecticide applications varied among the farms (see chapter "4.3.2 Their methods") ranging from 0 to 3 applications. The median number of applications was 2. Therefore, in

the calculations I assumed that synthetic insecticides were applied twice and biopesticides were applied four times.

- I defined the cost of products for the biopesticides based on the producers recommendation and the price of purchasing them. For the treatment BITDADIN WP/ METABE, the mean cost per hectare was calculated by averaging the costs of both individual treatments. For the synthetic insecticide, (Positive control), the mean cost per hectare per crop cycle was calculated based on the results of the farmer survey (see chapter “4.3.3 Economics about FAW and maize”). Note that only data from seven farmers were included in this calculation, as one farmer did not apply any insecticide.
- The price for a single application of BITADIN WP is US\$ 16.4/ha. For METABE it is US\$ 28.8/ha. For BITDADIN WP/ METABE it is US\$ 22.60/ha. For synthetic insecticide it is US\$ 25.9/ha per crop cycle.

The qualitative data from the farmer evaluation of the trial was analyzed descriptively by using Microsoft Excel Version 16.88 because the sample size of eight farmers was very small for statistical tests. To present the data graphs were created, also by using Microsoft Excel Version 16.88.

3.2.3 Farmers survey about FAW control methods

In order to assess farmers practices how they manage FAW in maize considering the principles of IPM (FAO no datea) and to summarize the efficacy, strength and weakness of the different methods a survey (see Appendix 3 and Annex 10) was conducted with the eight farmers participating in the on-farm trial. For an icebreaker the author of this study assessed their knowledge about insects which are present in upland cropping areas in Cambodia (Chanthy et al. 2010). For this the method described by Mwambi et al. (2023) was followed. Farmers were shown photos of 10 insects (see Appendix 4) and asked if they recognized them. For the insects they recognized, they were further asked to identify whether the insect was beneficial or harmful to the crop. Correct answers were coded as 1, while incorrect answers were coded as 0. The outcome variable was expressed as the proportion of correct answers, ranging from 0 to 1.

Additionally, mainly open questions were asked regarding their crop and pest management practices, including the list of pesticide label collected by Robert Martin (see Annex 11). Furthermore, their cost structure in maize cultivation and general information about the household, their education level and some other information relevant for the Nurture project were collected.

Maize farmers in Koas Krala District were not randomly selected due to limited time for sampling, conducting, and analyzing the survey. This decision was made after consulting with the individuals supervising this work (Martin 2024b, personal communication; Allen 2024c, personal communication). We chose to survey the eight farmers participating in the on-farm trial to obtain more detailed qualitative data rather than a larger, more representative sample.

In the analyzed data, the data collected by Penny Kimhoun (2024, field report) were integrated to simplify this work. The data used from the field report include the number of herbicide treatments, the number of fertilizer applications, and the number of insecticide treatments per farm throughout the entire trial period.

Data analysis

The qualitative data from the farmer survey was analyzed descriptively by using Microsoft Excel Version 16.88. To present the data graphs were created, also by using Microsoft Excel Version 16.88.

3.2.4 Semi-structured key person/expert interviews about FAW in Cambodia

To find out which preventative and intervention FAW management options are available in Cambodia with a focus on northwest Cambodia and to assess bottlenecks in the market. Therefore, we planned to do semi structured interviews with key persons working on FAW in Cambodia. Semi structured interviews are characterized by questions not formulated in all details in advance (FAO no dateb). The prepared questions only should provide a framework for the interview (FAO no dateb). Additionally, the key person interviews will be complemented through literature research for secondary data by using Web of Science, Ovid and Google Scholar.

We planned to apply the snowball sampling method to identify and find relevant key person interviewee. The most common definition of snowball sampling is, that one interviewee gives the researcher the name and contact details of one or more potential interviewee (Atkinson and Flint 2001 cited in Kirchherr 2018; Cohen and Arieli 2011 cited in Kirchherr 2018).

3.3 Collaboration with tandem student from National University of Battambang (NUBB)

Through Dr. Alessandra Giuliani from HAFL the collaboration with NUBB was initiated, building on the experiences gained over the past few years with the lecturer Peuol Vibol from NUBB. The primary goal of this collaboration was that two tandem students conduct joint research in the same field of study. After meeting at NUBB and an assessment with the responsible project staff at the Nurture office in Battambang, I decided to collaborate with the student Pich Por, primarily based on his English-speaking skills. Pich Por was in the second-last year of his bachelor's studies in animal science. Due to Pich Por's field of study, Nurture, with the agreement of all parties involved, decided to give up the goal of joint research. Nurture primarily hired the NUBB student for translation and transportation services during our field visits.

The collaboration overall took place over approximately 15 working days. Firstly, to identify current farmer practices in maize cultivation for developing the research protocols on which the field trials were based. Furthermore, to translate during the interviews for the trial evaluation and the farmer survey about the FAW management methods. Therefore, Pich Por translated from English to Khmer and vice versa. A big portion of the collaboration additionally took place during the harvest of the on-farm trial where he assisted me.

Despite his background in animal science, Pich Por quickly adapted to the technical terms in crop science and pest management. Before each field mission for conducting interviews, a training and review session was held with Pich Por and I, led by Nurture field officer Vibol Nget.

In addition to the collaboration with the tandem student, NUBB provided me access to various laboratories and materials at the university.

4 Results

This chapter presents the analyzed data from the on-station trial, on-farm trial, farmer survey, and key person interviews, following the methods outlined in the previous "Materials and Methods." The results provide the data foundation for answering the study's hypotheses.

Field trial results are presented separately by experiment, chronology, efficacy and economic impact to ensure clarity.

The chapters on the data obtained from interviews and surveys are organized by thematic focus within their respective data collection groups.

4.1 On-station trial

4.1.1 Efficacy

To measure the efficacy of the three biopesticides, they were compared with each other, as well as with the positive and negative control. To assess the efficacy, the plant damage, the number of larvae per plant and the yield for each treatment were measured.

Data for different target variables were collected as explained in chapter "3.2.1 On-station trial". The collected data was analyzed for the entire trial period and not for individual assessments. Further information on the parameters and statistical tests from the following chapters can be found in Annex 4 and Annex 5.

Marginal estimated mean of damage according to Davis scale

In this section, the plant damage will be assessed. It is assessed according to the Davis scale with 10 levels. As discussed previously, the value 0 means no damage and 9 expresses the highest possible damage.

To improve the clarity of the results, the treatments and controls are abbreviated as follows: Negative control (Neg) i.e. no application of insecticides, positive control (Pos) i.e. Emamectin benzoate, Bitadin (Bit) i.e. BITADIN WP, Metabe (Met) i.e. METABE and Neem oil (Nee) i.e. Nimbecidine. Furthermore, in the following both treatments and controls are referred together to treatments to improve the readability.

The marginal estimated mean (MEM) damage varies over all treatments between 2.19 and 3.91.

The MEM for Neg is the highest and significantly higher than all the other treatments, except Nee (see Figure 18). The MEM with 2.19 for Met was the lowest, but not significantly different than Pos and Bit. As visible in Figure 18, the number of damaged plants varied among the treatments. The MEM and the standard deviation (SD) for Neg, Pos, Bit, Met and Nee were $3.91(\pm 0.28)$, $2.83(\pm 0.31)$, $2.86(\pm 0.26)$, $2.19(\pm 0.28)$ and $3.51(\pm 0.26)$, respectively.

The significance was analyzed on the p-value level <0.05 .

Prior to the analysis, the data was pre-processed due to its non-normal distribution and the presence of numerous zero values (Burren 2024, personal communication). Consequently, the data was transformed and divided into samples containing damage values >0 and damage values $=0$.

After the transformation, the sample size was no longer equal for all treatments and was thus unbalanced. Therefore, MEM was calculated, as it is well-suited for this situation (Burren 2024, personal communication; Russel et al. 2024, 3).

The MEM model calculates the estimated mean from the unbalanced data to a model which would be balanced and is more appropriate for the arithmetic mean (Russel et al. 2024, 3). In the Figure 18, the results from the sample with damage values >0 are presented.

Marginal estimated mean of the probability for no damage

To assess the probability of undamaged plants, the two samples mentioned above containing damage values >0 and damage values $=0$ were compared. The MEM probability for undamaged plants varied over all treatments between 0.68 and 0.32. In other words, the number of damaged plants among ten plants ranged across all treatments from approximately 3.2 plants to 6.8 plants.

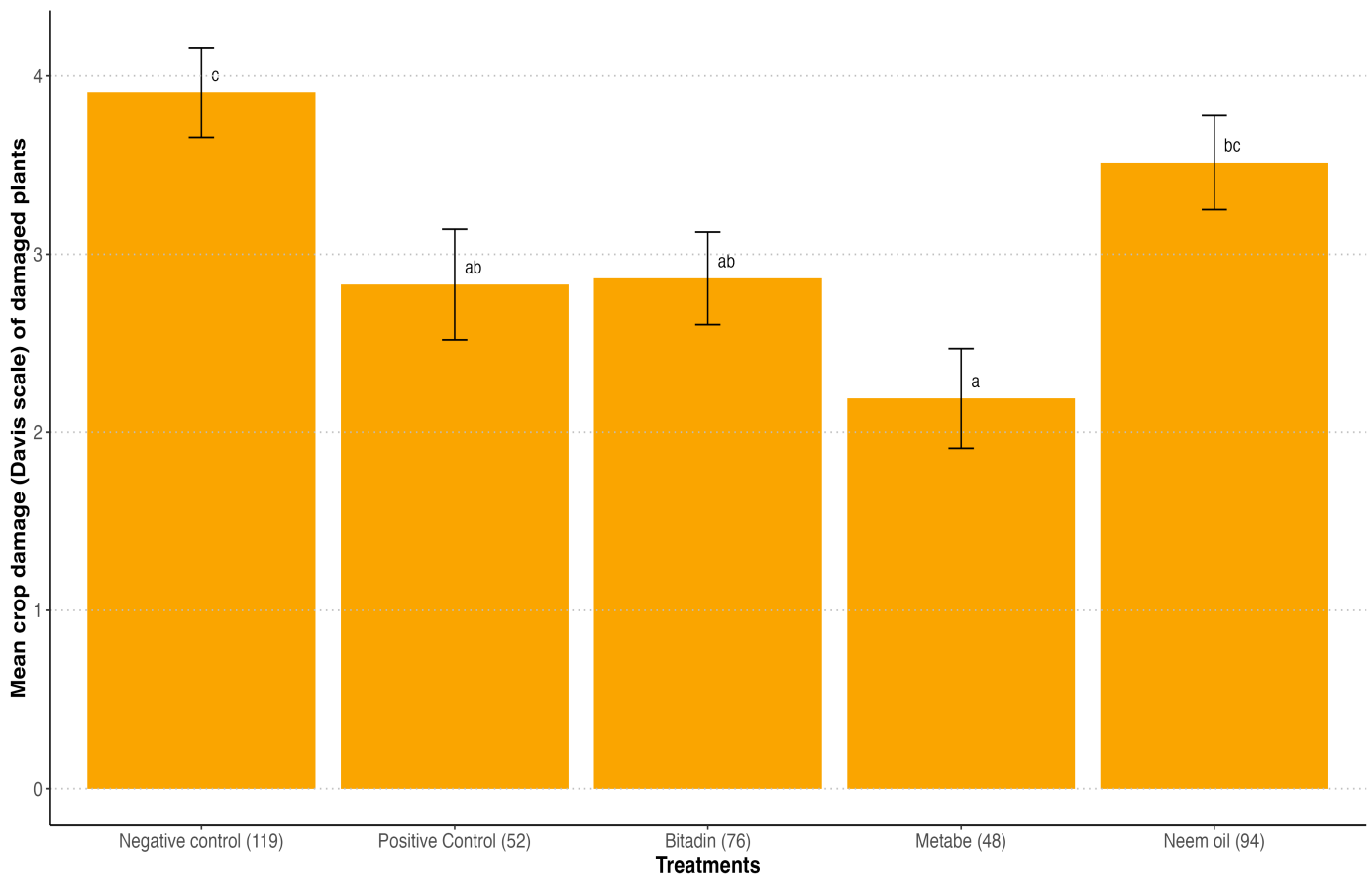


Figure 18: Mean crop damage based on the Davis scale over the whole trial period. The numbers on the x-axis indicate the number of damaged plants per treatment. The active ingredients of the tested products are as follows: Positive control – Emamectin benzoate; Bitadin – *Bacillus thuringiensis* & granuloviruses; Metabe – *Metarhizium anisopliae* & *Beauveria bassiana*.

The MEM for having no damage was the highest for Pos and Met. Both were significantly different from the other treatments (see Figure 19). Bit tended to have a higher MEM compared to Nee, but the difference was not statistically significant. Neg had the lowest MEM, which was significantly different from all the other treatments. In other words, the MEM probability of having damaged plants was the highest for Neg and the lowest for Pos and Met. The probability of plant damage was more than twice as high for Neg compared to Pos and Met.

The MEM for having no damage and the SD for Neg, Pos, Bit, Met and Nee were 0.30 (± 0.03), 0.68 (± 0.04), 0.53 (± 0.04), 0.68 (± 0.04) and 0.44 (± 0.04), respectively.

The significance was analyzed on the p-value level < 0.05 . Due to the unbalanced samples, the MEM was used.

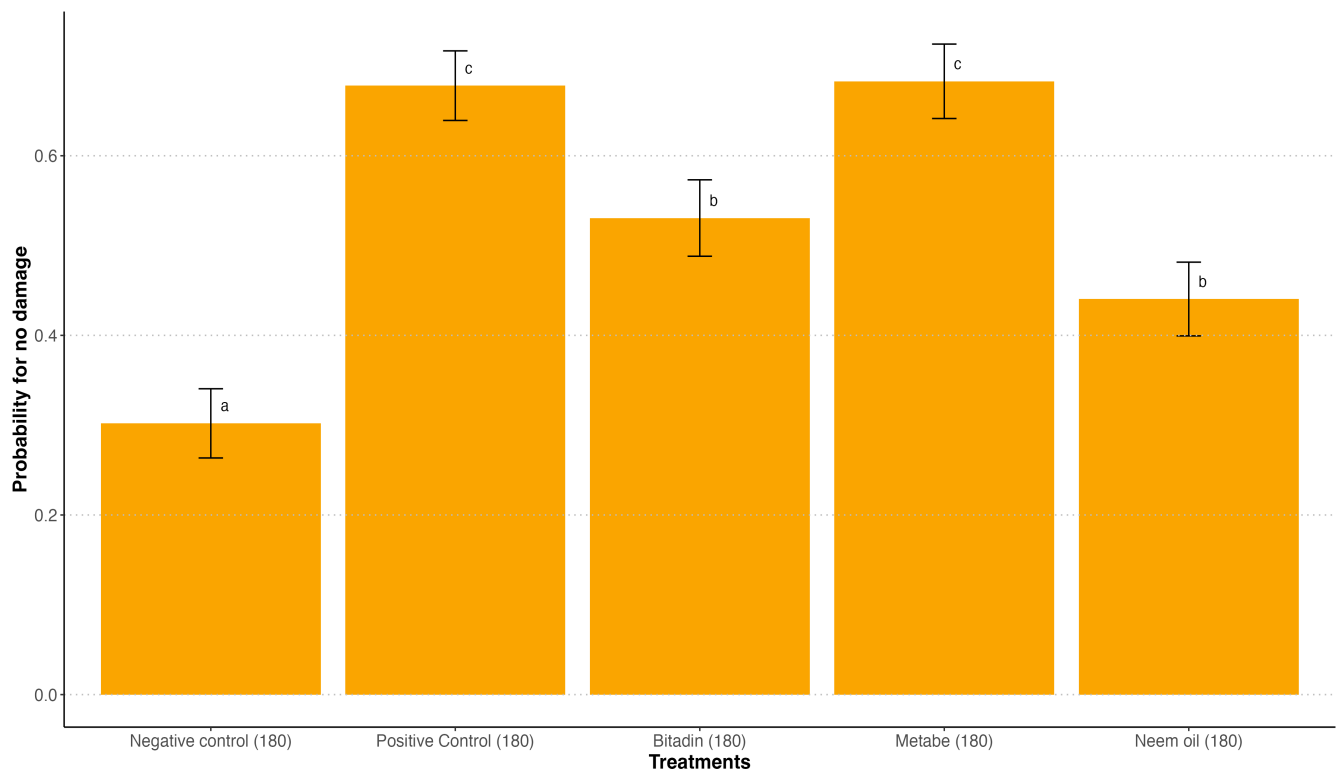


Figure 19: Probability of undamaged plants per treatment, based on two samples: assessed plants with damage values >0 and assessed plants with damage values =0. The active ingredients of the tested products are as follows: Positive control – Emamectin benzoate; Bitadin – *Bacillus thuringiensis* & granuloviruses; Metabe – *Metarhizium anisopliae* & *Beauveria bassiana*.

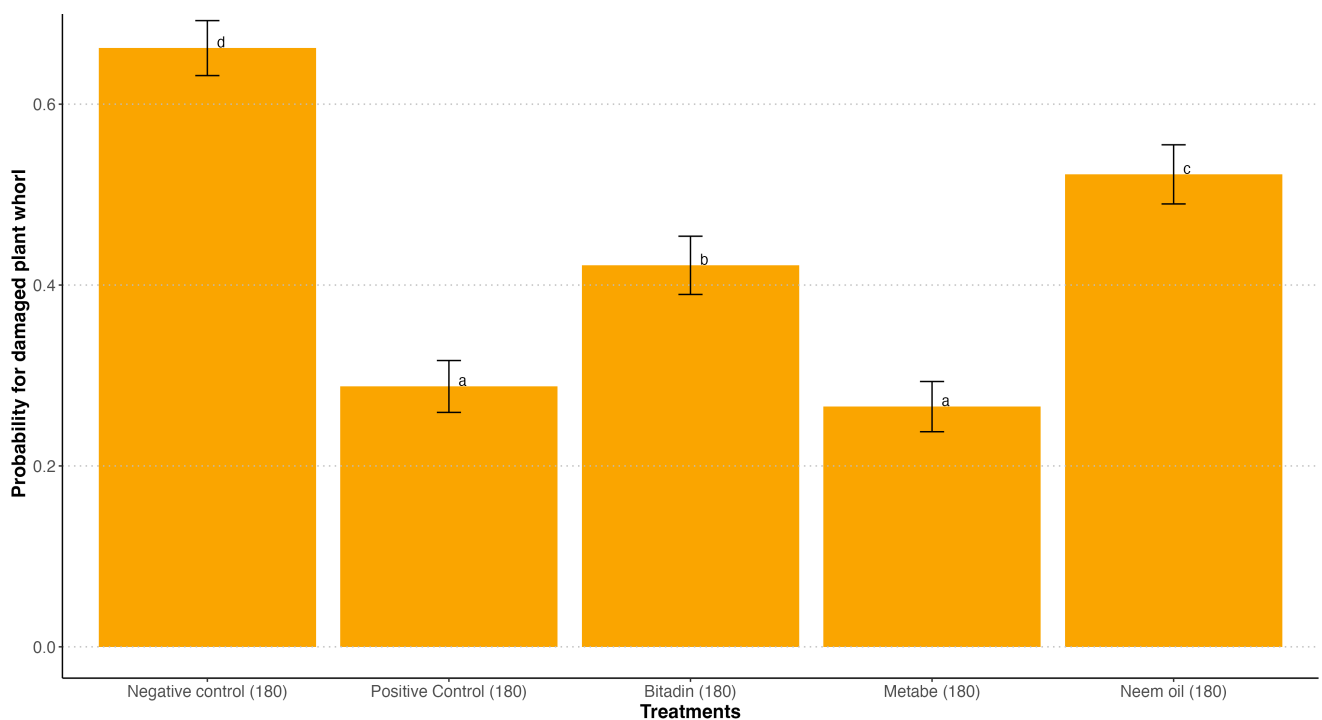


Figure 20: Probability of damaged plant whorls per treatment, based on two samples: assessed plant whorls with damage and assessed plant whorls without damage. The active ingredients of the tested products are as follows: Positive control – Emamectin benzoate; Bitadin – *Bacillus thuringiensis* & granuloviruses; Metabe – *Metarhizium anisopliae* & *Beauveria bassiana*.

