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EVALUATING THE EFFICACY OF ORGANIC PESTICIDES IN SEMI ARID MAIZE PRODUCTION

BY

MALVERN MARIRE

B223831B

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SUPERVISOR: MR J CHITAMBA

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DECLARATION

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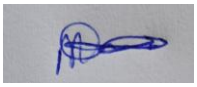
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The undersigned certify that they have read and recommended to the Department of Crop Science, this thesis entitled:

EVALUATING THE EFFICACY OF ORGANIC PESTICIDES IN SEMI ARID MAIZE PRODUCTION

Supervisor: 

Date: 26/06/2026

Author 

Date 26/06/2026

Mr Mutsengi (Chairperson) 

Date 02/09/26

DEDICATION

To my family, whose unwavering love, patience, and sacrifice made this journey possible? To the smallholder farmers of Zaka District, whose resilience and dedication to the land inspired every page of this work? And to all those who believe that knowledge, carefully cultivated, can grow into change.

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ABSTRACT

Maize (*Zea mays L.*) is the primary staple food in Zimbabwe, yet smallholder yields in semi-arid Zaka District are constrained by fall armyworm (*Spodoptera frugiperda*) and other pests, with losses of 35–55% reported in unmanaged fields. Synthetic pesticides are often unaffordable and pose environmental risks, creating demand for accessible organic alternatives. This study evaluated the efficacy of neem oil, insecticidal soap, and garlic extract against maize pests in semi-arid conditions during the 2025/2026 season. A Randomized Complete Block Design with four treatments and five replications was used. Treatments were T1 Neem Oil at 5 ml/L, T2 Insecticidal Soap at 10 ml/L, T3 Garlic Extract at 50 g/L, and T4 Untreated Control. Data on pest population density, plant height, leaf damage, damage score and grain yield were collected at 21, 35, 49, and 63 days after sowing. All organic treatments significantly reduced pest populations and damage scores compared to the control from 35 DAS onward, $p<0.001$. At 63 DAS, Neem Oil recorded the lowest pest density at 1.426 insects/plant and lowest damage score at 1.555 while the control had 5.102 insects/plant and 2.676 damage score. Leaf damage at 63 DAS was lowest in garlic extract at 5.548%, and all botanicals were significantly lower than the control at 7.047%, $p<0.001$. Grain yield was significantly influenced by treatment, $p<0.001$. Neem Oil produced the highest yield at 2.153 t/ha, statistically similar to insecticidal soap at 2.045 t/ha, and both significantly out-yielded garlic extract at 1.835 t/ha and the control at 1.532 t/ha. The results demonstrate that neem oil and insecticidal soap are effective, low-cost options for pest management in semi-arid maize, increasing yield by 40.5% and 33.5% over the control respectively. Garlic extract provided effective pest suppression but lower yield gains possibly due to phytotoxicity under high temperatures. The study addresses critical gaps in semi-arid organic pest management and provides location-specific recommendations for Masvingo Province smallholders.

Keywords: *Spodoptera frugiperda*, botanical pesticides, semi-arid, neem oil, maize yield, Zimbabwe

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LIST OF ABBREVIATIONS

AN - Ammonium Nitrate

DAS - Days After Sowing

FAO - Food and Agriculture Organization

FAW - Fall Armyworm

IPM - Integrated Pest Management

RCBD - Randomized Complete Block Design

SPAD - Soil Plant Analysis Development

ZIMSTAT - Zimbabwe National Statistics Agency

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Maize (*Zea mays* L.) is the major cereal crop grown in sub-Saharan Africa, supplying most of the calories and income to millions of smallholder farming households (FAO 2022). In 2021, global maize production is estimated at 1.2 billion metric tonnes, where Africa is producing an estimated 75 million tonnes, mainly from smallholder farms under rain fed conditions (FAO, 2022). Maize is the staple food crop in Zimbabwe, with an estimated 1.4 million hectares planted annually and more than 60 per cent of national caloric consumption (The Zimbabwe National Statistics Agency [ZIMSTAT] 2021). Zaka District is part of agro-ecological region III and IV in Zimbabwe which has a mean annual rainfall range of 450 to 650 mm and occurs with a mid-seasonal dry spell, which makes the production of maize relatively difficult (Mugandani et al., 2012).

Maize production is one of the most affected biotic constraints in semi-arid Zimbabwe and pest infestation is one. The losses due to key economic pests such as African maize stalk borer *(Busseola fusca*), spotted stalk borer *(Chilo partellus),* fall armyworm *(Spodoptera frugiperda),* corn leaf aphids *Rhopalosiphum maidis* and cutworms *(Agrotis spp.)* have been estimated to range between 20 – 80 % depending on the level of infestation and the time of pest management intervention (Sisay et al., 2019; Day et al., 2017). This fall armyworm (FAW) (first detected in Zimbabwe in 2016) has resulted in significant losses; the Food and Agriculture Organization (FAO) estimates that 12 African countries (Day et al., 2017) lose between USD 2.5 and USD 6.2

billion annually. In Masvingo Province, it has been reported that severe infestations of FAW in fields can result in complete crop failure during outbreak seasons (Chikosi et al., 2020).

Traditional pest control in smallholder maize farming in Zimbabwe has been primarily based on synthetic chemical insecticides such as organophosphates and synthetic pyrethroids (Chikosi et al., 2020). But prolonged use of these synthetic chemicals has had several negative impacts. Firstly, evidence of the development of insecticide resistance has been reported from all over southern Africa, including strains with reduced susceptibility to commonly used active ingredients (Nagoshi et al., 2019). Second, synthetic pesticides pose serious hazards to the environment, such as soil and water pollution and a reduction in beneficial arthropod populations, and bioaccumulate in the food chain (Isman, 2006). Thirdly, more importantly for resource-poor smallholder farmers in semi-arid Zimbabwe, the cost of the synthetic pesticide is often too high to allow for optimal doses, application or even complete pesticide use (Sisay et al., 2019).

Smallholder integrated pest management (IPM) is now seeing interest in organic and botanical pesticides as cheap, locally available, and environmentally friendly alternatives to synthetic insecticides, both scientifically and in policy. Neem oil obtained from *Azadirachta indica* contains a bioactive limonoid called azadirachtin that interferes with the molting cycle, reduces feeding, and prevents egg laying by insects in a number of synergistic ways (Schmutterer, 1990). Insecticidal soap is a mixture of potassium salts of fatty acids which is instantly contact toxic to soft-bodied insects due to the ability to permeate and break down the waxy cuticle (Lawson, 2007). Volatile organo-sulphur compounds in garlic extract *(Allium sativum)* are known to repel adult insects, to inhibit oviposition and to be toxic to larvae (Ogah et al., 2011). All these organic treatments can be made from locally available resources, are environmentally safe and are

potential tools that can be incorporated into the smallholder pest management strategies in semi-arid Zimbabwe.

Although the use of these organics appears to have potential success in theory, there are no extensive, field-based comparative assessments in the published literature specifically in the agro-ecological context of semi-arid Zimbabwe. The bulk of present information comes from humid tropical environments or controlled laboratory conditions, which do not mimic the high sunlight exposure, temperature and sporadic rainfall typical of Zaka District and other semi-arid environments (Dougoud et al., 2019 and Mgoo et al., 2020). The need for location specific, multi-parameter field research is therefore imperative to evaluate the impact of selected organic pesticides on the density of pests, plant health indicators and maize grain yield under the specific conditions in semi-arid Masvingo Province.

1.2 Statement of the Problem

Maize farmers in Zaka District, Masvingo Province are still experiencing unacceptable yield losses (Chikosi et al., 2020; ZIMSTAT, 2021) due to insect infestations, especially fall armyworm, maize stalk borers and aphids. Synthetic chemical pesticides are the most readily available management tool, but are rapidly becoming too costly and ecologically harmful and can be resistant (Nagoshi et al., 2019). Theoretically there are a number of alternatives to using pesticides that are organic, but these have not been tested against the efficacy of other pesticides for use in this semi-arid, field-specific context in Zaka District. Without location-specific evidence, there is no scientific basis for recommending, adopting and optimizing organic pest management programmes for maize production in the semi-arid regions of Zimbabwe.

1.3 Justification of the Study

This study is well-founded in agronomic, environmental and socio-economic perspective. From an agronomic perspective, the efficacy in suppressing pests, plant health, and yield response of neem oil, insecticidal soap and garlic extract in Zaka District field conditions will provide location-specific evidence that can be directly applied to the recommendations of extension programs and to farmer advisory services in semi-arid Zimbabwe (Prasanna et al., 2021). Incorporating the recommendations of Dougoud et al. (2019), the study fills a major gap in the literature for comparative multi-treatment trials of organic pesticides currently available for application in Southern African semi-arid maize systems.

In the context of improving the environment, it is important to note that a viable organic alternative to synthetic insecticides promotes sustainable agriculture and conservation of natural resources in line with the Zimbabwe Agenda for Sustainable Socio-Economic Transformation (ZimAsset) and the United Nations Sustainable Development Goals which include SDG 2 (Zero Hunger) and SDG 15 (Life on Land) (Government of Zimbabwe, 2013). Socioeconomically, adoption of organic pesticides, which are able to generate protection and achieve meaningful pest suppression using locally available plant materials, could cut down household spending on commercial pesticides, boost the net farm income and thus improve food security for the resource-constrained smallholder farmers in Masvingo Province (Sisys et al., 2019).

1.4 Objectives of the Study

1.4.1 General Objective

This study is aimed at comparing the efficacy of neem oil, insecticidal soap (IS) and garlic extract to the control of pest infestation, and also its effect on maize productivity under semi-arid field conditions in Zaka District, Masvingo Province, Zimbabwe.

1.4.2 Specific Objectives

1. To compare the effect of neem oil, insecticidal soap, garlic extract, and no treatment on pest population density (*Spodoptera frugiperda*, *Busseola fusca*, *Rhopalosiphum maidis*) in semi-arid maize production in Zaka District.
2. To evaluate the effect of organic pesticide treatments on plant health indicators, namely plant height (cm), leaf chlorophyll content (SPAD index), and visual pest damage severity scores (1-9 scale) in semi-arid maize at Zaka District, Zimbabwe.
3. To compare the maize grain yield (t/ha) achieved under neem oil, insecticidal soap, garlic extract, and untreated control treatments.

1.5 Research Hypotheses

- H_0: There is no significant difference ($p > 0.05$) in pest population density among maize plots treated with neem oil, insecticidal soap, garlic extract, and the untreated control in Zaka District.
- H_0: There is no significant difference ($p > 0.05$) in plant health indicators (plant height, SPAD index, visual pest damage severity score) among the four treatment groups.

- H_0: There is no significant difference ($p > 0.05$) in maize grain yield among plots receiving organic pesticide treatments and the untreated control.

CHAPTER TWO

Literature Review

2.1 Introduction

This chapter reviews critically the existing literature on the effectiveness of organic pesticides in the management of maize pests in semi-arid agro ecological conditions of Zaka District, Masvingo Province, Zimbabwe. The review is thematic and focuses on the status of maize production under the semi-arid conditions in Zimbabwe, nature, and economic significance of the key maize pest species in the study area, chemistry, mode of action, and documented efficacy of each of the organic pesticides to be tested (neem oil, insecticidal soap, and garlic extract) and the effects of organic pesticides applications on plant health indicators, and documented relationships between pest management, plant health, and maize grain yield. The chapter ends with an outline of the gaps in the literature that justify this study scientifically on the main points.

2.2 Maize production in the Semi-Arid environments in Zimbabwe

2.2.1 Maize is of great importance in Zimbabwe

Maize *(Zea mays L.)* is an unparalleled crop in the agricultural and food security situation in Zimbabwe. Maize is the main staple food crop in the country accounting for over 60 percent of the dietary requirement of majority of the rural and urban population and is the cash crop of preference for smallholder farmers in communal farming areas (ZIMSTAT, 2021). It is grown on an area of around 1.4 million hectares per year, mainly by smallholder farmers on plots of less than 3 ha of rain fed farming (FAO, 2022). Maize is the backbone of household food security

and the major seasonal agricultural income in Zaka District which forms part of Masvingo Province (Chikosi et al., 2020).

Although maize is a key food security crop in Zimbabwe, the country's productivity is far from its genetic potential. In communal farming areas, the national average yields ranged from 0.7 to 1.2 tonnes per hectare while the attainable yields under optimum conditions in research stations were 5 to 8 tonnes per hectare (ZIMSTAT, 2021). The productivity gap is due to a combination of abiotic stresses such as irregular rainfall, high temperatures and low soil fertility, along with biotic stressors such as pest infestation, disease and weed competition (Cairns et al., 2013). Maize production in Zaka District is also being limited by mid-season dry spells, limited soil water holding capacity and frequent occurrence of pests especially in the district, all of which limit maize production to below the comfort level of the household food needs (Mugandani et al., 2012).