Marginal estimated mean of the whorl damage

The damage of the plant whorl was assessed by the logical target variable (“Yes”/ “No”). “Yes” for signs of damage and “No” for no sign of damage.

The MEM probability for having a damaged plant whorl varied over all treatments from 0.27 to 0.66. In other words, the number of expected damaged plant whorl among ten plants ranged across all treatments from approximately 2.7 plants to 6.6 plants.

The MEM for a damaged plant whorl was the highest for Neg (see Figure 20), which was significantly different from all other treatments. Nee had the second highest probability with a significant difference to all other treatments. Pos and Met had the lowest MEM, with no significant difference among them. The probability of having a damaged plant whorl was more than twice as high for Neg compared to Pos and Met.

The MEM and the SD for Neg, Pos, Bit, Met and Nee were 0.66 (± 0.03), 0.29 (± 0.03), 0.42 (± 0.03), 0.27 (± 0.03) and 0.52 (± 0.03), respectively.

The significance was analyzed on the p-value level <0.05 . Due to the unbalanced samples, the MEM was used.

Estimated marginal mean of total larvae per plant

The target variable total larvae is the sum of the number of larvae observed before the application of the products and seven days later.

The MEM of larvae/ plant varied over all treatments from 0.13 to 0.34.

Neg had the highest MEM which was not significantly different than Nee and Bit (see Figure 21).

Met had the lowest MEM followed by Pos. They were not significantly differently from each other, but they were significantly different from the other three treatments.

Neg, Bit, and Nee had more than twice the number of larvae per plant compared to Pos and Met. The MEM and the SD for Neg, Pos, Bit, Met and Nee were 0.34 (± 0.07), 0.14 (± 0.04), 0.28 (± 0.06), 0.13 (± 0.03) and 0.33 (± 0.07), respectively.

The significance was analyzed on the p-value level <0.05 . The MEM was used for analyzing the data.

Marginal estimated mean of the probability for larvae/ plant before and after treatment

In this section, the number of larvae per plant before the application of the products and seven days later is analyzed for every treatment.

The MEM of the probability of larvae on a plant varied over all treatments and time of observation from 0.05 to 0.18.

All treatments tended to have a higher MEM of probability after spraying as it had before. Except for Met, where the opposite trend was observed, with the probability tending to be higher before applying the products than afterwards. For all treatments, there was no statistically significant difference in the MEM probability before and after applying the products, except for Neg, where the MEM probability was significantly lower before the application than after (see Figure 22).

The MEM of the probability for each treatment and observation time along with the respective SD can be seen in Table 10.

The significance was analyzed on the p-value level <0.05 and the MEM was used for the analysis.

Because the dataset had many zero values and not many observations >1 the statistician Burren (2024, personal communication) recommended to split up the dataset for each treatment and observation time in two samples: Number of caterpillars=0 and number of caterpillars >1 .

Table 10: Marginal estimated mean of the probability for having larvae on a plant for each treatment and observation time along with the respective standard deviation

Treatment	Time of observation	MEM of the probability	Standard deviation	Group of significance
Neg	Before	0.07	± 0.02	ab
Neg	After	0.18	± 0.03	d
Pos	Before	0.06	± 0.02	a
Pos	After	0.08	± 0.02	abc
Bit	Before	0.10	± 0.02	abcd
Bit	After	0.12	± 0.02	bcd
Met	Before	0.07	± 0.02	ab
Met	After	0.05	± 0.02	a
Nee	Before	0.12	± 0.02	bcd
Nee	After	0.15	± 0.03	cd

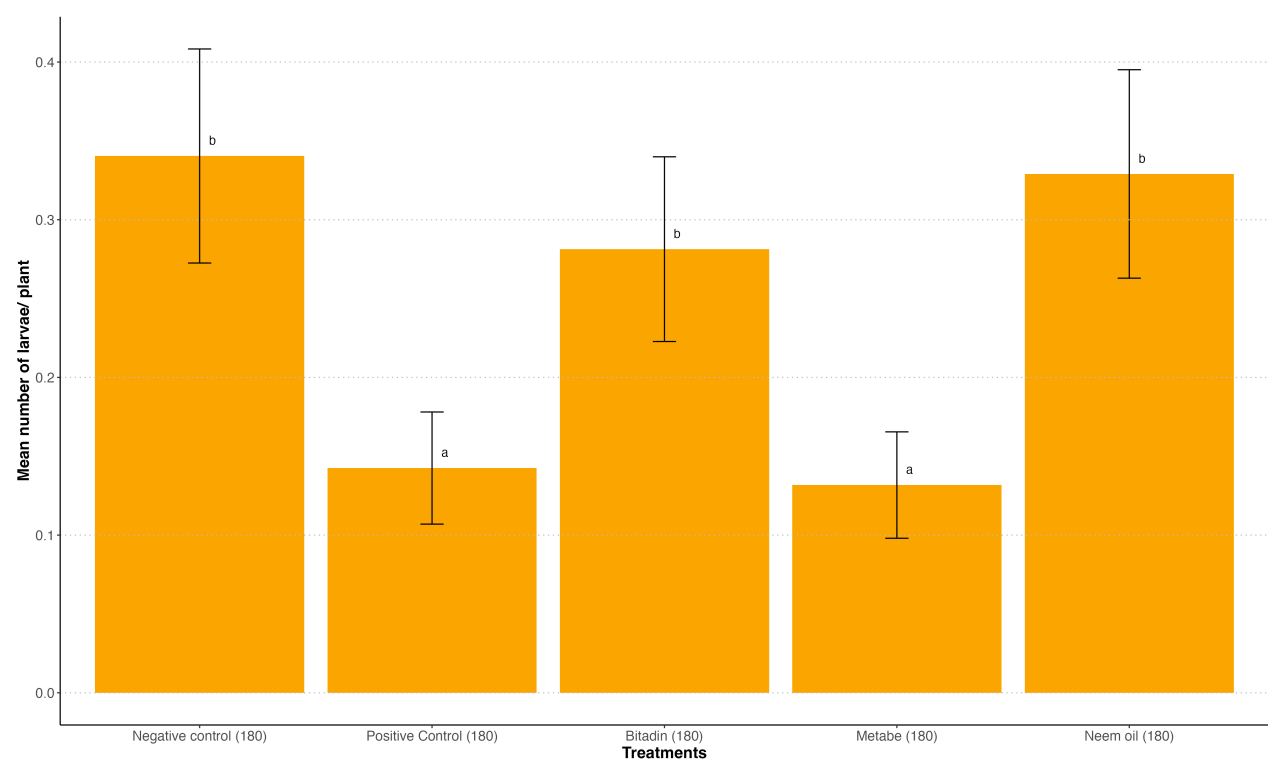


Figure 21: Mean number of larvae per plant per treatment over the trial phase. The active ingredients of the tested products are as follows: Positive control – Emamectin benzoate; Bitadin – *Bacillus thuringiensis* & granuloviruses; Metabe – *Metarhizium anisopliae* & *Beauveria bassiana*.

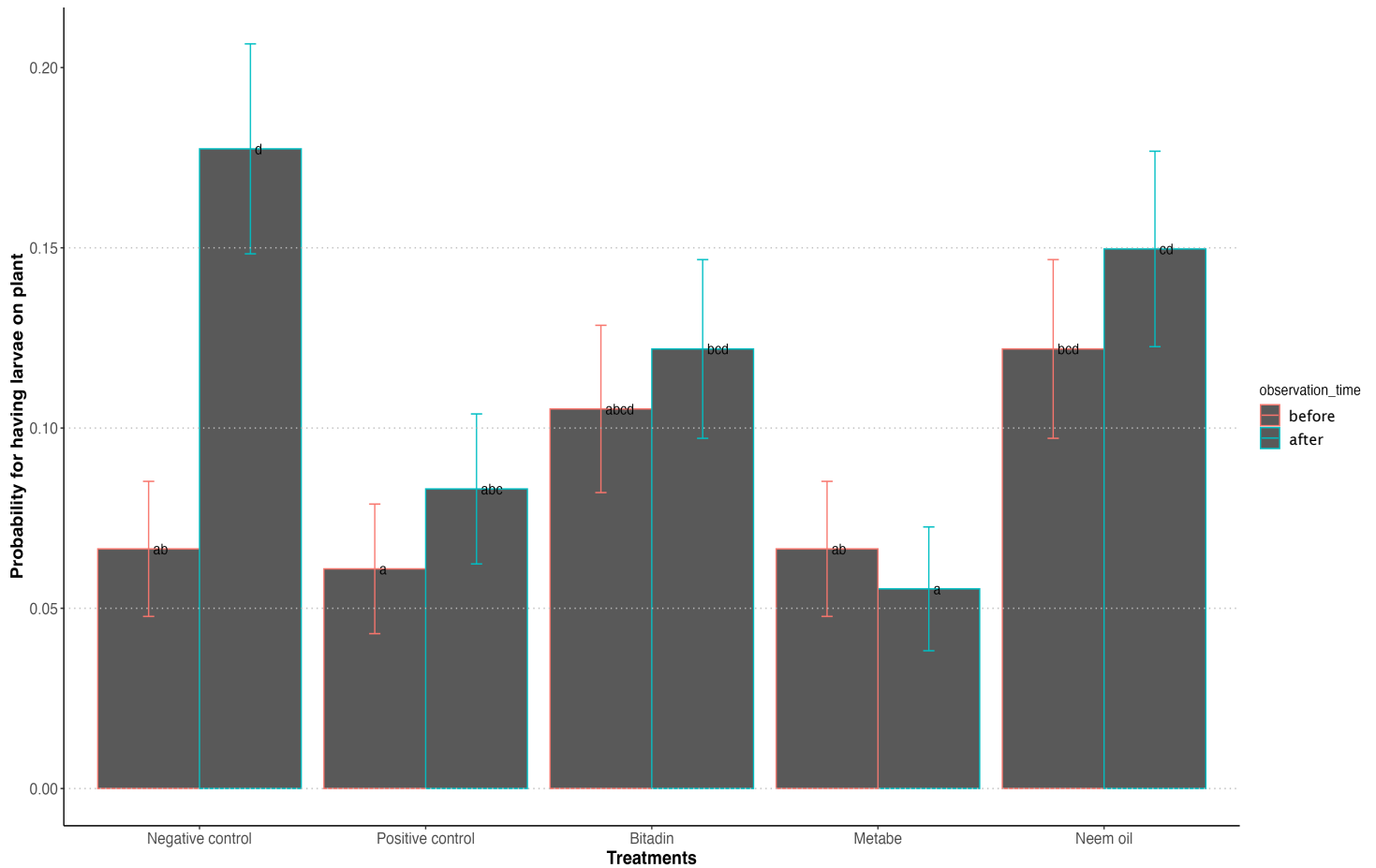


Figure 22: Probability of larvae presence on a plant before and after product application over the trial phase. The active ingredients of the tested products are as follows: Positive control – Emamectin benzoate; Bitadin – *Bacillus thuringiensis* & granuloviruses; Metabe – *Metarhizium anisopliae* & *Beauveria bassiana*.

Yield

The MEM of the kernel yield at 14% moisture content, varied from 1429 kg/ha to 4277kg/ha among the treatments. The MEM yield of the positive control was the highest but not significantly different from the other treatments except Neem oil. Neem oil had the lowest yield with 1429 kg/ha and was significantly lower than all the other treatments (see Figure 23).

The MEM of the kernel yield (kg/ ha)for Neg, Pos, Bit, Met and Nee were 3272, 4277, 4206, 3609 and 1429, respectively. The SD was ± 753 .

The significance was analyzed on the p-value level <0.05 and the MEM was used for the analysis, which in this case was the same as the arithmetic mean (Burren 2024, personal communication). The requirements for ANOVA I were met (Shapiro test: $p = 0.503$; Levene test: $p = 0.528$)

According to Russel et al (2024, 27) as a Post Hoc test, a pairwise comparison was made without any correction.

The block factor explained 38.2 % of the variance. This indicates that most of the variability in yield is due to differences between the treatments.

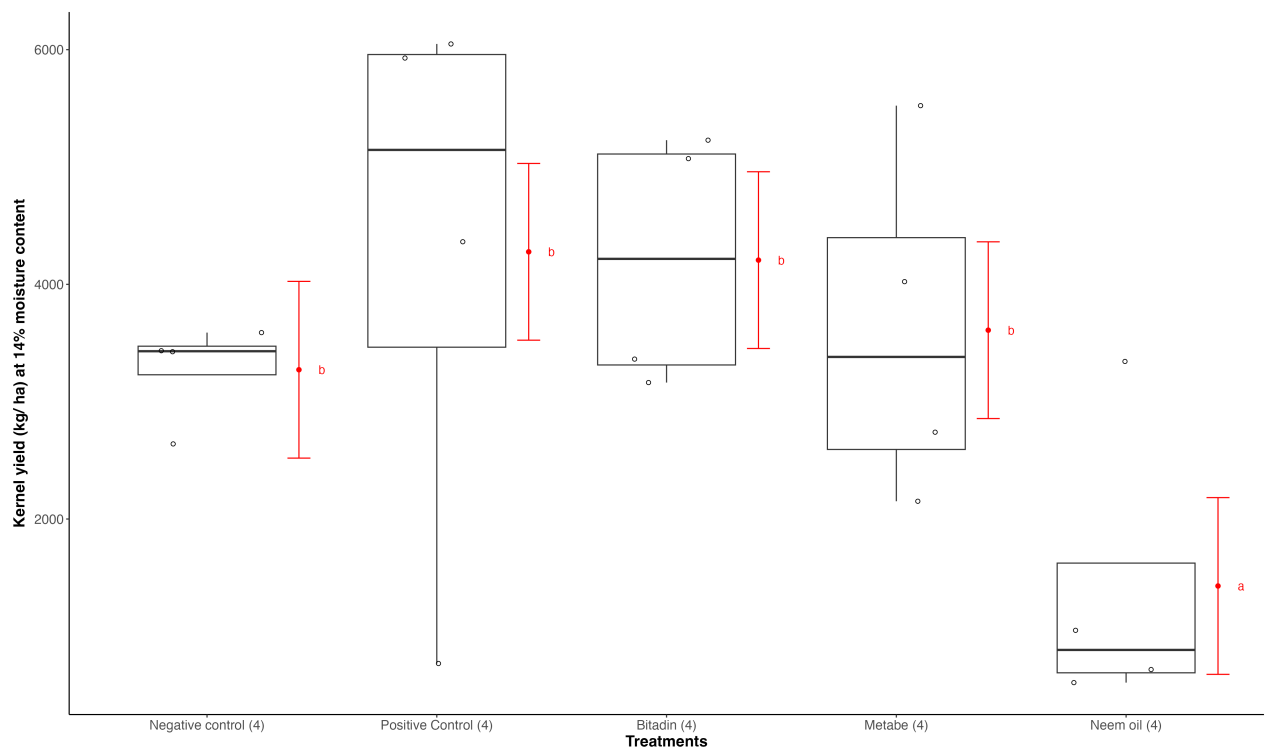


Figure 23: Kernel yield (kg/ha) for each treatment: red dots represent the mean values, the thick black lines indicate the medians and the letters show the group of signifiacne. The active ingredients of the tested products are as follows: Positive control – Emamectin benzoate; Bitadin – *Bacillus thuringiensis* & granuloviruses; Metabe – *Metarhizium anisopliae* & *Beauveria bassiana*.

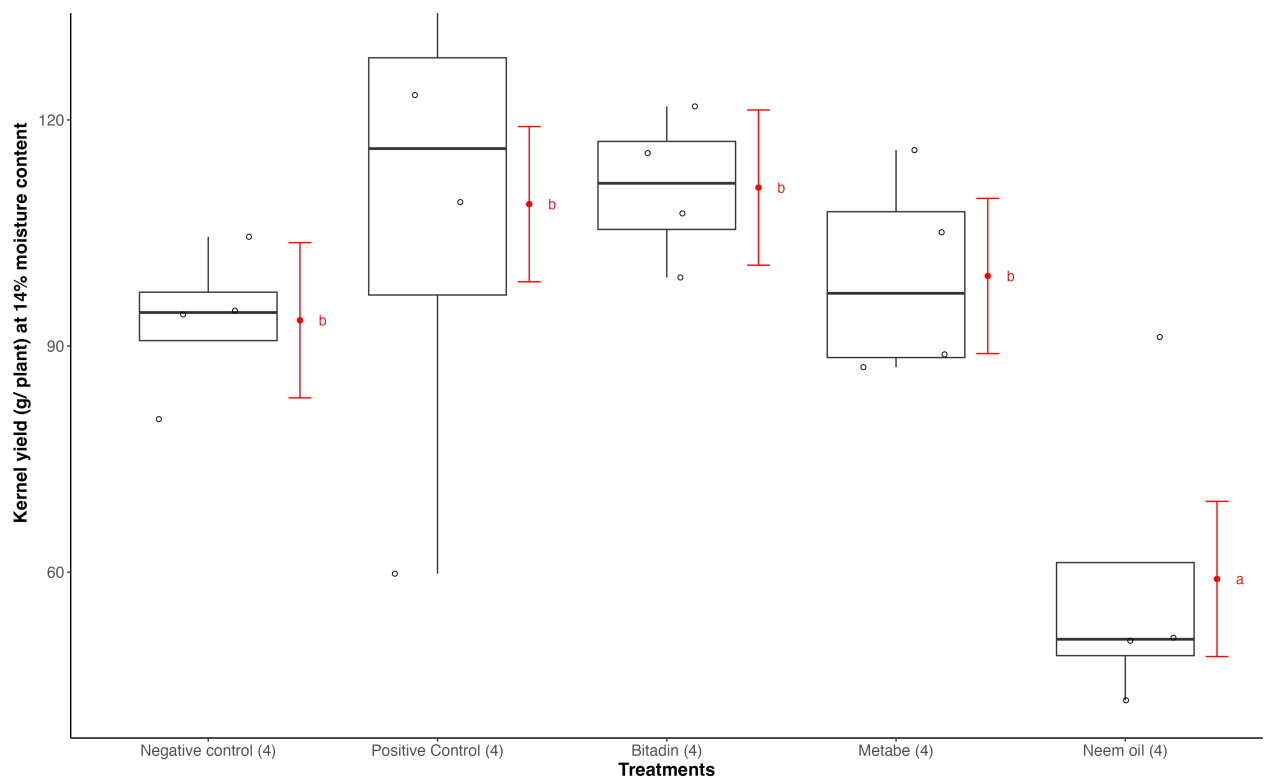


Figure 24: Kernel yield per plant (g/plant) for each treatment: red dots represent the mean values, the thick black lines indicate the medians and the letters show the group of signifiacne. The active ingredients of the tested products are as follows: Positive control – Emamectin benzoate; Bitadin – *Bacillus thuringiensis* & granuloviruses; Metabe – *Metarhizium anisopliae* & *Beauveria bassiana*.