2.2.2 Semi-Arid Agro ecological Conditions in Zaka District

Zaka District is largely in Agro-ecological Regions III and IV as defined by Mugandani et al (2012) in the revised Agro-ecological Regionalisation of Zimbabwe. Part of the district falls within Region III with mean annual rainfall ranging from 650 to 800 mm, drought tolerant crops under risk management conditions, and a high frequency of mid-season dry spells posing threats to crop water requirements at critical phonological stages. The mean annual rainfall of the District ranges between 450 to 650 mm and the larger portion of the District (region IV) is marginal for rain fed production of maize without supplementary moisture conservation measures and selection of stress-tolerant varieties.

The semi-arid conditions present certain problems for crop physiology and pest management. Drought stressed maize plants have less stomatal conductance, poorer photosynthetic partitioning and poorer ability to synthesize chemical defence compounds and thus are more vulnerable to feeding damage by the insect (Cairns et al., 2013). The temperature, ultraviolet radiation and low relative humidity of Zaka District facilitates photo degradation and evaporation of the pesticide formulations applied as spray, which can shorten the pesticides' residual efficacy (Isman, 2006). It is thus essential to have an understanding of pest management in these particular circumstances to develop actionable recommendations for the farmers of the Zaka District.

2.2.3 Smallholder Maize Farmers' Challenges in Zaka District

The lack of productivity and household food security in maize farms is a cumulative problem for smallholder maize farmers in Zaka District. Financial constraints are especially high as most farming households cannot afford recommended amounts of inorganic fertilizers, improved seed and synthetic pesticides at the same time (ZIMSTAT, 2021). Poor road condition in the remote communal areas of Zaka District, limited access to agro-dealer outlets and limited supply of agricultural inputs in the areas further hinder access to agricultural inputs. Extension service coverage has consistently been weak and extension worker to farmers ratio far exceeds the recommended ratio of 1:400 (Chikosi et al., 2020).

In this resource-limited environment, pest management is often ad hoc, unpredictable, or non-existent. Chikosi et al. (2020) reported that less than 30% of the surveyed smallholder maize growers in Masvingo Province practiced any of the pest management practices during the growing season and that those who did use pesticides often used sub therapeutic rates because of cost constraints. This management deficit provides ideal conditions for pest populations to

increase and crops are damaged, which can highlight the importance of low-cost and easily accessible pest management options, such as organic pesticides.

2.3 Major maize pests species in Semi-Arid Zimbabwe

2.3.1 Fall Armyworm *(Spodoptera frugiperda)*

The fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) *(Lepidoptera: Noctuidae)* is the most economic threatening pest of maize in Zimbabwe and Sub Saharan Africa. A native of the Americas, FAW was first detected on the African continent in West Africa in early 2016 and had spread to Zimbabwe, including Masvingo Province, by mid-2016 (Day et al., 2017). It rapidly spread across the continent because of its high capacity of long-distance adult flight, its wide host range (more than 80 plant species) and the lack of co-evolved natural enemies in agro-ecosystems in Africa (Prasanna et al., 2021).

The FAW larvae are highly polyphagous, and infest maize at all vegetative growth stages. Earliness instar larvae (L1-L3) feed superficially on the leaf tissue, creating windowed symptoms while later instar larvae (L4-L6) bore into the ear and developing whorl, causing high levels of mechanical damage to the developing ear and grain fill organs. Stokstad (2017) estimated that, if not managed, FAW could cause a reduction in maize yields of 20-73 per cent. Chikosi et al. (2020) reported average losses of 35–55 percent in unmanaged fields due to FAW in Zimbabwe in 2017/2018 during an outbreak season where 12 percent of the surveyed plots had total crop failure. Its ability to build up in numbers very rapidly, to have several generations every season and to hide the larvae in the maize whorl makes control difficult when using contact insecticides, such as some of the organic preparations.

Past control of FAW in smallholder agriculture in Zimbabwe has depended on synthetic insecticides, especially *emamectin benzoate*, *spinetoram* and *chlorpyrifos*, as well as some (limited) biological control agents and cultural measures (Prasanna et al., 2021). Reports have emerged in eastern and southern Africa of a decline in FAW susceptibility to some of the major active ingredients used to control them (Nagoshi et al., 2019), however, suggesting a potential decline in the sustainability of synthetic insecticide reliance for management and the need to assess botanical options.

2.3.2African Maize Stalk Borer *(Busseola fusca)*

The African maize stalk borer, *Busseola fusca* (Fuller) (*Lepidoptera: Noctuidae)* is an important native pest of maize in sub-Saharan Africa and the most prevalent species of stalk borer in the Highveld and transitional areas of Zimbabwe (Overton et al., 2016). In early vegetative phases, female moths lay egg batches between the sheath and stem; first-instar larvae bore into the stem or whorl when they hatch and feed first on young leaf tissue. Larval stem tunnelling disrupts the vascular system resulting in the typical dead heart symptom in small plants and failure of ear formation in older plants.

In eastern and southern Africa, losses due to *B. fusca* in unmanaged fields are estimated at 15 to 40 percent (Overton et al., 2016), and losses can be high if the crop is drought stressed and plant compensatory growth is limited. Physiological stress caused by moisture deficits in the maize plants affects the ability of the plants to produce defensive secondary metabolites in semi-arid areas like Zaka District, which results in greater attractiveness and vulnerability to stalk borer oviposition and feeding by larvae (Cairns et al., 2013). In unmanaged maize grains in semi-arid

Kenyan conditions, Songa et al. (2007) reported up to 3.5 *B. fusca* larvae per plant, which compare to conditions in poorly managed maize fields in semi-arid Zimbabwe.

2.3.3 Spotted Stalk Borer *(Chilo partellus)*

The spotted stalk borer, *Chilo partellus* (Swinhoe) (*Lepidoptera: Crambidae*) is a foreign, highly destructive insect pest of maize that has become a serious pest of maize in semi-arid eastern and southern Africa where it occurs at lower elevations. While *Busseola fusca* is better adapted to the cooler highland environments, *C. partellus* is adapted to the warmer and drier conditions typical of Regions III and IV, and has gradually replaced *B. fusca* at low altitude locations such as parts of Masvingo Province (Overton et al., 2016). The spotted stalk borer has a broader host range, is more tolerant of hot, dry conditions, and may have a higher reproductive rate in favorable temperatures than *B. fusca*, but shares with it many biological characteristics such as the larval life cycle of boring stems.

Compound pest pressure occurs where *C. partellus* and *B. fusca* are present together in the transition areas of Masvingo Province, particularly in Zaka District, making it more difficult to manage than when present alone. Based on the findings of Overton et al. (2016), combined infestations of stalk borers in mixed-species populations resulted in significantly greater yield loss compared to equivalent numbers of larvae in single-species populations, which are due to differences in feeding site preference and timing of damage.

2.3.4 Corn Leaf Aphid (*Rhopalosiphum maidis*)

The corn leaf aphid, *Rhopalosiphum maidis* (Fitch) (*Hemiptera: Aphididae),* is an important piercing and sucking insect pest of maize which causes direct damage and indirect damage through virus transmission. In maize aphids colonise the underside of the leaves, within the whorl and tassel, sucking out phloem sap and producing honeydew which encourages the growth of sooty moulds, which further reduce photosynthesis. The species is the major vector for Maize Dwarf Mosaic Virus (MDMV) and Barley Yellow Dwarf Virus (BYDV), which can cause systemic yield reducing infections in the early stages of crop growth in Zimbabwe (Kieckhefer & Gellner, 1992).

In semi-arid regions, aphid populations increase explosively during dry warm spells with low activity of natural enemies. Kieckhefer and Gellner (1992) reported that when aphid infestation levels reached more than 500 aphids per plant in the grain filling stage, the grain yield of maize plants was decreased by up to 18 percent due to a combination of direct nutrient removal and virus induced physiological upset. Early season aphid population levels in Zaka District can reach damaging levels within weeks after crop establishment, due to conditions of dry season prevailing from July to November that enable ideal conditions for aphid build up on ratoon and volunteer maize plants.

2.4 Rationale and an Overview of Organic Pesticides

Organic and botanical pesticides have attracted new interest in recent years, as part of sustainable integrated pest management (IPM) systems, due to the well-recognized drawbacks of using synthetic chemicals as the sole method of pest control, especially in smallholder farming systems with limited resources (Isman, 2006). Organic pesticides, in a general sense, those pesticides

with a biological origin (plant, microbial, or other biological) that do not contain a synthetic chemical active ingredient, have several theoretical benefits over their synthetic counterparts.

Most botanical pesticides have a short environmental half-life and consequently do not present soil accumulation, water pollution or residues in harvested grain problems, especially in Zaka District where water sources are scarce and used mainly for field irrigation and household purposes (Isman, 2006). Secondly, many organic pesticide preparations can be made locally using plant materials found within the farming community, thus reducing the need to rely on expensive commercial products for pesticide production and reducing the economic cost of implementing pesticide control strategies among resource-constrained smallholder farmers. Thirdly, the mammalian toxicity of most botanical pesticide active ingredients tends to be lower, which decreases occupational health risks on farms where workers apply pesticides often without personal protective equipment in resource-limited environments (Ogah et al., 2017). Fourth, botanical pesticides work by a variety of and often multiple modes of action that are less likely to produce resistance than single action synthetic pesticides (Schmutterer, 1990).

The organic pesticides tested in this study, namely neem oil, insecticidal soap and garlic extract, are viable solutions in the smallholder agricultural setting in Zimbabwe, and are in line with the direction the country is taking in terms of sustainable and climate-smart agriculture as outlined in ZimAsset (Government of Zimbabwe, 2013) and the economic realities of the farmers in Zaka District. All three treatments were easily accessible, with neem (*Azadirachta indica*) being grown as shade and multipurpose trees in many of the villages of Masvingo Province, and garlic being a familiar crop of the household while soap is available in every village.

2.5 Neem Oil: Chemistry, Mode of Action and documented efficacy

2.5.1 The botanical origin and active compounds

Neem oil is obtained from the seed kernels of the neem tree (*Azadirachta indica* A. Juss., family *Meliaceae*) which is native to the Indian subcontinent and now widely naturalised throughout tropical and subtropical Africa, even in Zimbabwe where it is grown as a multipurpose agroforestry tree (Schmutterer, 1990). Cold-pressed neem oil contains more than 100 biologically active compounds, including the most extensively documented compound, azadirachtin, which is believed to be the major insecticidal component. *Azadirachtin* is a member of the limonoid class of tetranortriterpenoids with four or more actions on insects, such as ecdysone-mediated disruption of larval molting and pupation; suppression of feeding behavior (antifeedancy) at concentrations below those required for direct insecticidal activity; inhibition of oviposition by adult females; and reduction of fecundity in surviving adults (Schmutterer, 1990; Isman, 2006).

Other insecticidal and repellent activities of neem oil are due to other bioactive compounds which help in the insecticidal effect by complementary mechanism: inhibition of digestive enzymes of insects and interfering with chemoreceptor mediated host plant recognition, *nimbidin, salannin, nimbin, and meliantriol*. Neem oil's multi-compound, multi-target activity has been suggested as an important benefit to resistance management, because the chance of an insect population becoming resistant to two or more of its acting components at the same time is much smaller than for single-target synthetic insecticides (Schmutterer, 1990).

2.5.2 Effectiveness against Fall Armyworm

The efficacy of neem based formulations on the control of Spodoptera frugiperda has been demonstrated under a variety of experimental scenarios. In Nigeria, Adebayo et al. (2014) tested NSKE at 50 and 100 g/L and found that the extract caused 62 and 84 percent larval mortality after 72 hours post-exposure in the laboratory. In addition to mortality, sub lethal concentrations of azadirachtin caused developmental disruption and killed a high proportion of the surviving larvae that did not pupate, which may be due to a reduction in contribution of adults to the field efficacy.

In semi-arid Tanzania, agro ecologically similar to Zaka District, Mgoo et al. (2020) showed that the application of neem oil at 5 mL/L at seven-day intervals from V3 stage resulted in a significant reduction in FAW larval densities compared to untreated plots, although the efficacy was lower than chlorpyrifos reference plots treated on the same schedule, whereas the whorl damage scores did not differ significantly. They pointed out that the low efficacy compared to synthetic insecticides was due to the rapid photo degradation of *azadirachtin* under high UV radiation and temperatures found at the semi-arid location, and as a result, suggested that changes in application time and frequency should be considered for semi-arid environments. Dougoud et al. (2019) conducted a comprehensive meta-analysis of African FAW management studies and found that neem treatment was the most consistently effective organic treatment in reducing FAW larval densities in the studies included in the analysis (45–68 percent reduction compared to untreated control).

2.5.3 Control against Aphids and Stalk Borers

The effect of neem oil on the stalk borer species, namely *Busseola fusca* and *Chilo partellus*, has been well established by mainly antifeedant and oviposition deterrent activity with no significant effect on larval mortality. In semi-arid field trials, neem oil application at 3 L/ha was reported to reduce stalk borer infestation level (dead heart incidence) by about 45 percent and the stand count and grain yield increased by 28 percent compared to the untreated controls (Sola et al., 2014). The antioviposition effect of *azadirachtin* is believed to be of particular benefit when used against stalk borers as it decreases the number of egg batches laid on treated plants which in turn decreases the number of larvae that bore into the plant stem.