As an additional target variable, the kernel yield per plant was analyzed. Therefore, the kernel yield per net plot at 14% moisture content was divided by the number of maize plants per net plot.

The MEM of kernel yield per plant varied from 59.1 g/plant to 111.0 g/plant. Bit had the highest kernel yield per plant and Nee the lowest (see Figure 24). The MEM of Pos was almost the same as for Bit. There was no significant difference among the treatments except Nee which was significant lower as all the other treatments.

The MEM for Neg, Pos, Bit, Met and Nee were 93.4, 108.8, 111.0, 99.3 and 59.1, respectively. The SD was ± 10.3 .

The significance was analyzed on the p-value level < 0.05 and the MEM was used for the analysis.

The requirements for ANOVA I were met (Shapiro test: $p = 0.144$; Levene test: $p = 0.482$). As above, a Post Hoc test a pairwise comparison was made without correction.

The block factor explained 12.9 % of the variance. This indicates that most of the variability in yield is due to differences between the treatments.

4.1.2 Economic impact

In the following partial budgeting analysis, the values in regular font are in US\$ and in italics in KHR. Furthermore, the synthetic insecticides for the positive control were applied three times, while all biopesticides were applied a total of six times.

Table 11: Partial budgeting analysis showing costs, yield, and profit per treatment: italicized numbers are in Khmer Riel per hectare, and values in regular font are in US\$ per hectare.

Treatment	Negative control	Positive control	BITADIN WP	METABE	Neem oil
Cost					
Labour	0	-5.25	-10.5	-10.5	-10.5
	0	-21'000	-42'000	-42'000	-42'000
Product	0	-43.5	-98.4	-172.8	-180
	0	-174'000	-393'600	-691'200	-720'000
Total costs	0	-48.75	-108.9	-183.3	-190.5
	0	-195'000	-435'600	-733'200	-762'000
Yield (ton/ ha)	5.45	7.13	7.01	6.01	2.38
Price/ ton	159.5	159.5	159.5	159.5	159.5
	638'000	638'000	638'000	638'000	638'000
Income	869.3	1137.2	1118.1	958.6	379.6
	3'477'100	4'548'940	4'472'380	3'834'380	1'518'440
Profit	869.3	1088.4	1009.2	775.3	189.1
	3'477'100	4'353'940	4'036'780	3'101'200	756'440

The results of the partial budgeting analysis reveal high differences in profitability across the five treatments. Profits ranged from US\$ 189.1/ha for Neem oil to US\$ 1088.4/ha for the positive control, representing a US\$ 899.3/ha difference between the most and least profitable treatments (see Table 11). BITADIN WP generated a profit of US\$ 1009.2/ha, closely matching the highest profit. The negative control produced a profit of US\$ 869.3/ha, slightly exceeding METABE, which yielded US\$ 775.3/ha. A similar trend was observed in mean fresh matter cob yield. However, METABE showed a higher mean yield, i.e. 6.01 tons/ha, than the negative control, i.e. 5.45 tons/ha, despite its lower profitability.

4.2 On-farm trial

For the agronomic data of the on-farm trial, as mentioned in the subchapter "5.3 Limitations of the study", only the yield data was analyzed due to various errors that reduced the credibility of the other data. Furthermore, the sample size for the agronomic data was limited to five farms, due to the limitations explained in the subchapter "5.3 Limitations of the study"

4.2.1 Efficacy

Yield

The abbreviations for the treatments are consistent with those used in previous chapters (see chapter “4.1 On-station trial”). The additional treatment BITADIN WP/METABE was abbreviated as “BiMe”. The MEM of the kernel yield at 14% moisture content, varied from 2267 kg/ha to 2867 kg/ha.

The MEM of Neg was the highest and significantly different from Bit and BiMe. The MEM of Met was generally the second highest and not significantly different from the other treatments. The MEM kernel yield of BiMe was the lowest (see Figure 25). The MEM difference between Neg (highest) and BiMe (lowest) was 600 kg/ha.

The MEM of the kernel yield (kg/ha) for Neg, Pos, Bit, Met and BiMe were 2867, 2383, 2273, 2762 and 2267, respectively. The SD was ± 421 .

The significance was analyzed on the p-value level <0.05 and the MEM was used for the analysis, which in this case was the same as the arithmetic mean (Burren 2024, personal communication). The requirements for ANOVA I were met (Shapiro test: $p = 0.6652$; Levene test: $p = 0.911$)

According to Russel et al (2024, 27) as a Post Hoc test a pairwise comparison was made without correction.

The block factor (Farm) explained 77.8 % of the variance. This indicates that most of the variability in yield is due to differences between farms.

Additionally, the kernel yield per plant was analyzed in the same way as mentioned above for the on-station trial.

The MEM of kernel yield per plant varied from 55.0 g/plant to 65.5 g/plant. Neg had the highest kernel yield per plant and BiMe the lowest (see Figure 26). There was no significant difference between all treatments.

The MEM for Neg, Pos, Bit, Met and BiMe were 65.5, 64.1, 61.7, 64.7 and 55, respectively. The SD was ± 5.58 .

The significance was analyzed on the p-value level <0.05 and the MEM was used for the analysis.

The requirements for ANOVA I were met (Shapiro test: $p = 0.7836$; Levene test: $p = 0.9925$). As above, a Post Hoc test a pairwise comparison was made without correction.

The block factor (Farm) explained 80.3 % of the variance. This indicates that most of the variability in yield is due to differences between farms.

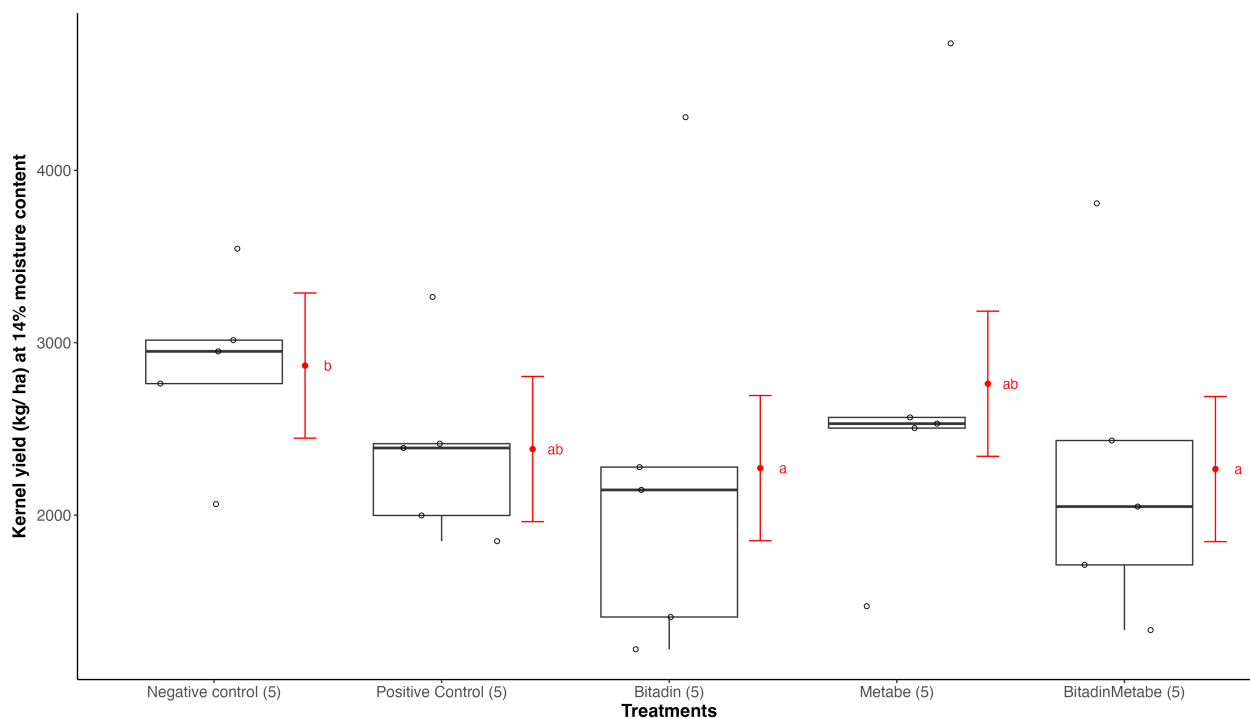


Figure 25: Kernel yield (kg/ha) for each treatment: red dots represent the mean values, the thick black lines indicate the medians and the letters show the group of signifiante. The active ingredients of the tested products are as follows: Bitadin – *Bacillus thuringiensis* & granuloviruses; Metabe – *Metarhizium anisopliae* & *Beauveria bassiana*.

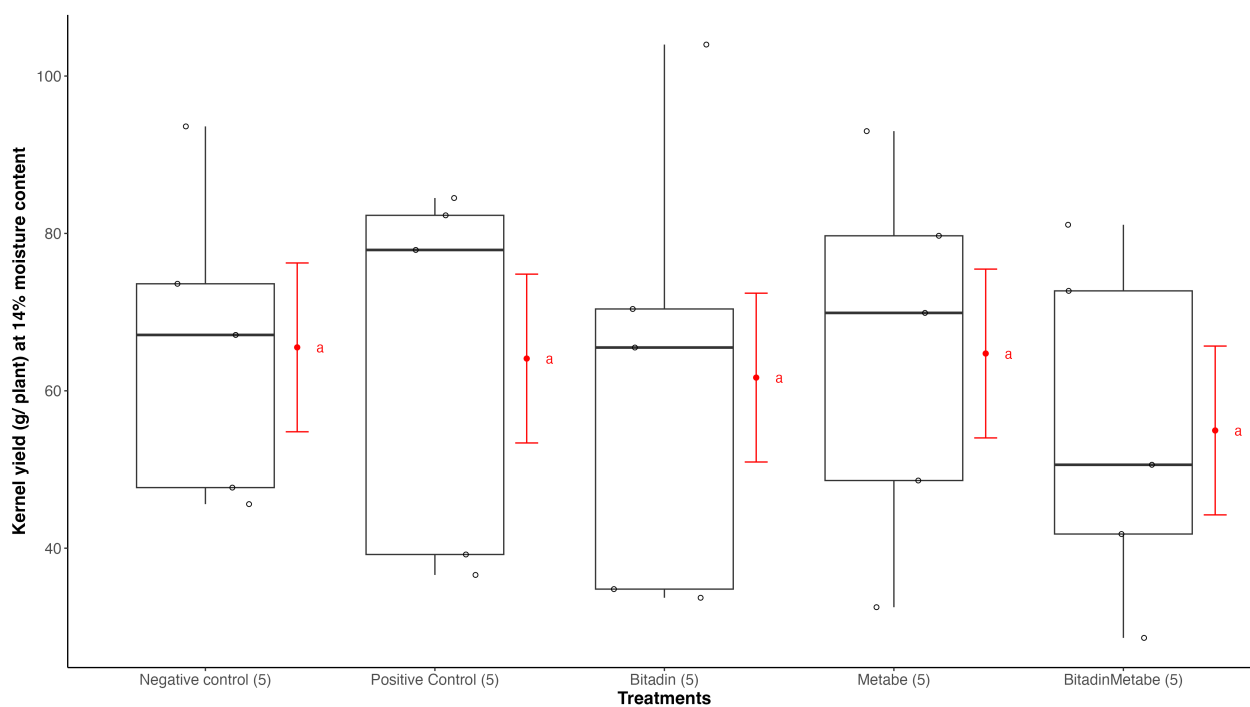


Figure 26: Kernel yield per plant (g/plant) for each treatment: red dots represent the mean values, the thick black lines indicate the medians and the letters show the group of signifiante. The active ingredients of the tested products are as follows: Bitadin – *Bacillus thuringiensis* & granuloviruses; Metabe – *Metarhizium anisopliae* & *Beauveria bassiana*.

4.2.2 Economic impact

As mentioned before, the number of synthetic insecticide applications were two. Therefore, the number of applications of biopesticides was four during the whole trial phase.

Table 12: Partial budgeting analysis showing costs, yield, and profit per treatment: italicized numbers are in Khmer Riel per hectare, and values in regular font are in US\$ per hectare.

Treatment	Negative control	Positive control	BITADIN WP	METABE	BITADIN WP/METABE
Cost					
Labour	0	-3.5	-7.0	-7.0	-7.0
	<i>0</i>	<i>-14'000</i>	<i>-28'000</i>	<i>-28'000</i>	<i>-28'000</i>
Product	0	-25.9	-65.6	-115.2	-90.4
	<i>0</i>	<i>-103'600</i>	<i>-262'400</i>	<i>-460'800</i>	<i>-361'600</i>
Total costs	0	-29.4	-72.6	-122.2	-97.4
	<i>0</i>	<i>-117'600</i>	<i>-290'400</i>	<i>-488'800</i>	<i>-389'600</i>
Yield (ton/ ha)	4.96	4.21	4.07	4.80	4.03
Price/ ton	159.5	159.5	159.5	159.5	159.5
	<i>638'000</i>	<i>638'000</i>	<i>638'000</i>	<i>638'000</i>	<i>638'000</i>
Income	791.1	671.5	649.2	765.6	642.8
	<i>3'164'480</i>	<i>2'685'980</i>	<i>2'596'660</i>	<i>3'062'400</i>	<i>2'571'140</i>
Profit	791.1	642.1	576.6	643.4	545.4
	<i>3'164'480</i>	<i>2'568'380</i>	<i>2'306'260</i>	<i>2'573'600</i>	<i>2'181'540</i>

The profit among all treatments varied from US\$ 545.4 to US\$ 791.1. The highest profit resulted in the negative control where no insecticides were applied, and the lowest profit was achieved by the treatment BITADIN WP/METABE. The difference between them was US\$ 245.7. A similar pattern is observed for the mean yield. The FM cob yield (tons/ha) ranged from 4.03 to 4.96, with the highest yield achieved in the negative control and the lowest yield recorded for the BITADIN WP/METABE treatment.

The highest total costs resulted with METABE, summing up to US\$ 122.20, followed by BITADIN WP/METABE with US\$ 97.40. The positive control incurred costs of US\$ 29.40, while no costs were associated with the negative control.

4.2.3 Farmers perception

Besides measuring agronomic data in the on-farm trial, interviews with the farmers were conducted about their perceptions of the trial. All eight farmers were interviewed individually. In the following sections, the farmers' perceptions are presented first. Subsequently, additional data gathered during the same interviews, including crucial criteria for purchasing insecticides, primary sources of pest management information and other relevant aspects, are presented.

For more detailed information about the results of these interviews, the raw data can be found in Annex 9.

Farmers perception

Initially, it was planned to rate and evaluate the treatments together with the farmer in the field. The damage caused by FAW across all treatments was very severe, making it impossible to visually evaluate the treatments.

The farmers did not have a strong opinion about the field trial, but the majority were interested in research or evaluating new methods.

Current situation with FAW

When asked how they perceive the current situation with the FAW, all farmers stated that FAW is a severe problem for them. Six out of eight farmers stated that infestation by FAW increased this year compared to the previous year. They primarily reported the increased severity caused by the lack of rainfall during May, June, and July which benefitted the FAW.

During informal conversations with five farmers while doing field visits in Koas Krala district, they reported that, after the lack of financial resources, followed by rainfall variability the FAW was the third most important issue affecting production on their farms. Another critical challenge mentioned was weed management.

Important characteristics for insecticides

When asked about important characteristics for buying insecticides six farmers out of eight stated that efficacy of the insecticide is crucial for them (see Figure 27). Other important characteristics mentioned were “Knockdown effect”, which was mentioned four times followed by price which was mentioned twice. Farmers defined the “knockdown effect” as the observable immediate impact on insect pests following the application of an insecticide, such as paralysis or death.

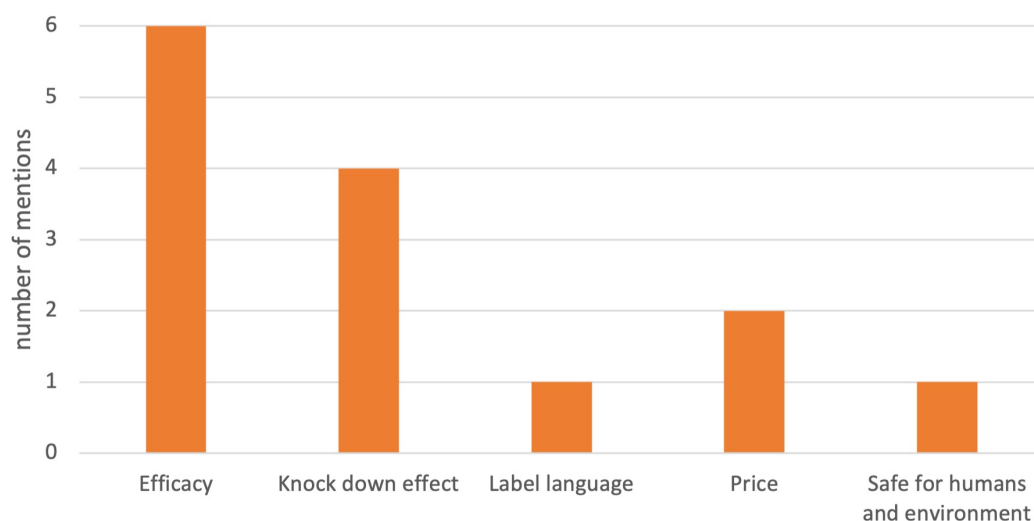


Figure 27: Important characteristics for buying insecticides mentioned by farmers (n=8)

Information source for pest management

As an information source for pest management, the input shop was mentioned by seven out of eight farmers (see Figure 28). Also other farmers as sources of information were mentioned five times. Extension service from the Provincial Department of Agriculture, Forestry and Fisheries (PDAFF) or other governmental institutions were never mentioned.

Four farmers reported that they find other farmers the most trustworthy source. The remaining four farmers indicated, they trust most in the information they got from the input shop. When asked about the experience of receiving wrong information, five farmers reported having received incorrect information from the input shop at least once. While only one farmer mentioned that he experienced getting wrong information from another farmer.

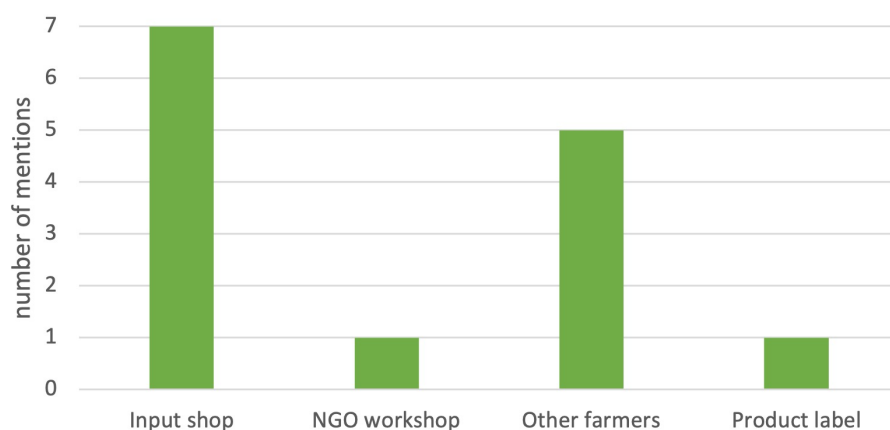


Figure 28: Information sources of farmers (n=8) for pest management

4.3 Farmer survey

For assessing the farmers knowledge about IPM. To find out which preventative and intervention control methods for FAW they apply and how they estimate the economic damage caused by FAW qualitative interviews with the eight farmers participating in the on-farm trial were conducted. Furthermore, some information which the Nurture project requested was collected.