Neem oil primarily works against aphid pests by means of the antifeedant, nymphal mortality, and fecundity reducing mechanisms. *Azadirachtin* has been shown to affect phloem-probing behaviour of aphids at levels routinely achieved in the field, which decreases the extent of population increase and the efficiency of virus transmission (Isman 2008). In another Nigerian field experiment, Ogah et al. (2017) recorded a reduction of 67% in corn leaf aphid population density on maize plants treated with neem oil compared to those that were not treated.

2.5.4 Limitations of Neem Oil under semi-arid conditions

The main constraint of neem oil use as a pest management tool in a semi-arid district like Zaka District is the photo ability of azadirachtin and active compounds. In the field, azadirachtin is rapidly degraded by UV radiation with a half-life of 1.5-4 days under tropical solar radiation intensity vs 13-22 days under shade (Isman, 2006). This is an accelerated degradation and requires frequent application rates (5-7 days) in semi-arid regions for biologically effective concentrations on plant surfaces, thereby compounds the manpower and operational expenses

that would occur with synthetic insecticides that have a longer residual activity. Also, neem oil is not particularly effective against the larval instars already inside the maize whorl or stem, because the plant architecture hinders the penetration of the spray to the protected feeding sites.

2.6 Insecticidal Soap: (A) Composition, (B) Mode of Action, and (C) Efficacy

2.6.1 The mechanism of action and chemical composition of the fungicide

Insecticidal soap is one of the oldest and most commonly used classes of organic pesticides, consisting of aqueous formulations of salts of fatty acids, which are mainly potassium palmitate, stearate, oleate and linoleate. The insecticidal activity of potassium fatty acid salts is attributed to their *amphiphilic* molecular structure, which enables them to penetrate the *lipophilic* insect cuticle and cause disruption of the integrity of the cellular membranes by membrane solubilisation, ion channel perturbation, and by interfering with respiration by disrupting the gas exchange through the spiracles (Lawson, 2007). The effects result in the quick desiccation and death of soft-bodied insect pests in minutes to hours after they are sprayed directly with the solution.

Insecticidal soap works by contact only not systemic in plant tissue and does not have a lasting effect after spray solution dries on foliage. This has two effects: first, it only affects individuals of pest species that are on the plant surface when the spray is applied; and second, it also reduces the effectiveness against concealed pests and makes insecticidal soap selective for beneficial arthropods that are not on the plant surface when they are sprayed (Lawson, 2007). Insecticidal soap also does not create any residual activity, which means that it can be used in a biological

control program because beneficial predator and parasitoid populations can quickly recolonize treated crops.

2.6.2 The efficacy against aphids and soft-bodied pests

Insecticidal soap is highly effective against a variety of soft-bodied insect and mite pests in a variety of crops. Under greenhouse conditions, Pickett et al. (2010) recorded > 90 percent mortality of corn leaf aphids (*Rhopalosiphum maidis*) when they were directly sprayed at the 2 percent soap concentration, which was caused by cuticle penetration and desiccation. Okonkwo and Obi (2013) recorded a significant decrease of 75 per cent aphid colony density in a sub-humid Nigerian maize system after a single application of 2 per cent insecticidal soap compared with the 20 per cent natural mortality in untreated controls at 7 days after application. The high knockdown effect of insecticidal soap on aphids could be a significant management benefit in Zaka District where aphids can cause economic damage in no time during warm dry periods.

In addition to aphids, insecticidal soap will work against thrips (*Frankliniella williamsi*) and mites because they are soft-bodied. As these piercing-sucking pests are secondary pests of maize in semi-arid Zimbabwe that can cause yield-reducing damage during dry spells that suppress natural enemy activity, the broad soft-bodied pest activity spectrum of insecticidal soap is of agronomical relevant to the Zaka District context.

2.6.3 CO_2 is highly effective and has no limitations in the presence of lepidopteron larvae

The effectiveness of insecticidal soap against *lepidopteran* larvae (e.g., FAW and stalk borer) is significantly reduced when compared to soft-bodied piercing-sucking pests. *Lepidopteron* larvae have a thicker cuticle that is more heavily sclerotized than the thin cuticle of aphids and larvae living inside the maize whorl or stem are physically inaccessible to contact spray applications. Kranthi (2014) found that early instar larvae (L1-L2) of FAW were 50 percent killed by direct contact with insecticidal soap spray while the older larvae (L4 and above) were less than 10 percent killed. The take-home message is that the egg or early larvae must be the target of the insecticidal soap when it comes to FAW.

In addition the effectiveness of insecticidal soap is also reduced by the rapid evaporation of aqueous spray solution when the temperature is high and humidity is low, similar to conditions in Zaka District, which limits the length of time that the spray is in contact with the pest cuticle, and may lead to lower amounts of effective insecticidal soap being delivered. Lawson (2007) suggested that insecticidal soap should be applied in the early morning (0600-0900 hrs) or evening (1700-1900 hrs) in hot, dry environments for maximum contact time because of lower evaporations. This study included optimizing the application times of the District of Zaka under its climatic conditions in its experimental method.

2.7 Garlic Extract: Phytochemistry, Mechanism, and Efficacy

2.7.1 Toxicity Test of Plant Products

Garlic (*Allium sativum L*., family *Amaryllidaceae*) has been incorporated in traditional agricultural pest management systems for centuries throughout Africa, Asia and Latin America, and its insecticidal and repellent properties are believed to be due to a complex mixture of volatile organo-sulphur compounds, which are enzymatically produced during the disruption of garlic tissue. *Allicin*, the primary bioactive compound, is formed in seconds upon crushing of garlic tissue to release the enzyme *alliinase*, which converts alliin to allicin; later, allicin is converted to other compounds such as diallyl disulphide (DADS), diallyl trisulphide (DATS), ajoene and vinyl dithiins (Isman, 2006).

The insecticidal activity of garlic organo-sulphur compounds is varied, such as inhibition of acetyl cholinesterase (AChE) enzyme activity, which inhibits insect nervous system function in a similar way to the organophosphate insecticides; olfactory repellence caused by the perception of sulphur volatiles by insect chemoreceptors, which affects host plant location, landing, and oviposition; direct contact toxicity as a result of penetration of the insect's cuticle; and antifeedant effect which affects the amount of plant material consumed by foraging larvae (Ogah et al., 2011). The dual action of repellent and toxicant is highly desirable since the repellent action can help exclude initial pest establishment even if the direct toxic action is not strong enough to kill a high percentage of the pests in the population.

2.7.2 Efficacy for Fall Armyworm

There is increasing empirical evidence to support the effectiveness of garlic extract against *Spodoptera frugiperda*, but not as extensive as neem extract. In Nigeria, Ogah et al. (2011) tested the aqueous extract of garlic bulbs at 50 g/L and 100 g/L against FAW larvae in the field and found that the garlic extract at 100 g/L killed 68 percent of the larvae at 72 hours after application. Importantly, the same study showed that numbers of FAW egg masses on plants treated with garlic extract were significantly reduced compared to plants not treated with garlic extract, indicating that garlic extract may be a significant indirect way for preventing egg mass formation in addition to killing larvae.

Garlic extract proved to be an intermediate efficacy treatment within the spectrum of organic pesticides by reducing FAW larval density by 51 per cent in a comparative field trial in West African guinea savannah when compared to the untreated control whereas neem oil reduced the density of FAW larvae by 67 per cent and insecticidal soap reduced the density of FAW larvae by 38 per cent (Ogah et al., 2017). The yield of maize grain obtained with the application of garlic extract was 31 percent better than the untreated plots, indicating an agronomic advantage although it is not as effective as neem oil treatment. Similarly, Dougoud et al. (2019) were able to validate their meta-analysis and show that garlic-based treatments improved yields by 10 to 28 percent over untreated controls in various sites across Africa, with greater variability than neem-based treatments.

2.7.3 Efficacy against Stalk Borers and Aphids

The antioviposition and repellent activity of garlic extract has been consistently reported against stalk borers while the direct mortality on the larvae has been less consistently reported. Sola et al.

(2016) reported that the garlic extract-treated maize plots in semi-arid Tanzania yielded significantly reduced stalk borer egg batch incidence and dead heart scores which were believed to be largely due to the smell of garlic volatiles that repelled gravid female moths. The real-world message is that garlic extract could be more useful as a preventative treatment applied before high points of oviposition, rather than a curative treatment to control established larval infestations.

Meissner et al., 2002, showed that garlic extract was effective against aphid pests in reducing the density of the infested plants on the field maize – in a 21 day trial period, the aphid population density was reduced by about 55 percent – the effect was due to direct contact toxicity to nymphs as well as adult emigration from treated plants due to olfactory repellence. The activity of the organophosphate (OP) insecticides in disrupting the AChE system in the nervous system of insects is also similar to the mechanism in which the garlic derived compound is effective in the control of aphid.

2.7.4 Stability and preparation considerations for semi-arid conditions

One of the important practical factors for the use of garlic extract as an organic pesticide in the Zaka District is the instability of allicin and other volatile sulphur compounds once they are prepared. Allicin is unstable in the presence of light, air and high temperatures and breaks down within hours to days at ambient temperature (Isman, 2006). The extracts from crushed garlic have been proven in numerous studies to be much more effective when prepared within 12–24 hours of crushing and used immediately, as opposed to older extracts or extracts stored under warm conditions. This instability presents a practical problem for standardisation in field trials

and commercial application, while farmers must make garlic extract on the day of application, something that may be feasible in a smallholder system but increases the operation difficulties.

2.8 Organic pesticide treatments have an impact on Plant Health Indicators (PHI)

2.8.1 The Chlorophyll content and Photosynthetic performance

The Chlorophyll content (CC) estimated non-destructively by SPAD (Soil Plant Analysis Development) meter reading is an indirect measure of leaf N status and photosynthetic capacity of maize (Prasanna et al., 2021). Damage by pests, especially from phloem-feeding insects like aphids, and by leaf-feeding FAW larvae, decreases chlorophyll levels by destroying mesophyll cells containing chloroplasts, and by the loss of nitrogen caused by the continuous feeding on phloem sap. In highly infested maize plants, Kieckhefer and Gellner (1992) reported decreases in the SPAD readings of ear-leaf tissues from 12 to 25 percent, which correlated with decreases in light use efficiency and dry-matter accumulation. Therefore, it is expected that rates of photosynthesis and chlorophyll content in plants would be higher in treatments that effectively suppress aphid colonies due to use of organic pesticide treatments when compared with the untreated controls.

The feeding injury caused by FAW and borers of the stalks of maize further compromises photosynthetic productivity via loss of functional leaf area. Larvae (whorl feeding) damage the unrolled leaves and permanently reduce leaf area for light interception during the important growth stages of the crop. In semi-arid Tanzania, maize plants damaged by FAW had 18 to 32 percent lower SPAD readings at V10 than those which had not been damaged in managed plots

of the same variety, and that the reduction in RUE was carried on to reduced rates of grain filling at maturity (Mgoo et al. 2020).

2.8.2 Plant height and plant vegetative growth

Maize plant height is a widely used integrative parameter of maize plant vigour, and summarizes the combined effect of plant genetic potential, soil fertility, water availability and biotic stress over the entire vegetative growth phase. When plants are in the dead heart stage of infestation, stalk borer and FAW damage the apical meristem, stunting plant growth and resulting in plant death or compensatory tillers which rarely end up in harvestable grain (Hruska & Gould, 1997). Hruska and Gould (1997) observed a 15 to 32 percent decrease in final height of plants of maize in Semiarid Nicaragua infested with the stalk borer, and a corresponding decrease in leaf area index and biomass.

In the Zaka District where plant height and leaf area are also limited by moisture stress and low soil fertility, the extra growth suppression caused by pest feeding adds to the yield reducing effects of abiotic stress, making it hard to untangle the role of biotic stress from abiotic stress in observational studies. All soil plots in each block are managed in the same manner regarding soil fertility, pest management timing, and are uniform in every other way besides treatment, thus the experimental design for this experiment is controlled and designed to eliminate the confounding effects of spatial soil variability on the treatment effects observed on plant height and other growth parameters.

2.8.3 Pest Damage Severity Scores

Visual rating scales for pest damage are standardized to measure the overall effect of the feeding activity of the pest communities on maize plant health. The 1-9 damage rating scale (Davis et al. 1992) has been widely adopted in FAW and stalk borer management research in Africa, and classifies the level of whorl leaf damage according to the severity of the attack, with a score of 1-3 being acceptable, and a score of 4-6 being moderate damage and justifying management action, while a score of 7-9 represents severe damage and high yield penalties. Sola et al. (2014) and Mgoo et al. (2020) both showed strong negative relationships between the whorl damage scores and the final grain yield from maize field experiments in semi-arid conditions, indicating potential for damage scores to predict the yield outcome.