All farmers were interviewed individually.

The structure of the chapter is as follows. First, demographic data of the eight farmers and general data about their farm is presented. Second, the assessment of their IPM knowledge. Third, their FAW monitoring, preventative and intervention methods are presented, followed by their use of pesticides and economic data about FAW and maize. The chapter concludes with the FAW control methods they would like to test in future and specific information for Nurture.

For more detailed information about the results of these interviews, the raw data can be found in Annex 10.

General data

The ages of the eight farmers ranged from 27 to 65 years, with seven of them being over 50 years old. Seven of the participants were male and one was female.

The level of education varied a lot among the farmers. Two farmers never attended school. Three attended primary school and three finished at least grade 7 during the KR regime.

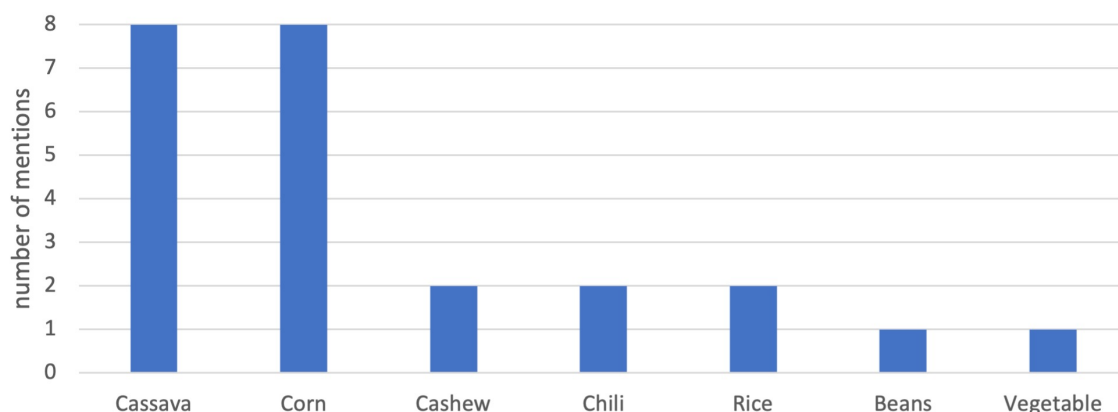


Figure 29: Food and cash crops that farmers (n=8) have on their farms

Six farmers had in common, that they migrated from other provinces to their current home during the last 20 years. One farmer migrated already in 1980 from Takeo province, and one migrated within the province of Battambang a few years ago.

All farmers, except for the youngest, primarily work on their own farms. The youngest farmer occasionally takes on labor outside his farm for tasks such as pesticide application or crop harvesting.

All eight farmers cultivate maize and cassava on their fields (see Figure 29). A few farmers also grow additional crops, including cashew, rice, chili, beans, and various vegetables.

4.3.1 Their knowledge

The farmers knowledge and perception about IPM was assessed by asking how many out of ten insects (which occur in the region of research) the farmers recognized. On average, the farmers identified approximately seven (7.1) correctly. The numbers of identified insects varied from 1 to 10. Additionally, the farmers were asked to identify which of the insects they know they perceive as beneficial or as pests for their crops. All eight farmers uniformly reported that they consider every insect to be a pest, with no insects viewed as beneficial.

4.3.2 Their methods

IPM methods

The following methods, that align with an IPM approach (FAO 2018, 14; Murray et al. 2019; ECHO Staff 2022, 2), are perceived to prevent FAW infestation and are used differently among the farmers.

Six farmers applied crop rotations with at least two species on their fields. Two farmers did consequently monocropping of maize and cassava on their fields. Seven farmers never applied intercropping on their fields. As main reason was reported the use of herbicides. One farmer practice intercropping with maize and cashew trees. He typically ceases intercropping three years after planting the trees due to excessive shade affecting the maize plants.

Regarding fertilizer application to grow a healthy crop, three farmers never applied fertilizer to maize. Four farmers applied approximately 2L/ha of liquid urea during one crop cycle. The primary reason reported for not applying or for using low dosages of liquid fertilizer was a lack of financial resources. Only one farmer applied 50kg/ ha of NPK (20-20-15 &TE) during planting.

For weed control, farmers solely relied on herbicides. Five of them sprayed once while two farmers did not spray at all. One farmer sprayed twice. For him the second application took place just before the harvest to prevent hired laborers from being harmed by certain weed species.

Seven out of eight farmers are regularly monitoring the maize for infestation signs of FAW. The remaining farmer reported, that he only does the monitoring during the second crop cycle of the rain season.

Farmers solely used synthetic insecticides as intervention methods for FAW. One of the farmers never sprayed insecticides during recent years because he doubted their efficacy and money is a constraint for him. Among the seven farmers who used synthetic insecticides six of them decided to spray when they perceive the abundance, or the damage is too high. A single farmer does calendar spraying. The mentions for average numbers of insecticide applications within one maize cycle during the last few years ranged from zero to three. The median for numbers of insecticide applications is two. Three farmers mentioned three applications, while two farmers reported two applications, and another two farmers indicated one application.

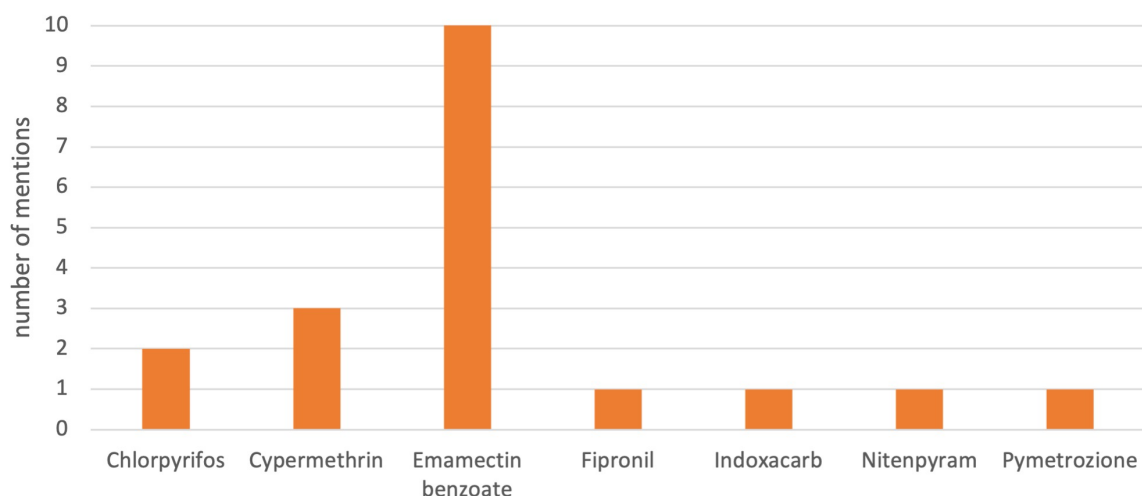


Figure 30: Active ingredients used by farmers (n=8) over the last three years for fall armyworm control

When asked about the a.i. in insecticides used during the last three years to control FAW, Emamectin benzoate was mentioned 10 times (see Figure 30). Cypermethrin followed with three mentions and Chlorpyrifos with two. More than half of the total mentions reported Emamectin benzoate as a.i. in insecticides.

Use of pesticide

In this section, the use of pesticides by the farmers is assessed. This includes reading product labels, using personal protection equipment (PPE), timing applications throughout the day, and other related practices. As visible in Figure 31, among eight farmers only three read the product labels of pesticides. The majority does not read the labels. The main reason for not reading the labels is illiteracy.

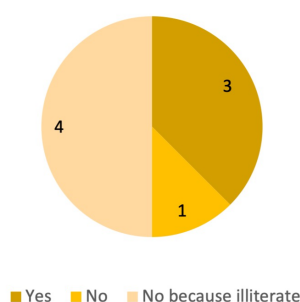


Figure 31: Farmers (n=8) responses when asked if they read and understand the pesticide labels on the products they purchase.

For preparing pesticide-water mixtures, farmers primarily rely on dug ponds for rainwater collection as their source of water. The ponds were mentioned eight times. Alternative sources were rainwater containers with two mentions and irrigation canal with one mention.

When the farmers were asked if they mix different kinds of pesticides, three farmers answered they never do this. Four answered they rarely mix herbicides with insecticides, and they are aware of potential

antagonism of the products. One farmer stated he often mixes herbicides with insecticides because the application windows are usually short.

For preparing and applying pesticides three out of eight farmers use long clothes, closed shoes and a face mask as PPE. One farmer reported he uses gloves, glasses, face mask, long clothes and closed shoes as PPE.

Two farmers never use PPE because they do not feel comfortable with it while spraying during the hot weather conditions. The remaining two farmers indicated that due to their age, they must consider their health and therefore hire labor for pesticide application. Two of the farmers reported that they feel dizzy and have headaches after spraying pesticides.

Regarding the timing and weather conditions for applying insecticides, particularly for FAW farmers reported the following: three farmers typically spray early in the morning, while three spray late in the afternoon. The two remaining farmers apply insecticides at night, as this is when the FAW appears to be most visible. Two farmers explained they prefer light rain during the application so the insecticide runs into the whorl and might increase the efficacy.

In general, the eight farmers reported, they do not spray pesticides when it is too hot, too windy or when there is heavy rain.

4.3.3 Economics about FAW and maize

In this chapter, the economic figures about insecticides for FAW, maize price and others are presented. The interviewed farmers estimated yield losses in their maize fields due to FAW ranging from 10 % to 60 % (see Figure 32). The average of these estimates is 35 %.

To control FAW, seven farmers spent on average US\$ 25.9/ha per maize cycle for insecticides. As mentioned before one farmer did not spray insecticides in recent years. The reported costs for insecticides ranged from US\$ 5 up to US\$ 75 per ha/maize cycle.

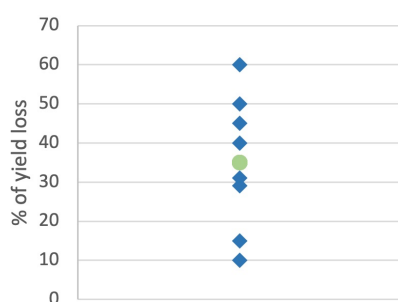


Figure 32: Farmers (n=8) estimations of yield loss due to fall armyworm, with the green point indicating the mean value.

The harvest of all farmers is sold to silos where the cobs are dried and threshed. The farmers sell their harvest as fresh dehusked cobs to the silo manager. The reported prices for fresh dehusked cobs ranged from US\$ 150/ ton up to US\$ 175/ ton. The farmers consistently identified moisture content as a relevant quality criterion. However, they were unable to quantify its impact on the price. As mentioned previously, the price and the quality criteria were crosschecked with a silo owner (Yurn 2024, personal communication). He reported an average price of US\$ 156.25/ ton which he pays to farmers for fresh dehusked cobs. Furthermore, he confirmed the moisture content as the only relevant criterion for setting the price.

4.3.4 FAW control methods for future testing

Farmers were asked to identify control methods for FAW out of the eleven in Figure 33, they would like to test on their farms in the future. All respondents expressed interest in evaluating more effective synthetic insecticides than those currently available.

FAW tolerant maize varieties, cover crops and monitoring methods were mentioned by seven farmers. Followed by biopesticides with six mentions. Farmers had the lowest interest in intercropping and agroforestry.

The majority of the farmers reported the lack of money and the lack of local availability as the two main reasons for not adopting new control methods.

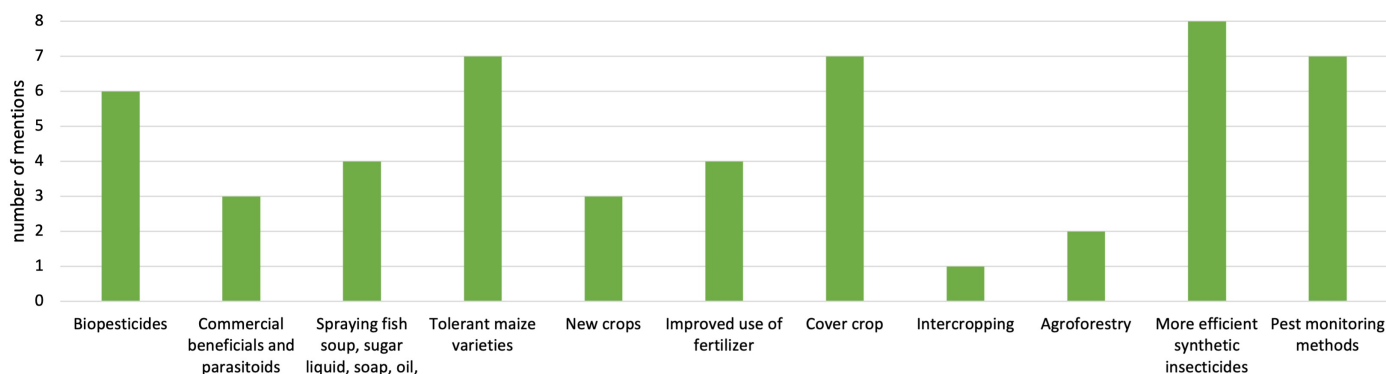


Figure 33: Fall armyworm control methods farmers (n=8) are interested in trying on their farms.

4.3.5 Nurture

During a field visit to the on-farm trial with the Nurture team in Koas Krala district, the question arose regarding the increasing number of farmers switching from maize to cassava production. Therefore, farmers were asked to identify the primary drivers behind this shift and whether this pattern occurs regularly.

As main reasons for this shift farmers identified cassava as more drought tolerant as maize (see Figure 34). Additional reasons mentioned by farmers included that cassava is less susceptible to pests, requires fewer inputs, and yields higher profits.

All farmers reported that this shift happens regularly. It primarily depends on the market price for both crops.

For personal interest, the farmers were asked whether they had observed FAW infestations in their cassava fields. Six farmers denied observing any infestations, while two reported that they occasionally experienced FAW infestations in cassava but found them easy to manage

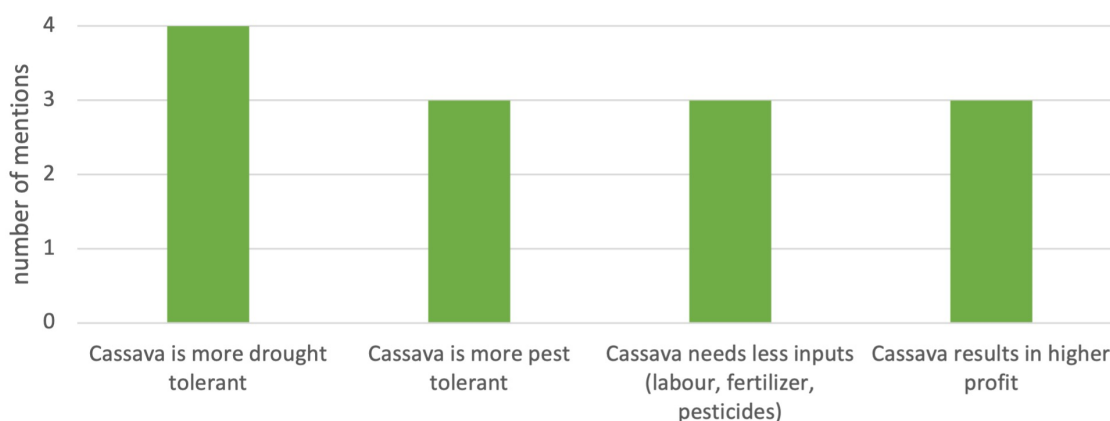


Figure 34: Reasons for shifting from maize to cassava mentioned by farmers (n=8) in Koas Krala and Samlout districts.

4.4 Semi-structured key person/expert interviews

4.4.1 FAW IPM control methods and market actors in Cambodia

The results from the key person interviews are summarized in Figure 35 and complemented with data from the literature review to map the market of IPM control methods for FAW that are commercially available in Cambodia. The interviewed key persons were the head of the ASEAN FAW Action Plan in Singapore, a deputy director from PDAFF in Battambang and two biopesticide sellers based in Phnom

Penh.

For more detailed information about the results of these interviews, the raw data can be found in Annex 12.

Below the MSD donut, additional information is provided about the value chain, its key actors, supporting services, and the regulations influencing the value chain. Given the high complexity of the market for IPM control methods for FAW, like many other markets, with numerous interdependencies and interactions, this model does not aim to fully represent the entire reality across Cambodia.

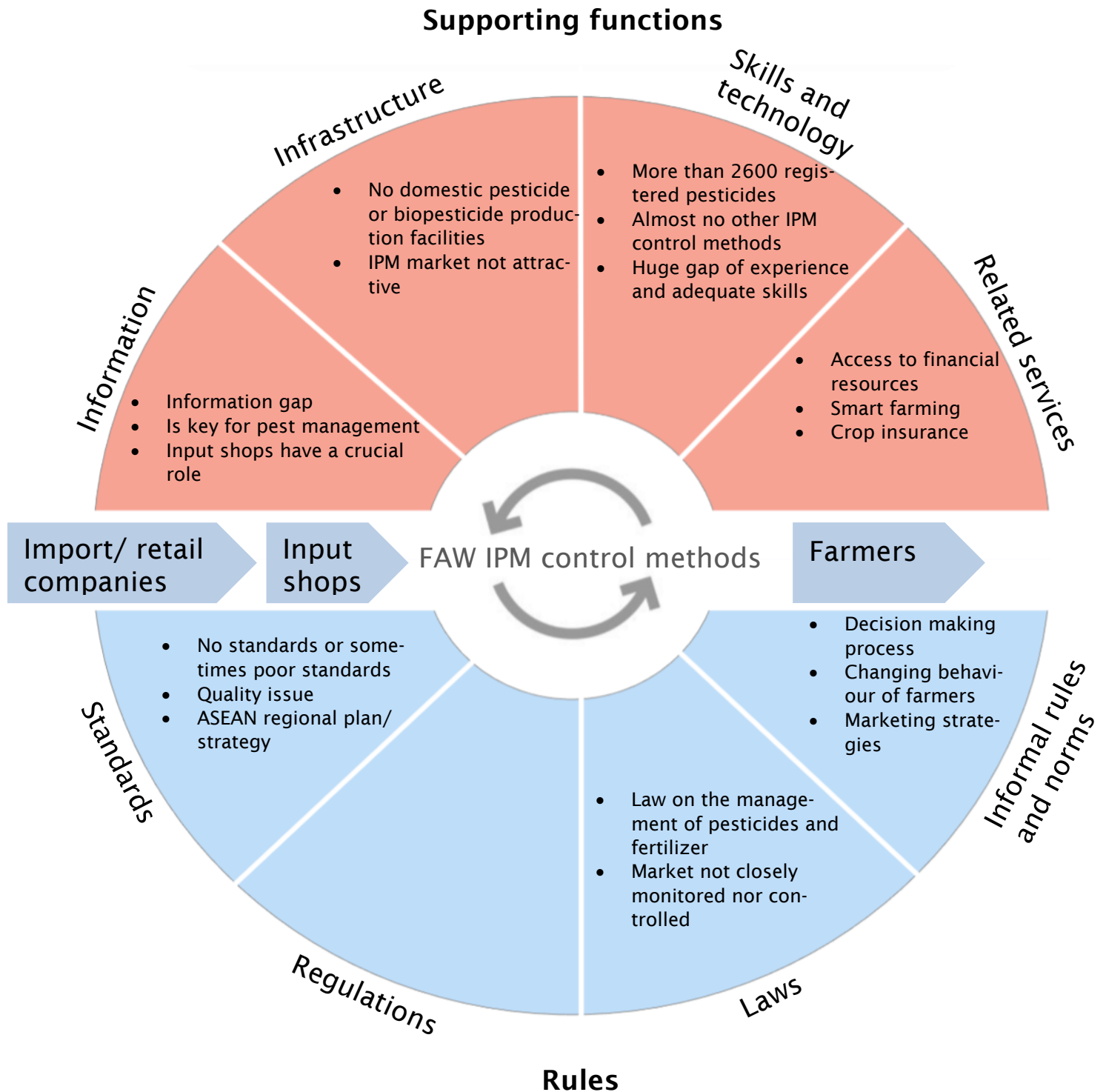


Figure 35: Market system development donut mapping the market system of integrated pest management methods for fall armyworm in Cambodia.