Significant reductions in the density of pests caused by organic pesticide treatments are expected to result in proportionally lower damage scores, especially when applied at critical growth stages V3-V6 when young larvae are most accessible to spray contact before whorl entry occurs. In the present study, an important intermediate factor between the input of pest management and yield outcome is the relationship between the reduction in pest density and the reduction in damage score that treatment causes.

2.9 Impact of Organic Pest Management on Maize Grain Yield

Maize grain yield is the final agronomic result of successful pest suppression, plant health maintenance and environmental conditions from planting to harvest. The most important output of this study for farmers and extensionists is the yield response to organic pesticide application since this is the criterion they use for determining value of any investment in pest management.

The magnitude of the productivity gap, which could be bridged through effective pest management, was highlighted by CABI's estimate of pre-harvest losses of USD 2.48 billion per annum due to FAW in 12 African countries, corresponding to 8.3 million tonnes of maize. The combined damage from stalk borer and FAW infestation in unmanaged smallholder fields in Zimbabwe alone has been estimated to be 35 to 55 percent of the potential yield in infested seasons (Chikosi et al., 2020).

There is evidence of yield response to organic pesticide treatments for maize in Africa, but it is variable. As part of the study, Dougoud et al. (2019) carried out a meta-analysis of 27 field trials in sub-Saharan Africa, which showed 22–35 per cent improvement in mean yield in neem-treated plots compared to untreated plots. The Garlic treatments yielded 10 to 28 percent improvement in yield with a significant variation from one trial site to the next due, largely, to differences in the composition of the pest complex, infestation level, climatic conditions, and application techniques. The yield advantage of the Garlic treatments ranged from 10 to 28 percent with a significant variation between the trial sites which reflected differences in the composition of the pest complex, pest level, climatic conditions, and application method. Importantly, the meta-analysis revealed that semi-arid regions are largely lacking from the existing evidence base, with less than 15 per cent of the trials included in the analysis being carried out under rainfall conditions similar to those in the Zaka District.

Comparative field trials using several organic treatments in the same field are especially useful when making actionable recommendations. In a field trial against FAW in West Africa, neem oil, garlic extract and insecticidal soap treatments produced 42, 31 and 22 percent higher yield than the untreated control (Ogah et al., 2017). In a semi-arid maize trial in Kenya, Chebet et al. (2013) concluded that neem oil was the most effective treatment for stalk borers and insecticidal

soap the most effective treatment against aphids, pointing to the necessity to prioritize the treatment methods according to the pest complex. The comparisons made above should, however, be taken to be an indication of the yield outcomes that may be obtained in the specific conditions of the Zimbabwean semi-arid conditions and different combinations of pest species, pest pressure and climatic conditions as well as crop management practices.

2.10 Integrated Pest Management (IPM) and Organic pesticides in Zimbabwe

ZimAsset (Government of Zimbabwe, 2013) and later the national strategic documents, clearly support the use of IPM as the preferred method for crop pest control in smallholder farming systems in Zimbabwe. According to the Food and Agriculture Organization, IPM is defined as the coordinated use of various complementary pest management strategies such as biological control, cultural practices, resistant varieties and the mindful use of pesticides to keep pests at an economically tolerable level with minimal impact on people and the environment.

The use of organic botanical pesticides is compatible with the IPM concept, as they are 'natural' pesticides that are low risk and environmentally friendly to complement the biological and cultural control measures. Botanical pesticides with selective activity and those that degrade quickly in the environment are less likely to impact beneficial arthropod communities that provide biological pest suppression services in smallholder maize fields than broad-spectrum synthetic insecticides, which tend to kill natural enemies and may lead to secondary pest outbreaks (Isman, 2006). Botanical pesticide promotion has been identified as a priority area for extension service development by both the Zimbabwe Farmers Union (ZFU) and the Department of Agricultural Research and Extension (AREX), but the evidence base to support specific recommendations to the smallholder farming systems of semi-arid areas like Zaka District has been limited (Chikosi et al., 2020).

The present study directly addresses this evidence gap by providing efficacy data for the three most practically available organic pesticide options to the Zaka District farmers, with a multi-parameter approach, at a location specific level. The study design combines assessment of pest population density, plant health indicators and grain yield which matches the multi-output evaluation recommended by Prasanna et al. (2021) for the research of IPM for controlling FAW in African smallholder systems, making the results easily interpretable in the context of FAW management in extension and farmer systems in Masvingo Province.

2.11 Identified Gaps in the Existing Literature

An examination of the literature reveals some important gaps which gives the scientific rationale for this study. The first is that most published organic pesticide efficacy trials have been done under sub-humid or humid conditions and the efficacy results from those experiments cannot be directly applied to the agro ecological context of Zaka District where the high temperatures, high UV radiation and low relative humidity systematically affect the degradation rate of pesticides, the dynamics of pests and plant physiological responses to the infestation (Dougoud et al., 2019; Mgoo et al., 2020).

Second, most published studies compare only one organic pesticide treatment and one untreated control, making it impossible to make direct comparisons of the efficiency of the organic pesticide treatment in comparison with the others under identical environment. No multi-treatment comparative trials have been done under the same experimental set-up, leaving farmers and extension workers with no scientific information to choose from when deciding which of the available organic methods to use.

Third, published studies usually do not assess all three key outcome domains (pest density, plant health indicators and grain yield) within the same experimental design, making it difficult to establish mechanistic links from pest control to yield improvement and to determine whether plant health benefits translate consistently to harvestable benefits under semi-arid conditions.

Fourth, there has been no published research in Zimbabwe that compares the relative effectiveness of neem oil, insecticidal soap and garlic extract in a maize production system, which leaves a specific national gap in knowledge that limits the ability of extension officers to provide evidence-based recommendations in Masvingo Province. In the present study these identified gaps will be addressed with a rigorous and replicated RCBD field trial to investigate the three organic treatments along with an untreated control in a semi-arid environment of Zaka District, using all three parameters of pest population density, plant health and grain yield.

CHAPTER THREE

Methodology and experimental design

3.1 Description of the Study Area

This study was carried out at a smallholder farming site in Zaka District of Masvingo Province in 2025/2026 cropping season. The Zaka District is located in the south-eastern part of Zimbabwe and is mainly in Natural Region III which has semi-arid climatic conditions with irregular and lower annual precipitation of between 450 mm and 650 mm. The district is located at a latitude of 20°20'S and a longitude of 31°29'E at an altitude of 400 to 600 metres above sea level.

Rainfall is unimodal and generally occurring in the Nov-Apr period. Average annual temperature is 18°C to 24°C and high evapotranspiration rates add to the semi-arid nature of the environment. The soils in the study area are mainly sandy loam/ clay loam and are *Fersiallitic* in the FAO soil classification system. The soils are moderately fertile with relatively low organic matter content (2.6-3.5%) and neutral pH (5.8-6.8) typical of most smallholder farming areas in Masvingo Province.