Value chain

The value chain for IPM control methods for FAW that are commercially available in Cambodia consists of the three actors, the import and retail companies, the input shops and the farmers. First there are the import and retail companies, which import the products from their parent companies or other foreign suppliers (Bureau-Point et al. 2024). In some cases, these companies reformulate and repackage the pesticides. The products are then distributed to provincial, district, and communal levels, reaching the so-called input shops. These input shops sell the products, along with advice on pest and pesticide management, to the final users, the farmers (Pheakdey 2014; Bureau-Point et al. 2024). The commercially available IPM control methods for FAW in Cambodia are simplified in the following as synthetic insecticides. According to Watson (2024, personal communication) biopesticides have currently no significant role in the system of FAW management in ASEAN countries. In the pesticide registration list of Cambodia out of 1000 registered products only six are biopesticides (Pesticide register Cambodia, 2019).

Actors

In this section, the important actors in the value chain are shortly described and how their business model looks like.

Import retail companies

The big players in the market are the import and retail companies who import pesticides from foreign markets. Primarily from Vietnam, Thailand, China and South Korea (Bureau-Point et al. 2024). Within Cambodia, no pesticides are produced. According to Bureau-Point et al. (2024) in 2020, 140 such companies were registered in Cambodia. A sharp increase, when considering that in 2013 there were only 28 registered companies (Bureau-Point et al. 2024).

After importing, pesticides are sometimes repackaged or mixed to create new products (Bureau-Point et al. 2024). These are then sold to input shops across the countryside throughout Cambodia (Bureau-Point et al. 2024). Retail companies employ field promoters, often agriculture graduates (Bureau-Point et al. 2024), who serve as the link to rural input shops. They promote new products, monitor pest problems and trends on farms, manage demonstration fields to showcase product effectiveness, and take orders from input shops (Bureau-Point et al. 2024).

The marketing strategies of these companies involve various mechanisms. They offer incentives such as free iPhones, fridges, and motorbikes to input shops that place larger orders, and they also provide credit options (Bureau-Point et al. 2024). Some input shops can delay payment for up to one month after receiving the delivery (Bureau-Point et al. 2024). To attract farmers, companies use product names like "Tiger," "Superbomb," and "Samurai" - names that sound powerful and are easy to remember. Another tactic is frequently changing product names and labels to give the impression that the company is constantly offering new and improved products (Bureau-Point et al. 2024). Additionally, they sometimes distribute free shirts with their logos, turning farmers into living advertisements on the fields (Bureau-Point et al. 2024).

Input shops

Input shops sell pesticides and other cropping inputs such as fertilizers and seeds locally to farmers (Pheakdey 2014; Bureau-Point et al. 2024). The input shops primarily obtain pesticides from retail companies, but some shops in border regions sell illegally imported pesticides, which yield higher profits, though the labels are often not in Khmer, the local language (Bureau-Point et al. 2024; Keo 2024, personal communication).

It is common practice at input shops for farmers to receive products on credit, with payment deferred for a few months or until after the harvest period. The input shops also offer loans to farmers to facilitate the purchase (Pheakdey 2014; Bureau-Point et al. 2024; Teng 2024, personal communication). In addition to selling inputs and providing loans, input shops are invaluable to farmers for offering advice on pest management (Pheakdey 2014; Bureau-Point et al. 2024), with farmers often heavily relying on them for such information (Bureau-Point et al. 2024).

The transfer of information is crucial for the business model of the input shops too, because during the last decade the competition on the market increased and to provide good information to farmers is eminent for sustaining on the market (Bureau-Point et al. 2024).

The input shops acquire their knowledge about pests and pesticides through the internet, YouTube, scientific papers, information from relatives who studied agriculture, the field promoters and through short trainings in neighboring countries provided by the retail companies (Bureau-Point et al. 2024). Additionally, the owner of an input shop has to attend a 3-4 days' workshop about business law and other topics at the district agriculture office before getting the license for selling pesticides (Savonmuni 2024, personal communication; Bureau-Point et al. 2024)

Farmers

When a pest occurs in a Cambodian farmer's field and they decide to intervene, they typically visit the nearest input shop (Pheakdey 2014; Bureau-Point et al. 2024). Often, the farmer have a preferred product based on their experience. Otherwise, they explain the problem to the shop, detailing the pest, its severity, and the crop's growth stage (Bureau-Point et al. 2024). Based on this information, the seller typically selects a product and provides advice on pest management, including dosage, application frequency, and other relevant details (Bureau-Point et al. 2024).

Even as farmers accumulate knowledge about pests, they still rely on the input shop for advice, as product labels change frequently (Bureau-Point et al. 2024), and effective products sometimes disappear from the market without explanation (Teng 2024, personal communication).

Beside depending highly on input shops farmers also face other challenges, including droughts, soil degradation, pest resistance, lack of market information, limited financial resources, and the hazardous use of pesticides (Pheakdey 2014; Bureau-Point et al. 2024). Many farmers report experiencing headaches or dizziness after applying pesticides (Bureau-Point et al. 2024).

Supporting functions

Information

According to ASEAN (2020, 29) there are multiple issues to deal with FAW. There is an information gap in Cambodia about how to control the FAW, there is an absence of a FAW management strategy and there is lack of resources for knowledge disseminations such as FFS and ToT. To close these gaps the public, private, research and NGO sector are currently working on it with different incentives (Watson 2024, personal communication).

Watson (2024, personal communication) mentioned that knowledge is the key factor for farmers to control the FAW in an effective and sustainable way. To know how to apply insecticides and in which pest stage is the most important thing for controlling the FAW (Watson 2024, personal communication). Without knowledge about the pests, beneficials and good practices for crop management, the farmers will highly depend on the input shops (Heusing 2020, 15; Parimi 2020, 16; Watson 2024, personal communication). Often low resource farmers are missing basic knowledge about Good Agriculture Practice and IPM (Huesing 2020, 15).

The knowledge which is provided to farmers about pesticides and pests by input shops might be unqualified and biased. It is often a mix from different sources which are not independent and transparent (Bureau-Point et al. 2024).

The information which input shops provide to farmers is often incoherent and sometimes wrong because they rarely consult PDAFF for information about pest management (Savonmuni 2024, personal communication).

Keo (2024, personal communication), one of the two biopesticide sellers, promoted and sold over the whole country biopesticides to input shops. During this time, he made the experience, that already on this level is a knowledge constraint how to use and apply them effectively and therefore the input shops did not sell the biopesticides to their clients (Keo 2024, personal communication).

The concerns of ASEAN mentioned above are addressed partially by PDAFF (Savonmuni 2024, personal communication). In some districts in the Battambang province, PDAFF guides FFS about FAW, but financial resources are limiting (Savonmuni 2024, personal communication). To increase the coverage PDAFF follows the Private Public Partnership by collaborating with the private and the NGO sector (Savonmuni 2024, personal communication).

Watson mentioned (2024, personal communication) that knowledge dissemination and access to information by FFS is very cost and personal intensive. A more effective and sustainable approach could be ToT. Thereby, the identification and the choice of the right people as trainers is the key point to tackle this issue (Watson 2024, personal communication).

Infrastructure

Currently, there are no pesticide production facilities existing in Cambodia (Bureau-Point et al. 2024). Neither are there rearing stations for breeding beneficials and parasitoids to control the FAW (Savonmuny 2024, personal communication). Once Thai International Cooperation Agency introduced Nematodes for pest control in a project, but failed to sustain, because the knowledge and infrastructure are not available locally (Savonmuny 2024, personal communication).

For making IPM methods beyond synthetic insecticides accessible to farmers, crucial changes are required, particularly in infrastructure and market structure (Keo 2024, personal communication). Under the current conditions, the market is unattractive to large companies selling IPM methods (Watson 2024, personal communication). This is primarily due to the low demand for IPM methods, such as biopesticides, and the challenge of reaching millions of farmers (Watson 2024, personal communication). These factors make it difficult to develop viable business models for IPM methods in such a fragmented market (Watson 2024, personal communication).

Skills and technology

In 2020, there were over 2600 registered pesticides in Cambodia (Bureau-Point et al. 2024). They contained 336 a.i. which means that a lot of products have the same a.i. (Bureau-Point et al. 2024).

Only few of these pesticides are biopesticides (Pesticide register Cambodia, 2019; Watson 2024, personal communication).

According to Savonmuny (2024, personal communication), there are currently limited technologies available in Cambodia for controlling FAW beside synthetic insecticides and pheromone-based mating disruption technology. He identifies a gap and sees potential in breeding FAW-tolerant maize varieties, which could support an IPM approach fitting the local context (Savonmuny 2024, personal communication).

Nemec (2024, personal communication) highlights that even the use of synthetic insecticides requires substantial knowledge and skills, and this is even more true for biopesticides. These skills are currently lacking in Cambodia's practice (Nemec 2024, personal communication). For instance, almost no input shops are selling wetting agents, and as a result, farmers do not use them to enhance product efficacy (Nemec 2024, personal communication). Additionally, few people know that biopesticides contain living organisms, such as entomopathogenic fungi, that need to be activated, or know how to activate them to achieve effective pest control (Nemec 2024, personal communication). Delatouche (2024, personal communication) reported, that currently no adequate FAW monitoring methods such as pheromone lures are commercially available in Cambodia. Watson (2024, personal communication) emphasizes that when developing and introducing new control methods for FAW in Cambodia, it is crucial to also consider other armyworm species that have recently caused significant damage to various crops. Additionally, Watson (2024, personal communication) identifies the examination and respect for farmers' and household decision-making processes as a key factor for the successful adoption of new technologies by farmers.

Related services

There are different related services to the market for synthetic insecticides. One is access to finance resources. The retail companies provide input shops delayed payments for the delivery and input shops provide informal loans to farmers for buying pesticides and other products (Pheakdey 2014; Bureau-Point et al. 2024). Other access to financial resources is provided by banks and microfinance institutes (Pheakdey 2014). But this capital is more difficult to access for most farmers because the credit officer checks the household status and the land titles before providing a credit (Pheakdey 2014). If the farmers do not have land titles, they must group at least 3 people who guarantee for the loan (Pheakdey 2014).

Another emerging service is the use of drones for spraying crops, which has gained popularity in recent years (FUTUREiOT 2022). This technology can help farmers save money and improve efficiency by reducing both the number of applied pesticides and labor costs, particularly during peak seasons when labor is not always readily available (FUTUREiOT 2022). The cost of spraying one hectare with a drone is approximately US\$ 7.5 per hectare (Ratt 2024, personal communication).

Crop insurance for key crops like rice, mango, vegetables, and others is another related service (Forte 2024). However, this insurance currently only covers crop losses caused by weather events such as droughts and floods and does not yet include losses due to pest infestations (Forte 2024).

Rules

Standards

Nothing is known about standards set by the pesticide industry itself in Cambodia. However, it is widely recognized among farmers that pesticide quality is sometimes poor (Bureau-Point et al. 2024; Watson 2024, personal communication; Martin 2024a, personal communication). This issue is due to retail companies altering formulas by reducing the quantity of the active ingredient or adding other substances not listed on the label (Bureau-Point et al. 2024; Watson 2024, personal communication). Martin (2024a, personal communication) noted similar concerns with other inputs, such as seeds. For example, some maize seeds on the market have shown germination rates below 50% in laboratory tests (Martin 2024a, personal communication).

According to Watson (2024, personal communication), the ASEAN region is developing a regional strategy for managing FAW, which will be implemented through national-level strategies. Given the globalization of trade and the spread of pests, FAW cannot be effectively controlled at the national level alone (Watson 2024, personal communication). Pest populations and resistance do not respect human-set borders (Watson 2024, personal communication).

Regulations

No local regulations are known and thereby all relevant laws are listed under the section “Laws”.

Laws

The most important law governing this market is the law on the management of pesticides and fertilizers. It regulates the registration process of pesticides, their labeling, the mandatory training sellers must complete to obtain a license, the trade and advertisement of pesticides, as well as conducting research related to these products (FAO 2012).

Although the law on the management of pesticides and fertilizers was adopted as a legal instrument to regulate the use and trade of pesticides in Cambodia the country faces numerous challenges related to pesticide management and the implementation of the law (Bureau-Point et al. 2024). The pesticide market is neither closely monitored nor effectively controlled (Bureau-Point et al. 2024).

Watson (2024, personal communication) reported that in China, the government legally subsidizes more sustainable pest control methods for farmers, which has led to an increase in the use of these methods. However, no similar initiatives are known to exist in Cambodia (Watson 2024, personal communication).

Informal rules and norms

One of the most important key elements is the decision-making process of farmers and their households (Watson 2024, personal communication). It is important to examine which factors influence them for decision-making process about farming and other matters (Watson 2024, personal communication). Another informal rule is, that when input shops sell more pesticides respectively place larger orders, they can get additional benefits such as free iPhones, fridges or participating in lotteries where they can win gold and other luxury items (Bureau-Point et al. 2024).

5 Discussion

This chapter discusses the previously presented results, focusing solely on those that are relevant and contribute to answering the research questions.

The chapter is structured as follows: each subchapter links the results to the research questions, followed by a discussion informed by the literature review. Finally, the implications for relevant actors in Cambodia's agricultural sector are highlighted. This chapter is complemented with the limitations this study faced.

5.1 Field trials

In both field trials, commercially available biopesticides (BITADIN WP, METABE) and for the on-station trial additionally Neem oil, were assessed for their impact on vegetative damage, yield, and economic viability. Furthermore, in the on-farm trial the treatments were evaluated together with the farmers.

5.1.1 On-station trial

To address the research question on how commercially available biopesticides (BITADIN WP, METABE, Neem oil) compared to Emamectin benzoate (positive control) and no spray (negative control) in terms of crop damage, yield, and economic impact, the following observations were made:

All treatments tended to reduce mean crop damage compared to the untreated negative control. However, the treatments differ significantly in their efficacy. BITADIN WP, METABE, and the positive control showed similar efficacy in reducing crop damage caused by FAW, with values ranging between 2.19 and 2.86. In contrast, Neem oil exhibited a mean crop damage of 3.51, which was nearly equivalent to that of the negative control (3.91). The lack of observable efficacy of Neem oil in reducing crop damage may be attributed to its low a.i. concentration, containing only 0.03% w/w of Azadirachtin.

In a similar field trial conducted by Babendreier et al. (2020) in Ghana in 2018, Neem oil treatments with higher concentrations (0.17% and 0.33%) demonstrated efficacy comparable to the positive control with Emamectin benzoate. Additionally, in the study of Babendreier et al. (2020), the mean crop damage was in tendency lower in the Neem oil treatments than in the untreated negative control. The differences between our results and those of Babendreier et al. (2020) are likely due to higher Azadirachtin concentrations, the use of soap as a wetting agent in their trials, and differing environmental conditions at the two experimental sites.

According to Nemec (2024, personal communication), wetting agents are essential for ensuring the efficacy of pesticides under Cambodian climatic conditions. Ramseier (2024, personal communication) stresses that in some cases the use of wetting agents can increase the efficacy of a product, but wetting agents are not generally required for the use of pesticides.

Overall, the three treatments and two controls had relative low mean foliar damage, especially considering that the crop damage scale ranges from 0 to 9, with 9 representing the highest possible damage level. One possible explanation for this relative low damage is the heavy rainfall events during the rainy season, which can wash young larvae off the plants or even kill them (Varella et al. 2015). According to WBG (2024), the monsoonal rains in Cambodia during the rainy season are often intense. During the data collection period, there were several heavy rainfall events, with daily precipitation ranging between 28 mm and 66 mm (PDWRAM 2024).

These heavy rainfall events and the subsequent reduction in larvae could explain why the probability of finding larvae on a plant (see Figure 22) is lower before the application of treatments compared to afterward for all treatments, except METABE. Logically, one would expect that if the applied products were effective, the probability of finding larvae on a plant would be lower after the application. However, examining the weather data (PDWRAM 2024) reveals that significant rainfall occurred three days prior to the first and second assessments (when the larvae per plant before the application was assessed), with 28 mm and 9 mm of rainfall recorded, respectively.

The treatments showed significant variation in their efficacy at reducing the mean number of larvae per plant. The positive control and METABE demonstrated high efficacy, with 0.14 and 0.13 larvae per plant, respectively. In contrast, the other treatments and the negative control had, on average, more than double the number of larvae per plant compared to the positive control and METABE. The higher number of larvae per plant in the BITADIN WP treatment compared to the positive control and METABE may be due to the active ingredients targeting other species rather than FAW (UNIFI 2022a). Most of the a.i. are

for other *Spodoptera* species or *Helicoverpa armigera* (UNIFI 2022a). Additionally, ballooning—where young FAW larvae are carried by silk threads and air currents to nearby plants (Prasanna et al. 2021)—may have contributed to the increased number of observed larvae. Because although the experimental design was a completely randomized block design most of the BITADIN WP and Neem oil plots were located at the border of the experimental site (see Figure 11). It could be that from the untreated surroundings of the experimental site larvae were migrating in the experimental area.

Regarding the impact of the different treatments on the yield, all treatments achieved yields between the positive control (4277 kg/ha) and the negative control (3272 kg/ha), except for the Neem oil treatment, which had a significantly lower yield (1429 kg/ha). Based on Neem oil's performance in reducing crop damage and larvae per plant, one might have expected its yield to be comparable to that of the negative control.

Also, for the yield per plant, which considered the varying number of plants per plot, a similar picture resulted. Although BITADIN WP (111.0 g/plant) had in tendency a slightly higher yield per plant as the positive control (108.8 g/plant) which is not particularly surprising and can be caused by various factors.

The significantly lower yield in the Neem oil treatment could be attributed to an unidentified disease that emerged during the final weeks of the trial phase. This disease caused plant tissue necrosis, small cobs, and in some cases, plants entirely lacking cobs, with the Neem oil treatment plots being heavily affected. On average, 42.31% of the plants in the Neem oil treatment showed symptoms of this disease, compared to only 18.81% in the other treatments and controls.

While Neem plant extracts have been reported to cause significant phytotoxicity to several plant species, including alfalfa (*Medicago sativa*), bean (*Vigna angularis*), and carrot (*Daucus carota*) (Xuan et al. 2004), there is no known evidence of such effects on maize. Additionally, it remains unclear whether Neem oil could increase the incidence of certain diseases in maize.

Across all treatments, the mean yield in the field was 3.4 tons/ha, which is relatively low compared to the national average yield of 4.3 tons/ha reported in 2013 (Pheakdey 2014). Only the positive control and BITADIN WP treatments, with approximately 4.3 and 4.2 tons/ha respectively, are within this range. In the study by Montgomery et al. (2016), conducted with rainfed maize in 2013 and 2014 in the Battambang province, even higher yields were achieved, with a mean yield of 7.2 tons/ha over five subsequent maize cycles using improved agronomic practices.

Several factors could explain the yield gap between our results and those of Montgomery et al. (2016). As noted earlier, the disease observed during the final phase of our trial affected all treatments and likely impacted yield. Moreover, Montgomery et al. (2016) applied significantly more fertilizer per crop cycle, with a total of 300 kg/ha (Montgomery et al. 2016). Additionally, the field used for the on-station trial in this study had a plough pan at a depth of 10 cm in many areas, severely limiting the root zone for water and nutrient uptake. The plough pan was not broken due to the lack of suitable machinery available in the region. Last the FAW which can cause significant yield losses was not present in Cambodia during the study of Montgomery et al. (2016) in 2013 and 2014.

When evaluating the impact of the achieved yield on farmers profit, the positive control resulted in the highest profit, primarily due to lower costs for labor and product combined with higher yield, compared to the biopesticides. The profit from the positive control, at 1088 US\$/ha, was 79 US\$/ha and 219 US\$/ha higher than the profit from the most economically biopesticide, BITADIN WP, and the negative control, respectively.

In this context, a profit difference of 79 US\$/ha is significant, given that the national poverty line is set at approximately 2.7 US\$ per day per person (Karamba and Tong 2022). Furthermore, farmers in informal interviews conducted on 07.06.2024 in the Koas Krala district reported earning a mean hourly wage of 1.4 US\$ when working on other farms.

Overall, the on-station trial demonstrates that almost all biopesticides were less effective than the positive control with Emamectin benzoate. Additionally, biopesticides, as applied in the trial, required twice the application time and resulted in lower profits for every treatment compared to the positive control. Regarding the evaluated biopesticides, there are further aspects to discuss beyond the low concentration of the a.i. in neem oil and the a.i.s in BITADIN WP, which were primarily targeted at other species than FAW.

Different studies have demonstrated that within the species of entomopathogenic viruses, fungi, and bacteria, there often exist various strains (Bravo et al. 2005, 176; Zamora-Avilés et al. 2024). Bioassays with BT, which is a component of BITADIN WP, have shown that the efficacy, specifically the mortality

rates of FAW, is significantly influenced by the strains used, the dosage applied, and the pest stage (Polanczyk et al. 2000; Karshanal and Kalia 2023).

Similar observations were made in bioassays with *Beauveria bassiana* and *Metarhizium anisopliae* strains, which are the a.i.s in METABE. The efficacy has been shown to vary depending on the particular strain (Akutse et al. 2018; Idrees et al. 2022).

Additionally, the formulation of biopesticides can greatly impact their efficacy and environmental stability in pest control applications (Maranga et al. 2005; Mweke et al. 2019). For example, a bioassay comparing oil and aqueous formulations of *Beauveria bassiana* and *Metarhizium anisopliae* showed that the oil formulation caused significantly higher mortality rates, while the aqueous formulation demonstrated lower performance (Maranga et al. 2005). Under field conditions, although the differences were no longer statistically significant, the oil formulation maintained the same trend of higher efficacy as observed in the laboratory (Maranga et al. 2005).

In a similar bioassay with *Metarhizium anisopliae* for FAW larvae control, the larval mortality rate seven days post-treatment was above 70% for the plant oil formulation, compared to only 15.2% for the aqueous formulation (Munywoki et al. 2022).

Concerning environmental stability, Paixao et al. (2017) reported that *Metarhizium anisopliae* mixed with various adjuvants, such as canola oil, mineral oil, and water, exhibited the highest relative viability when mixed with oil and afterwards exposed to 45°C for several hours. This viability was significantly higher than that observed with water. Furthermore, Fernandes et al. (2008) stressed that heat tolerance is a critical criterion in selecting entomopathogenic fungi for arthropod control in tropical regions.

Overall, these findings suggest that, under the current market conditions for maize and pesticides, the biopesticides which are currently commercially available are not a viable alternative to synthetic insecticides because of the lower profitability and efficacy.

5.1.2 On-farm trial

In the on-farm trial, due to various limitations (see chapter “5.3 Limitations of the study”), only the yield could be analyzed.

Regarding the impact of the treatments on the yield, the untreated negative control achieved the highest yield at 2867 kg/ha, followed by METABE at 2762 kg/ha. The mean yield across all treatments and replications was 2510 kg/ha.

For the region where the on-farm trial took place, an average yield of 2.9 tons/ha in 2011 (Brown and Johnstone 2012) and 3.4 tons/ha in 2012 (Montgomery et al. 2017b) were recorded. The lower mean yield across the entire on-farm trial (2.5 tons/ha) compared to these reported higher yields from 2011 and 2012 can be attributed to reduced soil fertility in recent years due to monocropping and erosion (Montgomery et al. 2016; Kong et al. 2021). Additionally, several farmers reported that yields in the first maize cycle, “dam dai” (when the trial took place), are typically lower than in the second cycle, “jiang dai,” primarily because rainfall is usually more stable during the second cropping cycle (Nget 2024, personal communication). Lastly, as mentioned, the FAW, which can cause significant yield losses, was not active in 2011 and 2012 when the reported yields were recorded.

Regarding the mean yield per plant, which accounts for the varying number of plants per plot, the yield ranged narrowly across all treatments, between 55.0 g/plant and 65.5 g/plant. This could be explained by external factors on the farms, such as drought and crop management, having a much greater influence than the treatments themselves.

The results for the yield of the on-farm trial contrast with those of the on-station trial. Several factors may explain these differing and generally lower yields in the on-farm trial compared to the on-station trial.

Firstly, the last farmer participating in the on-farm trial planted maize on 25th May. During the subsequent two weeks, only 20 mm of rainfall was recorded in the Battambang province (PDWRAM 2024). This likely resulted in seeds germinating but with an increasing number of seedlings dying due to insufficient water availability. Montgomery et al. (2016) reported that maize farmers face declining yields and increasing crop failures during this period of the year, attributed to unreliable rainfall patterns, high day and night temperatures, decreasing soil fertility and insect pest pressure.

Secondly, the low germination rate of the seeds used by participating farmers could have further affected the results (Martin 2024a, personal communication). Martin (2024a, personal communication) reported for the farmers seeds germination rates ranging from 28% to 78% after 48 hours, which is

inadequate. This may result from some seed companies repackaging seeds from previous seasons (Martin 2024a, personal communication).

Thirdly, the crop management practices on the farms were generally extensive and insufficient to produce healthy plants (see Figure 36). Three farmers never applied fertilizer to their maize, while another three applied only 2 L/ ha of liquid urea. Also, the use of herbicides happened often too late and too infrequent. Farmers reported lack of knowledge, financial resources and recommendations by input shop sellers as the main barriers to improved crop management.

Another factor that may have reduced the efficacy of the biopesticides was the water quality of the water used for mixing the sprays. The ASR staff responsible for applying the biopesticides used water from dug ponds, as it is common practice among farmers. Nugraha (2024, personal communication) noted that poor water quality can reduce the efficacy of biopesticides.

Finally, it should be mentioned that one farmer, who was excluded from the agronomic data collection, admitted spraying synthetic insecticides in the experimental area. It remains unclear whether other farmers in the analyzed sample may have done the same, which could have introduced bias into the results.

The potential for an increased yield and income through improved agronomic practices seems huge when considering the yield gap between the mean yield from the on-farm trial (2.5 tons/ha) and the mean yield (7.2 tons/ha) in the study of Montgomery et al. (2016). But one must consider that a lot of different factors are influencing the complex decision-making process of smallholder farmers whether and how to adopt improved technologies (Mwangi and Kariuki 2015). Furthermore, given the poverty conditions under which smallholder farmers live they often avoid activities that could frequently bring more income but involve more risks (Cervantes-Godoy et al. 2013). Therefore, they usually opt for a low-risk, low-return strategy (Cervantes-Godoy et al. 2013). In developing countries risk is frequently a significant barrier for technology adoption among smallholder farmers (Cervantes-Godoy et al. 2013). Overall, we can conclude that there is potential for increased yields and profits through improved crop management and input goods among farmers in the Battambang province. However, they cannot achieve these higher yields independently without support from other relevant actors. Many farmers in this region have migrated or were displaced from other provinces and have limited experience in upland cropping (Touch et al. 2016; Montgomery et al. 2016).

To answer the research question how farmers evaluate the different treatments we can state that none of the farmers saw a significant visual difference between treatments. This was mainly due to the fact



Figure 36: Maize field (12.657014, 103.094183) of a farmer participating in the on-farm trial before harvest, showing weeds as tall as the maize plants and a low density of maize plants.

that all the treatments had severe damage by FAW and due to the previously mentioned factors which were affecting the growth of the maize plants.

The on-station trial demonstrated that most biopesticides can reduce foliar damage and the number of larvae, although their profitability is lower compared to the positive control. Under practical conditions in the on-farm trial, the biopesticides showed no measurable effect. This indicates that addressing other challenges, such as improving crop management practices, is more immediately necessary to enhance the yields and incomes of smallholders than the adoption of biopesticides.

5.2 FAW management practices in Battambang considering the IPM framework

To answer the research question of what preventative and intervention FAW management options are available in Cambodia (with a focus on Northwestern Cambodia) and what is known about the efficacy, strengths and weaknesses of the methods following can be stated:

No FAW specific preventative methods are currently available in Northwestern Cambodia, apart from the practices that farmers typically apply as part of their usual crop management, which will be discussed in more detail later.

However, according to Nget (2024, personal communication), there are currently two companies in the Battambang province selling cover crops, although not specifically for use in FAW control. As reported by FAO (2018, 14), increasing plant diversity within the field, such as using cover crops, can reduce the abundance and severity of damage caused by FAW.

Regarding available intervention methods, only synthetic insecticides currently hold relevance on market and farms in Northwestern Cambodia. According to Watson (2024, personal communication), biopesticides presently play no significant role in the system of FAW management in ASEAN countries. This is also reflected in the pesticide registration list, where only a few out of 2'600 registered pesticides are biopesticides (Bureau-Point et al. 2024) and as reported by biopesticide companies (Keo 2024b, personal communication). According to Matsukawa et al. (2016) and Schreinemachers et al. (2017), this is also valid for other crops such as rice and vegetables. In contrast, the study by Sok et al. (2023) reported that out of 183 vegetable farmers approached, 112 had experience with biopesticides. However, this data might be biased because their sampling strategy was not transparently declared. Regarding the efficacy of synthetic insecticides, different studies reveal that the efficacy varies significantly between a.i. (Deshmukh et al. 2020; Karki et al. 2023). In Cambodia the efficacy of synthetic insecticides not only relies on the a.i. but also on the product quality which is poor sometimes (Bureau-Point et al. 2024; Watson 2024, personal communication; Martin 2024a, personal communication) due to manipulations by retail companies (Bureau-Point et al. 2024).

As our study demonstrates, the strengths of synthetic insecticides are that they are often cheaper and result in higher profits compared to biopesticides. This is consistent with findings in other studies (Babendreier et al. 2020; Nboyine et al. 2022; Aniwanou et al. 2020).

A further advantage of synthetic insecticides is that they are widely available in Cambodia (Bureau-Point et al. 2024). According to Bureau-Point et al. (2024) this is crucial because farmers usually buy pest control products in the input shops next to their home. Buying pesticides on the internet, at the farm gate and or at a villager's house is less common (Bureau-Point et al. 2024).

Weaknesses of synthetic insecticides are that they often negatively impact the environment, endanger the operator and eliminate beneficial arthropods (Nboyine et al. 2022; Aniwanou et al. 2020). Furthermore, from different countries FAW insecticide resistance has been reported (Yu 1991; Gutiérrez-Moreno et al. 2018) what can make it difficult to control the pest (Gutiérrez-Moreno et al. 2018).

Pertaining to answer the research question, how the accessibility (awareness, know-how, affordability, cultural) is for smallholder farmers for the different available FAW preventative and intervention management options in Cambodia following can be stated:

Only the accessibility of synthetic insecticides is discussed in this section because, as previously mentioned, other control methods have no relevance for controlling FAW besides the crop management practices that farmers perform by default.

Awareness of synthetic insecticides as a control method for FAW among farmers is high. During the interviews, all eight farmers reported having experience with synthetic insecticides for FAW control, and seven out of eight use them regularly.

Know-how regarding synthetic insecticides is very limited among farmers. Only a few farmers read pesticide labels. The major constraint to reading them is illiteracy. Although the farmers in this study did

not report it, other sources found that an additional constraint for Cambodian farmers is that labels are sometimes written in foreign languages such as Vietnamese or Thai (Jensen et al. 2011).

Synthetic pesticides are widely used among smallholder farmers; therefore, it is assumed that synthetic pesticides are affordable. Otherwise, they might not be used extensively. This intensive use is also reported in other studies (Bureau-Point et al. 2024; Flor et al. 2018; Schreinemachers et al. 2017). Nevertheless, some of the farmers interviewed reported that they occasionally lack the financial means to purchase pesticides when needed. In such cases, they buy the products on credit from input shops and repay the loans after several weeks or after the harvest. This pattern was also identified by Pheakdey (2014), Bureau-Point et al. (2024) and Flor et al. (2018).

Regarding cultural respectively social accessibility, it is important to consider that the optimal spraying window for applying insecticides is often short, as reported by farmers, due to wind and high temperatures. It is difficult to compensate for this short spraying window with hired labor because, over the last decade, there has been significant migration outflow of the workforce from rural areas to urban areas and foreign countries in search of work (Chhun et al. 2015, 6; UNFPA 2014). This could be one reason among others why farmers identified efficacy as the most important criterion for buying insecticides and a potential barrier for adopting more labor intensive biopesticides.

These findings indicate that synthetic insecticides are widely used and well-known for pest control on Cambodian farms. However, various challenges persist, such as a lack of information and limited financial resources.

To examine the methods farmers are using to manage FAW in maize in the region and how they evaluate the efficacy, strengths and weaknesses of the different methods according an IPM approach. It was observed that most farmers apply crop rotations on their farms as a preventative measure (Barzman et al. 2015). As reported by Bureau-Point et al. (2024), farmers implement crop rotations primarily because they adjust their crop choices based on market prices. Consequently, crop rotations are applied by default rather than as a specific measure to prevent FAW or other pests. This is also reflected in farmers responses, where they emphasized that the shift from maize to cassava occurs regularly depending on market prices.

Another preventative method, to use seeds which germinate quickly and grow well (Barzman et al. 2015), is facing some constraints on the farm level as mentioned in the previous chapter with the low germination rates. Further preventative methods, such as intercropping, are less common among farmers. Additionally, efforts to grow healthy plants more resilient to pests through good crop management practices such as weeding and fertilizing are very limited.

For FAW monitoring, most of the eight farmers or members of their households regularly monitor respectively scout their maize fields for signs of damage and larvae. However, due to their low educational levels and limited access to accurate information (Bureau-Point et al. 2024), their scouting practices may lack systematicity and fail to represent the entire field. Prasanna et al. (2021, 69) emphasize the importance of systematic scouting for FAW to obtain a representative and accurate assessment of risk, which can lead to more economically justified insecticide applications (Prasanna et al. 2021, 32).

Regarding decision-making on when to intervene and apply control measures for FAW, almost all farmers reported spraying insecticides when they perceive the damage or FAW abundance getting too high. Like scouting practices, it appears that economic thresholds or practicable action thresholds—which guide interventions based on crop stage and damage levels (Prasanna et al. 2021, 32)—are currently not relevant for smallholder farmers in Cambodia. These action thresholds are intended to support farmers in making decisions that prevent unacceptable crop losses while also indicating when intervention is unnecessary, thus avoiding unjustified insecticide applications (Prasanna et al. 2021, 32). No specific information is available regarding economic, or action thresholds tailored to the Cambodian context, beyond the general action thresholds developed by Prasanna et al. (2021, 32–34). Moreover, the relevant stakeholders capable of disseminating this knowledge appear to be largely absent.

Regarding FAW intervention methods, only synthetic insecticides are used among the eight surveyed farmers. According to Barzman et al. (2015) the rational selection of pesticides that minimize risks to human health, the environment and the lowest disruption of the agroecosystem is crucial for an IPM approach. This might not be crucial for upland cropping farmers in Northwest Cambodia as the eight farmers reported uniformly that they consider every insect to be a pest and therefore might not care about the selectivity of a certain intervention method. This perception may slightly differ between farmers in Cambodia, because rice farmers (n = 168) interviewed by Dunn et al. (2023) in the Battambang province could identify some of the beneficial insects. Although farmers had difficulties with allocating lady beetles, spiders and other insects as beneficials (Dunn et al. 2023).

For the a.i. used in FAW control, Emamectin benzoate was reported 10 times out of 19 instances, making it the most used a.i. among the eight farmers. However, there is a significant risk of FAW developing resistance to this a.i., as it has been documented in other countries due to overuse (Muraro et al. 2022). Implementing an anti-resistance strategy for target species is a crucial component of IPM (Barzman et al. 2015). Such strategies to avoid resistance in target species include the use of preventative methods and, when synthetic pesticides are necessary, the rotation of a.i.s with different modes of action (Barzman et al. 2015).

According to Bureau-Point et al. (2024), Cambodian farmers may lack awareness of the risks associated with resistance development. Bureau-Point et al. (2024) reported that a common practice among farmers involves using a specific pesticide continuously. Over time, as the pesticide loses effectiveness due to resistance, farmers typically respond by increasing the dosage. When this no longer works, they switch to another product (Bureau-Point et al. 2024).

Insecticides are primarily evaluated based on their efficacy and its immediate impact on pests by the eight farmers.

The negative health effects reported by farmers after spraying pesticides, such as dizziness and headaches, are consistent with findings from other studies on Cambodian farmers (Schreinemachers et al. 2017; Jensen et al. 2011). Schreinemachers et al. (2017) even reported symptoms such as vomiting, muscle twitching, and chest discomfort, with rates exceeding 20% in a survey of 900 farmers in Cambodia, Laos, and Vietnam.

To mitigate such symptoms, four of the eight farmers reported using “adequate” PPE, such as long clothes, closed shoes, and face masks, with one farmer extending PPE use to include gloves and glasses. The survey by Dunn et al. (2023) in the Battambang province revealed a similar trend. Bureau-Point et al. (2024) also highlights the limited use of PPE among farmers and emphasizes that some types of PPE required in Europe, such as masks with filter cartridges, are unsuitable for Cambodian farmers. Bureau-Point et al. (2024) notes that while sellers in Cambodia attempted to introduce these masks, farmers reported difficulties using them.

According to WHO (2019, 21-49) none of the a.i. reported by the eight farmers were classified as extremely hazardous or highly hazardous. Most of them were classified as moderately hazardous and one as slightly hazardous WHO (2019, 21-49).

We can conclude that, regarding both preventative and intervention methods for FAW, farmers consciously rely solely on synthetic insecticides as a control measure. While synthetic insecticides offer certain advantages, they also present notable negative aspects, including human toxicity, environmental pollution, and the risk of pest resistance. Thereby the knowledge and information gap among farmers is very important to address for a more durable and sustainable pest management strategy.

When investigating where farmers primarily obtain information for managing insect pests in maize and how they evaluate the usefulness of different information channels, we found that among the eight farmers surveyed, input shops were their most important source of information, followed by neighboring farmers. Similar studies have shown that input shops are the primary source of pest management information for farmers in Cambodia (Pheakdey 2014; Dunn et al. 2023; Flor et al. 2018). According to Dunn et al. (2023), access to alternative, potentially more reliable, information sources remain limited, with only 43% of farmers having access to agricultural training and 36% to extension officers.

Regarding the trustworthiness of their information sources, five out of the eight farmers reported receiving incorrect information from input shops. This finding aligns with Bureau-Point et al. (2024), who noted that input shops often acquire their knowledge through sources such as the internet, YouTube, field promoters, scientific papers, and other materials.

In summary, farmers heavily rely on input shops for pest management information, while other actors who could provide more reliable guidance are largely absent. The information provided by input shops can be biased, as many shop owners or staff often lack formal agronomy training (Bureau-Point et al. 2024).

This section discusses how smallholders assess the economic impact of FAW on maize production in Northwestern Cambodia. On average, the eight farmers estimate that they face yield losses of 35% due to FAW. However, the yield data from the on-farm trial (see chapter “4.2 On-farm trial”) are not suitable for comparison due to the highest mean yield occurring in the negative control. Instead, yield data from the on-station trial are used for comparison.

To evaluate yield loss, the mean yield of the positive control in the on-station trial is compared to the average maize yield in the Battambang province in 2013, prior to the arrival of FAW in Cambodia. It is assumed that environmental conditions, including damage and yield loss from pests other than FAW,

remained unchanged between 2013 and 2024. Additionally, it is assumed that yield loss in the on-station trial is solely due to FAW.

The mean yield in the positive control (4.3 tons/ha) differs from the mean yield in Battambang province reported by Pheakdey (2014) (5.4 tons/ha) by 20.3%. This observed yield loss is notably lower than the 35% estimated by the farmers.

Similar findings have been reported in other contexts. Baudron et al. (2019) observed that farmers in Sub-Saharan Africa often overestimate the impact and yield loss caused by FAW. Overton et al. (2021), in a literature study, similarly noted discrepancies between yield losses of high confidence (from experiments) and medium confidence (from farmer surveys and interviews). One explanation is that maize plants can compensate for a certain level of foliar damage depending on their growth stage, which reduces the impact on final yields (Baudron et al. 2019). Additionally, Baudron et al. (2019) highlighted that yield losses estimated by farmers may also result from factors unrelated to FAW, such as poor weeding, dry spells, and damage from other pests. Observations in the on-farm trial align with these findings, as drought conditions following planting and inadequate weeding management were also evident, potentially contributing to yield losses.

Baudron et al. (2019) emphasizes the importance of not focusing solely on FAW but also on promoting good agronomic practices, including the use of seeds adapted to local conditions, timely planting, adequate fertilization, and proper crop protection. These recommendations are equally relevant for small-holder farmers and other stakeholders in the Battambang province.

5.3 Limitations of the study

The research generally proceeded as planned, with no major challenges encountered. Nevertheless, some limitations should be acknowledged. For both field trials, it was assumed that all foliar damage and yield loss were attributable to the FAW. During a field visit to farm 2 and farm 7 caterpillars were identified systematically. 90% of 72 caterpillars on farm 2 and 88% of 85 caterpillars on farm 7, respectively, were visually identified as FAW. However, other insect pests were also active in the trials, and their impact was not considered into the analysis. Additionally, the results and conclusions drawn from the field trials are limited because the experiments were conducted over a single cropping cycle. Conditions such as weather, pest pressure, and other factors can vary significantly between cropping seasons, and a more reliable dataset would have required trials conducted over multiple cycles. Unfortunately, time and financial constraints for a bachelor's thesis made this unfeasible.

The number of plants per plot varied significantly, both between and within blocks, due to factors such as germination rates, drought, waterlogging, and weed competition, which affected the yield data for both field trials.

In the on-station trial, an agronomic limitation was the presence of a plough pan 10 cm below the surface, restricting the root zone and limiting nutrient and water availability for maize plants. Furthermore, while the trial was initially designed as a completely randomized block design, spatial constraints made it necessary to place the plots for the positive control outside the blocks, deviating from the intended design. An additional limitation in the on-station trial was the emergence of an unidentified disease during the final weeks of the trial. This disease caused plant tissue necrosis, small cobs, and in some cases, plants entirely lacking cobs, thereby affecting the yield data.

In the on-farm trial, crop damage assessments had to be excluded from the analysis due to inconsistencies in the recorded data. Some damage ratings exceeded the defined scale, and plant counts per plot increased by 20–30% between assessments, which was improbable. This incident happened because some assistants were involved in the agronomic data collection in the on-farm trial.

Additionally, three farms were fully excluded from the agronomic data analysis: one farmer did not spray insecticides due to financial constraints, another allowed cattle to graze in the trial area after being dissatisfied with the crop performance, and a third farmer sprayed synthetic insecticides in the trial area despite instructions to the contrary. The on-farm trial was intended to follow a randomized experimental design, but practical considerations necessitated modifications. For example, the positive control was placed at the border of the block for ease of farmer management, and another treatment was positioned at the opposite border based on uncertainties about whether it would be implemented. The sample size of eight farmers in the on-farm trial may be considered too small to provide a representative picture of maize farming in the upland cropping area. However, resource limitations prevented the inclusion of additional farmers. The joint evaluation of treatments with farmers also faced

challenges, as neither the farmers nor the research team could observe clear visual differences between treatments. This was likely due to high FAW infestation rates, strong weed competition, drought and other factors, leading to the omission of treatment ratings and instead limiting farmer feedback to general observations.

For the key person interviews on available IPM methods and adoption barriers, limitations arose from the inability to fully implement the snowball sampling method. Only four of the approximately ten contacted individuals responded and agreed to participate, and none offered further connections. As a result, the sample size of four interviewees was insufficient to provide a comprehensive overview of available IPM methods for FAW in Cambodia.

Lastly, the literature review and use of secondary data were constrained by the limited availability of scientific research on FAW in Cambodia, leading to repeated citations of the same studies throughout this work.

6 Conclusion and recommendations

6.1 Conclusion

This research focuses on assessing available IPM FAW management practices in Cambodia, examining how farmers currently manage FAW, and evaluating the efficacy of commercially available biopesticides. The findings are used to develop IPM recommendations for improved FAW control management by local smallholders and for future research.

Thanks to data collected through the on-station trial, participatory on-farm trial, semi-structured interviews with farmers, and semi-structured interviews with four key informants, all research questions and objectives were addressed.

The main gaps identified by ASEAN in 2020 regarding FAW control—lack of a control strategy, insufficient knowledge dissemination about FAW and IPM, and limited identification of potential beneficials and parasitoids—remain unresolved in Cambodia.

This study identified several bottlenecks hindering the implementation of IPM FAW management among smallholders.

On the governmental side, the pesticide and agricultural input market is poorly monitored and regulated due to financial limitations and corruption. As a result of that, some commercially available pesticides are either ineffective or highly toxic. The mistrust in products and a missing strategy for pest resistance in practice leads to an overuse of pesticides.

A further identified barrier is knowledge dissemination by governmental institutions which seem to be largely absent in some regions of Cambodia.

At the market level, it was found that only synthetic insecticides are available as control methods for FAW. Other products such as biopesticides are not widely available in rural areas.

In rural areas, synthetic insecticides and pest management knowledge is primarily provided to farmers by input shops. However, the information transmitted is often biased and lacks a foundation in scientific evidence.

At the farm level, several constraints hinder the adoption of IPM for controlling the FAW. Farmers rely heavily on input shops for pest management advice and frequently use synthetic insecticides for FAW control. Additionally, crop management practices for cultivating healthy and resilient plants are generally inadequate. Key limiting factors include low levels of education, widespread illiteracy, and financial constraints.

Addressing the initial research question posed on the title page—*Are biopesticides and integrated pest management feasible for controlling fall armyworm among smallholders in Battambang, Cambodia?*—this study concluded that biopesticides presently play a minimal role in FAW management in ASEAN countries, including Cambodia. This is due to limited availability, higher costs, lower profitability compared to synthetic insecticides, and an inability to meet farmers' expectations for effective pest control products. However, in the long term, biopesticides have the potential to play a critical role in an IPM strategy for FAW management due to their environmental and health benefits compared to synthetic insecticides.

IPM can be feasible for smallholder farmers with collaboration among all relevant agricultural sector actors. It represents the most sustainable approach to addressing FAW in Cambodia. Nevertheless, several constraints must be overcome for successful IPM implementation. These include the development of economic and action thresholds for FAW control, effective dissemination of IPM and crop management knowledge to farmers, research on native beneficial organisms for FAW control, methods to augment their populations, and increased awareness among farmers of their importance.

To address these challenges and provide recommendations for optimized FAW management and further research, the subsequent sections of this paper outline specific strategies and capacity-building measures aligned with an IPM approach.

6.2 IPM recommendations for smallholder farmers on maize in Battambang, Cambodia

- Stay open-minded as you are, think critically, make your own observations, and evaluate products independently.
- Share your observations, experiences, and questions with other farmers.
- Consider delayed planting for the first maize cycle when rainfall conditions are more stable.
- Regularly check your crops for signs of nutrient deficiencies, weeds, and insect pests.

- If you observe problems, seek accurate information and solutions, for example, from the local commune agriculture officer.
- Purchase only products labeled with the code of the Ministry of Agriculture, Forestry, and Fisheries, as this may correlate with product quality.
- Continue spraying early in the morning or late in the evening, as this increases the efficacy of some products.
- Try the fertilizer and weeding manuals for improved crop management (see Annex 13 and Annex 14) on small plots of your maize field. Observe and evaluate the results.
- Consider using local drone operators for pesticide spraying, if affordable, to reduce health risks.

6.3 Recommendations for the relevant actors in the agricultural sector and for further research

Public sector

- Conduct a study on different communication channels: “How can farmers be reached most efficiently and effectively?” (Keep in mind that some farmers are illiterate.)
- Disseminate knowledge through the identified channels about crop management, FAW, IPM, and shifting precipitation patterns, using a public-private partnership to increase funding and scalability.
- Ensure the quality of available pesticides and other input goods on the market through improved monitoring and control mechanisms.
- Make a background in agronomy mandatory for input shop licenses to improve the quality of information provided to farmers.
- Develop and implement a pest resistance strategy. Consider evaluating the use of color codes on product labels to indicate different modes of action.

Research sector

- Investigate which native beneficials and parasitoids against FAW are present in Cambodia.
- Research measures to promote the identified species.
- Identify species with potential for mass rearing and commercialization.
- Develop action thresholds for FAW in Cambodia.
- Identify strains and formulations of entomopathogens with high efficacy under practical conditions and evaluate them through participatory methods.
-

Private sector

- Develop business models that provide high-quality inputs and reliable information to the millions of farmers in Cambodia.
- Create biopesticides with higher efficacy, evaluated under practical conditions through participatory approaches.
- Develop biopesticides tailored for regions where multiple *Spodoptera* species are active, as well as for regions where only FAW is prevalent.

NGO Sector

- Support the public sector in disseminating knowledge on the previously mentioned topics.
- Utilize business incubators to support and encourage start-ups that can transform the pesticide market by providing high-quality products and reliable information to farmers in rural areas.
- Examine the feasibility of implementing training-of-trainers programs instead of farmer field schools to reach a larger number of farmers.
- Consider having at least one agronomist on provincial teams to ensure that the agronomic needs of farmers are addressed through project activities which are implemented by private partners.

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Appendix 1: Disposition

Name of student	Rauser Noah
Title (provisional)	Are biopesticides and integrated pest management of fall armyworm feasible for smallholders in Battambang, Cambodia?
	Fall armyworm (FAW) <i>Spodoptera frugiperda</i> is a polyphagous pest which cause significant damage to many economic plants such as maize, sorghum, sugarcane, wheat et cetera (IPPC no date). More than 350 plant species are host plants for the FAW (Montezano et al. 2018). FAO counts the pest as one of the top 10 most devastating pests for food and agriculture (FAO 2020). According to van den Berg et al. (2021) yield losses range from 11 to 100% on the African continent. Similar to Africa, FAW has caused major economic damage mostly to the maize crop across Asia (Prasanna et al. 2021). The pest is likely to become endemic in many Asian countries due to the conducive environment (Prasanna et al. 2021). FAW's major preference for maize, a crop that serves as food, feed, and fodder, and provides income to millions of smallholders in Asia, is indeed a major concern (Prasanna et al. 2021; Ingber et al. 2021). FAO (2022) recommends an Integrated Pest Management approach (IPM) to control the pest. As defined by ECHO (2022) "IPM is a management approach that focuses on the larger system and aims for long-term prevention of pests using a combination of preventative and suppressive control strategies in a way that minimizes economic, health, and environmental risks. According to the Association of Southeast Asian Nations (ASEAN) major barriers for an IPM approach are that appropriate, cost-effective and practical IPM methods wait to be developed, validated, promoted and/or scaled up (ASEAN 2020). Additionally, IPM-compatible agrochemical and biological crop protection products against FAW wait to be registered (ASEAN 2020). This situation is also reflected in Cambodia, where maize is the third important crop after rice and cassava in terms of cultivated area (Pheakdey 2014). Ever since it's first discovery in Cambodia in 2019 (Hadi 2019), the FAW has been causing severe damage (Raksmey 2024; Kongnov 2024) especially Cambodias largest maize growing area in Battambang province (EuroCham Cambodia 2023). According to Martin (2024) maize farmers mainly rely on synthetic pesticide for pest control. Farmers in Cambodia are using pesticides classified as extremely and highly hazardous by World Health Organization (WHO) (Jensen et al. 2011 cited in Chem 2023; Kai et al. 2020 cited in Chem 2023). Extremely and highly hazardous pesticides can pose a threat to human health and the environment (WHO 2020). Biopesticides can be a less toxic alternative to synthetic insecticides and are often recommended within an IPM approach. In Battambang some biopesticides are commercially available, however, it is unclear how effective and cost-efficient the biopesticides are compared to the commonly used synthetic insecticides. Therefore, the aim of this research is to assess the efficacy of three commercially available biopesticides and to give an overview of available fall armyworm management practices in maize in Battambang province, Cambodia in order to devise integrated pest management recommendations for local smallholders. We are using a participatory on-farm trial, an on-station trial and qualitative farmer and key-person interviews to assess this research gap. The BSc thesis is held in the framework of the Nurture project, that has the outcome to strengthen agro-ecological practices and diversification of the source of income for vulnerable smallholder farmers in the target area of the project (Suess and Melara 2022). Beside the climate change the FAW could become a further threat to smallholder farmers, wherefore the project is investigating in this area.

Problem and re-search questions	See 'importance of the topic' Research questions: • Who are important stakeholders working on FAW in Cambodia? • What preventative and intervention FAW management options are available in Cambodia (with a focus on NW-Cambodia) and what is known about the efficacy, strengths and weaknesses of the methods? • How is the accessibility (awareness, know-how, affordability, cultural) for smallholder farmers for the different available FAW preventative and intervention management options in Cambodia? • Where do farmers primarily get information for management of insects pest in maize from and how do they evaluate the usefulness of the different information channels? • What methods are farmers using to manage FAW in maize in the region and how do they evaluate the efficacy, strengths and weaknesses of the different methods? • How do commercially available bio-pesticides (BITADIN WP, METABE, Neem oil) perform compared to frequently used synthetic pesticides in terms of yield, vegetative damage and economic impact? How do farmers evaluate them? • How do smallholders assess the economic impact of FAW on maize production in NW Cambodia? • What are recommendations to optimize FAW-management of smallholders in Cambodia according to an IPM approach? What are recommendations for further research and capacity building in Cambodia?
Main objective of the thesis	To give an overview of available fall armyworm management practices in maize in NW Cambodia, to assess current management practices by farmers and to evaluate the efficacy of commercial bio-pesticides, in order to devise integrated pest management recommendations for local smallholders and further research
Secondary objectives of the thesis	- To design a map, list or description of relevant actors working on IPM methods against FAW in Cambodia. - To create an overview of available preventive and intervention strategies for FAW control in (NW-) Cambodia, and summarize the strengths and weaknesses of the methods. - To evaluate the efficacy of biopesticides and the impact on smallholders profit and to assess possible constraints for their adoption - To document farmers assessment of the economic impact of FAW, and their main sources of information for insect pest management To give recommendations for further research and for optimized FAW management for smallholder farmers in NW Cambodia

State of knowledge	The first biopesticide evaluated in the field trials contains <i>Bacillus thuringiensis</i> (BT) and granulosis virus. In lepidoptera the ingested BT is activated in the gut of the larvae (Polanczyk et al. 2000; Schünemann et al. 2014). The toxin destroys the membrane of the gut which leads to an osmotic imbalance (Polanczyk et al. 2000; Schünemann et al. 2014). This results in cell lysis and in the death of the larvae (Polanczyk et al. 2000; Schünemann et al. 2014). Different bioassays show that the strain of BT (Polanczyk et al. 2000; Karshanal and Kalia 2023) and dosage highly positively correlated the efficacy for controlling FAW (Lara-Becerra et al. 2020). The second biopesticide contains the entomopathogenic fungi <i>Beauveria bassiana</i> (BB) and <i>Metarhizium anisoplia</i> (MA). Similar to many other entomopathogenic fungi BB conidia firstly germinate on the insect cuticle and subsequently penetrate it. (Keswani et al. 2013). Within the host body the fungus proliferates and leads to the saprophytic outgrow of the insect body (Keswani et al. 2013). Different bioassays show for BB as for MA that the FAW stage, the strain of entomopathogenic fungus and the dosage have significant impact on the efficacy (Idrees et al. 2021; Akutse et al. 2018). The third biopesticide contains Neem oil. The most important active ingredient in Neem oil is azadirachtin (Hellpap 1994 cited in Förster and Moser 2000). The Neem oil has antifeedant and repellent effects on insect pests (Förster and Moser 2000). The insecticide used as farmers practice respectively positive control is the semi-synthetic (Jansson et al. 1997) Emamectin benzoate (EB). EB intoxicate arthropods mainly by ingestions but can also be effective through contact (Jansson et al. 1997; US EPA no date). A bioassay shows that EB with a median lethal concentration of 0.0051 ppm is very toxic to FAW larvae compared to other insecticides (Sharanabasappa et al. 2020).
Concept definition	Integrated Pest Management (IPM) is a management approach that focuses on the larger system and aims for long-term prevention of pests using a combination of preventative and suppressive control strategies in a way that minimizes economic, health, and environmental risks (ECHO staff 2022). It is an effective and environmentally sensitive approach to pest management that relies on a combination of common-sense practices (EPA 2023). IPM programs use current, comprehensive information on the life cycles of pests and their interaction with the environment (EPA 2023). This information, in combination with available pest control methods, is used to manage pest damage by the most economical means, and with the least possible hazard to people, property, and the environment (EPA 2023). Pesticides are used only after monitoring indicates they are needed according to established guidelines, and treatments are made with the goal of removing only the target organism (UC IPM, no date).

Materials & methods	<i>How do commercially available bio-pesticides (BITADIN WP, METABE, Neem oil) perform compared to frequently used synthetic pesticides in terms of yield, vegetative damage and economic impact? How do farmers evaluate them?</i> To answer this questions an participative on-farm-trial and an on-station-trial are established On station-trial The on-station trail was designed in a one-factorial randomized complete block design with four blocks. The factor 'insecticide treatment' has the following 5 levels: • no spray (negative control) • farmer's synthetic pesticide (positive control) • Biopesticide 1 (Metarhizium + Beauveria) • Biopesticide 2 (Bacillus thuringiensis + Granulosis virus) • Biopesticide 3 (Neem) Recorded parameters are: • the number of FAW caterpillars per plant before and after spraying • visible damage of the maize plants with the 1-9 damage scale of Davis et al 1992. • visible damage of plant whorl (yes/no) • Yield (fresh weight, dry weight) Participatory on-farm trial The on-farm trial was designed in a randomized complete block design with the factor 'insecticide treatment' with 5 levels: • no spray (negative control) • farmer's synthetic pesticide (positive control) • Biopesticide 1 (Metarhizium + Beauveria) • Biopesticide 2 (Bacillus thuringiensis + Granulosis virus). • Biopesticide 1 and 2 are applied to the same plot but at different times. The trial was established with 8 blocks/repetitions on 8 different farms. Recoded parameters are: • the number of FAW caterpillars per plant • visible damage of the maize plants with the 1-5 damage scale (described in Toepfer et al. 2021 based on work of previous authors) • visible damage of plant whorl (yes/no) • Yield (fresh weight, dry weight) In a participatory on farm trial it is necessary that not only technical data is gathered, but that the farmers are included in the evaluation of the field trial. Therefore in August 2024, before the first farmer will harvest the maize, an evaluation of the different implemented treatments will take place on the farmer field (n=8) by guiding an evaluation with each farmer. Because the sample size for the interview and evaluation with eight farmers is very small the results will be analyzed with descriptive statistics.
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Materials & methods	• <i>Who are important stakeholders working on FAW in Cambodia?</i> • <i>What preventative and intervention FAW management options are available in Cambodia (with a focus on NW-Cambodia) and what is known about the efficacy, strengths and weaknesses of the methods?</i> To answer this questions semi structured key person interviews will be guided with relevant actors working on IPM and FAW in Cambodia. Snowball sampling will be used to identify and find relevant key person interviews. The key person interviews will be complemented through literature research on IPM methods available in Cambodia. • <i>How is the accessibility (awareness, know-how, affordability, cultural) for smallholder farmers for the different available FAW preventative and intervention management options in Cambodia?</i> • <i>How do smallholders assess the economic impact of FAW on maize production in NW Cambodia?</i> • <i>Where do farmers primarily get information for management of insects pest in maize from and how do they evaluate the usefulness of the different information channels?</i> • <i>What methods are farmers using to manage FAW in maize in the region and how do they evaluate the efficacy, strengths and weaknesses of the different methods?</i> To answer these questions qualitative interviews with the 8 farmers, participating in the on-farm trial, will be held, other information relevant for the nurture project will also be included. Results will be analyzed descriptively with Excel.
Justification of chosen methodology	• The <u>on-station trial</u> allows for the collection of precise agronomic data, which is a good basis for statistical analysis. The <u>on-farm trial</u> will not have as reliable agronomic data, but it's main purpose is to understand the perceptions and views of local farmers on the treatments, but then also on pest-management in general and further barriers and enabling conditions for farmers to apply integrated pest management. • The information from farmers will be completed through key-person interviews. • Where possible data will be analyzed with an analysis of variance (ANOVA). However, since we expect many "0" for certain parameters we might have to switch to other models, the advice of statisticians will be followed here
	CABI and FAO (Centre for Agriculture and Bioscience International and Food and Agriculture Organization of the United Nations, 2019. Fall Armyworm Field Handbook: Identification and Management, First Edition. CABI and FAO, 36 S. Deguine JP, Aubertot JN, Flor RJ, Lescourret F, Wyckhuys K, Ratnadass A, 2021. Integrated pest management: good intentions, hard realities. A review. Agronomy for Sustainable Development, 41, 38. Ingber DA, McDonald JH, Mason CE, Flexner L, 2021. Oviposition preferences, Bt susceptibilities, and tissue feeding of fall armyworm (Lepidoptera: Noctuidae) host strains. Pest Management Science, 77, 4091-4099. Kenis M, Benelli G, Biondi A, Calatayud PA, Day R, Desnèze N, 2022. Invasiveness, biology, ecology, and management of the fall armyworm, <i>Spodoptera frugiperda</i>. Entomologia Generalis, 43 (2), 187-241. Kongnov T, 2024. Fall armyworm spread into 15 provinces. KHMER TIMES, 25.06.2024. Accessed on 03.09.2024, https://www.khmertimeskh.com/501511616/fall-armyworms-spread-into-15-provinces/

Work structure	<i>Front page, declaration of independence, List of Abbreviations, List of Tables, List of Figures, Abstract,</i> 1. Introduction 1.1. Study objective and research questions 2. Current state of research 2.1. Context of Cambodia 2.2. Agriculture in Battambang Farming systems 2.3. Fall armyworm <i>Spodoptera frugiperda</i> 2.4. Integrated Pest Management 2.5. Nurture project 3. Material and Methods 3.1. Secondary data collection 3.2. Primary data collection 3.2.1. On-station-trial 3.2.2. On-farm-trial 3.2.3. Farmers survey about FAW control methods 3.2.4. Semi-structured key person/expert interviews about FAW in Cambodia 3.3. Collaboration with tandem student from NUBB 4. Results 4.1. On-station-trial 4.1.1. Efficacy 4.1.2. Economic impact 4.2. On-farm-trial 4.2.1. Efficacy 4.2.2. Economic impact 4.2.3. Farmers perception 4.3. Farmers survey 4.3.1. Their knowledge 4.3.2. Their methods 4.3.3. Their perception towards FAW 4.4. Key person/expert interviews 4.4.1. Map of actors working on FAW IPM methods in Cambodia 4.4.2. FAW IPM control methods in Cambodia 4.4.3. Suitability of FAW IPM control for smallholder farmers in Cambodia 5. Discussion 5.1. Limitations of the study 5.2. Field trials 5.3. FAW management practices in Battambang considering the IPM framework 5.4. IPM recommendations for smallholder farmers on maize in Battambang, Cambodia 5.5. Recommendations for further research in this topic 6. Conclusion 7. References • Acknowledgements • Appendix <i>Disposition, data from on-station-trial, data from on-farm-trial, notes from farmer evaluation, notes from farmer survey, notes from key person interviews, R-codes.</i>
Schedule/ resource planning	☐ is already included in PR1_Annexes_Noah_Rauser_Cambodia_2024_2.0.xlsx

Appendix 2: Questionnaire for farmers evaluation

Farmers evaluation of biopesticides against the fall armyworm (*Spodoptera fugiperda* (J. E. Smith)) in maize

Objective

The objective of these interviews is to find out how and based on which criteria farmers evaluate new technologies against FAW and how they perceive the different treatments in the on-farm-trial.

This should help to understand what is important for farmers for making decisions about the implementation of new technologies regarding the control of FAW and embedding the findings in further research.

Important things

- Your honest opinion is extremely important and valuable for me, because I would like to learn for the future what can I recommend and learn to other farmers.
- The interview should take place at the farmers home, because it would be uncomfortable to do it on the field under the hot sun.
- Bring with some cool drinks, maybe a camping table and chairs so everyone is on the same level.
- Make sure the farmer feels comfortable, talk to him as equals and treat him as an expert.
- Explain the farmer shortly again the purpose, the treatments and the goal of the trial.
- Explain him why (the purpose) we are asking about his opinion and that his responses have no consequences, we are highly interested in his opinion however if it's positive or negative (we are neutral, we have no opinion, we are sincerely interested in his opinion)
- Make sure you are ATTENTIVE LISTENING and not influencing the answer (avoid head-shaking and do nodding to show you are actively listening in Cambodia etc.).
- Take notes as a sign of attention and respect.
- Summarize from time to time the answers of the farmer and ask him if you understand this correctly.
- Ask for clarifications and how he means something.
- Keep record of the interview with the voice-memo application on the phone.
- If the farmer doesn't answer immediately wait some seconds and keep silent until you repeat the question or reformulate the question. Maybe he needs a moment for reflecting.

Interview

Trial evaluation

- What do you think about the trial in your field?
- Why do you think there are differences?
 - Can you explain them?
- How do you rank the different treatments and why (ask for the why respectively for an explanation after the whole rating took place)?
(Make a quick walk to the plots to ensure, the farmer knows which treatment belongs to which plot. For the ranking place a printed map with the four treatments in Khmer on the table. Give four stones to the best treatment, three to the second best et cetera.)

Farmers Practice	
Bitadin	
Metabe	
Bitadin and Metabe	

Divers

- How do you perceive the current situation with FAW/ caterpillars on your farm? (show them the pictures)
- If you could order a new biocontrol product, for what product qualities would you ask?
- Are there any other crucial characteristics when you buy pesticide products which you did not mention before?
- What criteria are important for you when you evaluate new methods to control (labour, cost, effectiveness, health, etc.)?
- What do other members of the household think about how to deal with the FAW? What is important to them? Who says so? (note down which member of the HH he is talking about)
- Where do you get information on how to manage pest from? (family member, neighbour, input-shop, radio, social media others)
- Of the sources you have mentioned, which have shown to be most trustworthy in the past? (Ask for examples to understand in which circumstances what actors are more or less trustworthy)
- Did you already experienced to get wrong information?
 - If yes, from whom?
- Do you think there is a need for new methods against the FAW in your region?
 - If yes or no why?
- Will you use on of the biopesticides in future in your own fields?
 - If yes or no why?

Appendix 3: Questionnaire for farmer survey

Survey of maize farmers

Approach the farmer in the same way like we did for the trial evaluation.

Integrated Pest Management knowledge

As an icebreaker I suggest assessing, at first **the farmers knowledge about insect pests and beneficials** with the method described by Mwambi et al (2023). For this the farmers can determine on 10 pictures of insects which occur in Cambodian maize fields firstly if they have seen this insect before or not. Afterwards they can decide of them they know either if it is a pest or a beneficial. For every right answer we note a 1, for a wrong answer a 0. The outcome variable will be expressed as the proportion of correct answers, ranging from 0 to 1.

Integrated Pest Management

How do you prepare the soil? (tillage, no till, direct sowing)

What was the previous crop on the maize field and what do you plan to plant next year?
(crop rotation)

Do you plant other plants in the field together with maize (intercropping)?

Do you apply fertilizer to maize (yes/no)

- If yes, what kind of fertilizer?

How do you weed the maize field?

Do you spray insecticides to decrease the damage of FAW?

Do you use other methods for controlling the FAW?

- If yes, which ones?

How do you perceive the strength/ weaknesses of the methods mentioned before?

Do you or members of your HH check your fields for FAW infestation?

- If yes, how do you check your field?
- What part of the field do you check and for what are you looking for?

How do you and the members of your household decide when it is time to spray insecticides?

When do you spray pesticides timewise and why?

Which weather conditions/ daytime do you prefer for spraying?

Are there certain weather conditions when you do not spray?

Use of insecticides

Which of the following insecticides did you use for controlling the FAW during the last three years?

(show them the list of Bob with the pictures of more than 80 products and note down the answer, if it does not work ask if they still have the conatines)

.....
.....

Could you read and understand the information about the label on your products?

Where do you fetch the water for the pesticide mixture?

Which of the following equipment's do you use for preparing and spraying the pesticides?
(The farmers can answer with yes/ no)

Gloves
Glasses
Protective mask
Long sleeves
Long trousers
Closed shoes

Do you mix different pesticides in one mixture?

Never
Rarely
Often
Always

Which type of pesticides do you mix together (include liquid fertilizer).

.....

How many times do you spray insecticide in maize within one crop cycle, in the past 3-5 years?

Constraints for adopting IPM

Are you interested in testing new control methods and technologies for the FAW?

If yes, which methods would you like to test?

Biopesticides
Commercial beneficials and parasitoids
Spraying fish soup, sugar liquid, soap, oil,
Tolerant maize varieties
New crops
Fertilization
Cover crops
Intercropping
Agroforestry
More efficient synthetic pesticide
Observational methods

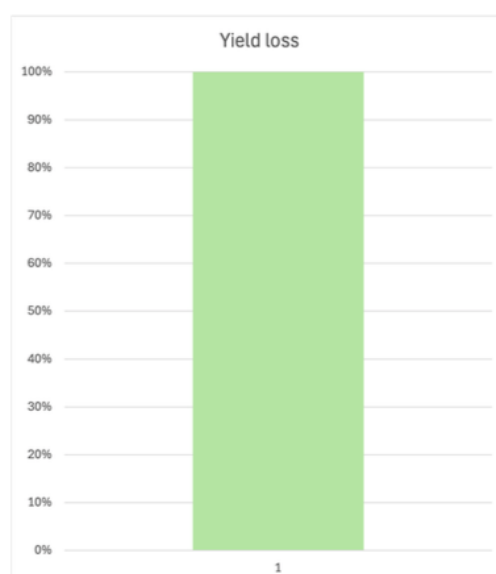
- If yes, what hinders you to try and implement new control methods and technologies?
- If no, why?

Divers

How much did you spend for insecticides during the current maize cropping cycle?

On which area did you spray these insecticides? (Ask about the unit which they use)

Which yield loss through the FAW do you estimate in your maize field this year? (in percentage, the farmers can show how much they lost due to FAW on the bar below.)



Why do a lot of farmers shift from maize to cassava in the Koas Krala, Rukah Kiri and Samlout district? (open question)

Market demand
Higher profit
Higher drought tolerance of cassava
Lower input costs for cassava
Low soil fertility
High pest pressure in maize
Others (specify).

Does this shift occur regularly? (yes/no)

Do you have infestation with armyworms in Cassava? (yes/ no)

Where and to whom do you sell the harvest? (open question)

Silo owner
Local collector
Provincial collector
Foreign trader
Processing company like CP
Others (specify)

Which price per ton do you fetch for your maize harvest? (specify for cobs/ grains and fresh/ dry)

Does the quality of the maize impact the price?

If yes, how?

Other components than maize (other seeds, stones, insects et cetera)
Broken kernels
Kernels with signs of insect feeding
Kernels with signs of disease
Kernels with different colors
Immature kernels

Farmer details

Age (mit Kategorien ab 25 Jahre 10er Schritte bei der Auswertung)

Fulltime or parttime farmer

What is the highest education you completed?

How many plots do you have?

Which crops do you have on the farm?

I learned a lot from your experience, many thanks for sharing! We addressed all topics that seem important to me. Still, you are the expert: Is there something else I forgot and that I should learn to understand your situation?

Appendix 4: Insect charts for farmer survey

Species	Know (Yes/No)	Pest/ Beneficial
<i>Spodoptera frugiperda</i> 		
Lady beetles 		
<i>Spodoptera litura</i> 		
<i>Nezara viridula</i> 		

Oechalia schellenbergii



Tachinid flies



Helicoverpa armigera



Earwigs



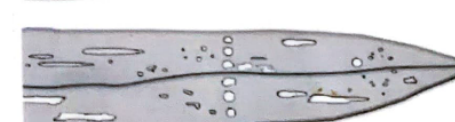
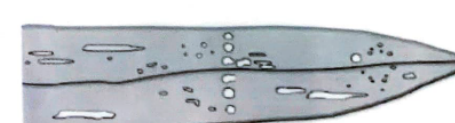
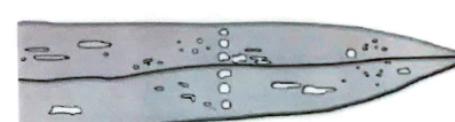
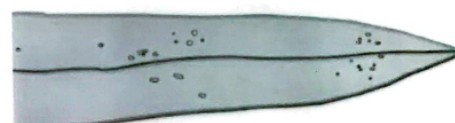
Predator ants 		
Termites 		

Appendix 5: Adapted Davis scale for the on-station trial

Simplified day-independent Davis scale 0-9 whorl & furl damage for the fall armyworm

3 leaves

Score	Description
0	No visible damage
1	Only pinholes on whorl leaves
2	Pinholes and small circular lesions on whorl leaves
3	Pinholes / small circular lesions and a few small < 1.3 cm elongated lesions on whorl leaves
4	Small elongated and a few mid-sized 1.3—2.5 cm elongated lesions on whorl leaves
5	Small elongated and several mid-sized 1.3—2.5 cm elongated lesions on whorl leaves
6	Small and mid-sized elongated lesions plus a few large > 2.5 cm elongated lesions on whorl leaves
7	Many small and mid-sized elongated lesions plus several large > 2.5 cm elongated lesions on on whorl leaves
8	Many small and mid-sized elongated lesions on whorl leaves plus many large > 2.5 cm elongated lesions on whorl leaves
9	Whorl and furl leaves almost totally destroyed



15

12

12

12

12

12

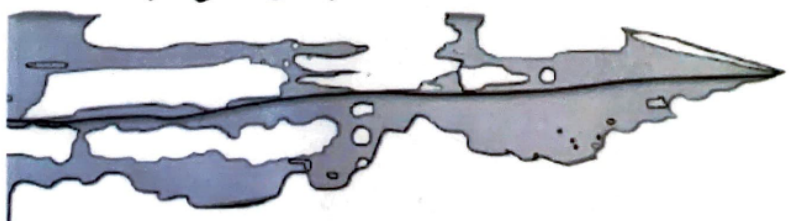
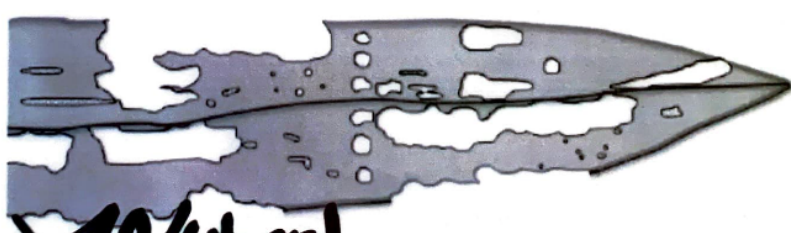
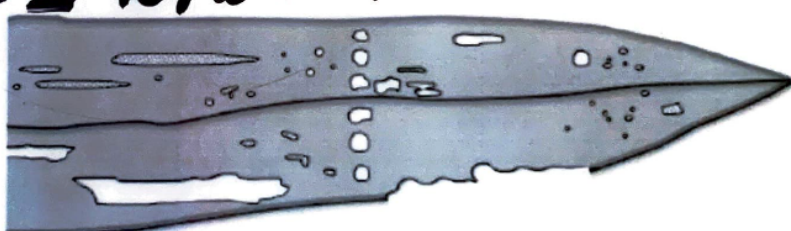
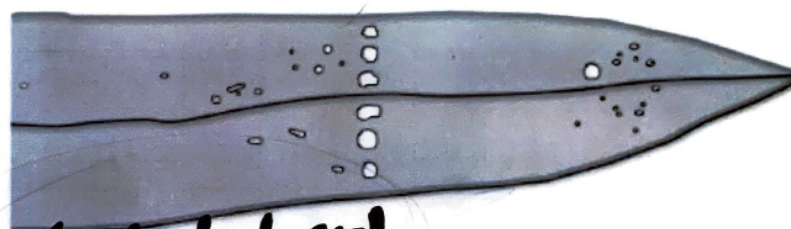
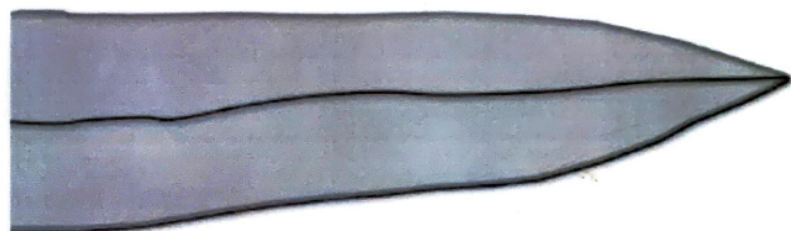
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15

Appendix 6: Adapted 1 to 5 damage scale for the on-farm trial

Simple 1-5 plant damage scale for the fall armyworm (only the plant whorl assessed)

Score	Description
1	No damage
2	Pinholes and small circular lesions on whorl leaves
3	Small and mid-sized elongated lesions plus a few large > 2.5 cm elongated lesions on whorl leaves
4	Many small and mid-sized elongated lesions on whorl leaves plus many large > 2.5 cm elongated lesions on whorl and furl leaves
5	Whorl and furl leaves almost totally destroyed



$\leq 10/\text{whorl}$

$> 10/\text{whorl}$