Despite the semi-arid climate, Zaka District is also an important maize producing district, and smallholder farmers highly depend on maize as a major food staple. The district is facing a major challenge in sustainable maize production due to the pest pressure mainly from fall armyworm (*Spodoptera frugiperda*), maize aphids (*Rhopalosiphum maidis*) and cutworms (*Agrotis spp*.). Moisture-stressed periods make crops more susceptible to pest infestations as a result of the semi-arid conditions and unpredictable rainfalls. The conditions were found to be suitable and

ecologically valid for assessing the effectiveness of organic pesticide treatments to control pests and their effects on maize productivity in Zaka District.

3.2 Experimental Design

The experiment was designed in Randomized Complete Block Design (RCBD) experimental design where four treatments were applied to five replications making a total of 20 experimental plots. The RCBD was chosen because it allows consideration of the environmental variability within the experiment, especially soil heterogeneity and topographical gradients found in smallholder farming plots in semi-arid regions. Blocking was used across the main gradient of environmental variation (moisture gradient) to reduce the variation within the blocks and to allow the comparisons between treatments to be made under uniform conditions.

The experimental plots were 5 m × 4 m (20 m^2) and had 1 m alleys between plots and 2 m between blocks, which was kept throughout the trial to prevent drift of spray between plots and areas for easy movement during data collection. The total experimental space (including alley and buffer space) was about 700 m^2. The trial was conducted on the variety of maize (*Zea mays L.*) SC403 which is a semi-drought tolerant hybrid generally recommended for semi-arid areas in Zimbabwe.

Table 3.1 Description of the experimental treatments

Treatment No	Treatment label	Description	Application Rate

T1	Neem Oil	Cold-pressed neem oil (*Azadirachta indica*) in water and emulsifier	5ml/L water
T2	Insecticidal Soap	Potassium salt based insecticidal soap solution	10 ml/L water
T3	Garlic Extract	Aqueous garlic (*Allium sativum*) extract emulsified with the aid of an emulsifier	50 g crushed garlic/L
T4	Control (Untreated)	No pesticide application; plots left to natural pest pressure	—

Note: DAS = Days After Sowing. All spray working in the early morning (06:00-08:00 hrs) where the level of photo degradation and evaporation is minimised.

Table 3.2: Randomized Complete Block Design Plot Layout (Treatment Allocation)

Block/Rep	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
Block 1	T2	T4	T1	T3	T2
Block 2	T1	T3	T2	T4	T1
Block 3	T3	T1	T4	T2	T3
Block 4	T4	T2	T3	T1	T4

T1 - Neem oil, T2 - Insecticidal Soap, T3 - Garlic Extract, T4 - Control (Untreated). One block is equal to 1 replication.

3.3 Land preparation and crop establishment

Two weeks prior to planting, land preparation was started. The experimental area was ploughed with a hand tractor down to 20-25cm and then harrowed with a disc to give a fine tilth for seed germination. The plots were marked with pegs and sisal string to the specified size. Maize was sown at the beginning of the rainy season (mid-November) with inter-row spacing of 90 cm and intra-row spacing of 30 cm resulting in plant density of about 37,037 plants per hectare which is consistent with the recommended plant density for maize in the semi-arid regions of Zimbabwe.

At planting, basal fertilizer (Compound D; 7N:14P:7K) was applied in each plot at the rate of 200 kg/ha. Top dressing / fertilizer (Ammonium Nitrate (AN 34.5%)) was applied at 21 days after sowing (DAS) and 42 DAS at the rate of 100 kg/ha each. The amount of fertilizer applied was the same for all treatments to help distinguish fertilizer from pesticide treatment effects on

yield. A common switch to all plots was the use of a hand hoe for weeding 21 DAS and 42 DAS, hand thinning to one plant per station 14 DAS and gap filling 10 DAS.

3.4 The preparation and application of organic pesticides

3.4.1 Neem Oil (T1)

The cold-pressed neem oil *(Azadirachta indica)* containing at least 3,000 ppm *azadirachtin* was purchased from a registered agricultural supplier. A stock solution was prepared containing 5ml of neem oil and 1ml of the liquid dishwasher soap (as emulsifier) added to a litre of clean water. The solution was agitated to ensure a good emulsion prior to loading into a knapsack sprayer. A 15litre hand operated knapsack sprayer with 300 L/ha was used to apply it at 21, 35, 49 and 63 DAS. Neem oil is primarily used as an antifeedant, insect growth regulator and repellent on soft-bodied insects like aphids, armyworms and thrips.

3.4.2 Insecticidal Soap (T2)

One percent potassium salt of fatty acids insecticidal soap concentrate (commercial) was diluted at a rate of 10 ml/l of water. The solution was made up fresh before each spraying to prevent degradation of the active salts of the fatty acids. Spraying was done on schedule and the same equipment as T1 (21, 35, 49 and 63 DAS). Insecticidal soap is toxic to soft-bodied insects upon contact and can be used against aphids, spider mites and early instar caterpillars.

3.4.3 Garlic Extract (T3)

Fresh garlic bulbs *(Allium sativum)* were collected from the local market and garlic extract was prepared. Garlic cloves were finely crushed and soaked in 1 litre of distilled water for 24 hours then filtered using double muslin cloth. Adherence and spreading on plant surfaces was improved by adding 1ml liquid soap per litre of filtrate. To avoid degradation of the

organosulphur compounds which are responsible for the insecticidal activity, the extract was prepared fresh within 12 hours before sprays were applied. Application was the same as with treatments T1 and T2.

3.4.4 Control (T4)

In the control treatment (T4) no pesticide was applied at all during the growing season. The other plots, which were not treated with pesticides, have been grown under the same agronomic management (fertilization, weeding, and/or irrigation) as the treated ones and have been left to natural pest attack. The efficacy of the three organic pesticide treatments was compared with the untreated control.

3.5 Data Collection

Three general types of response variables were measured which are pest population density, plant health variables (plant height, plant leaf colour, and visual pest damage severity ratings) and maize grain yield at harvest. The data were obtained from five randomly selected plants in the net plot area (excluding border rows) in each experimental plot and the measurements were made at fixed times of day to reduce the effect of diurnal variation.

Table 3.3: Data Collection Variables, Methods, and Schedule

Variable	Measurement Method	Frequency	Growth Stage (DAS)
Pest Population Density	Direct count on 5 tagged plants/plot	Bi-weekly	21, 35, 49, 63 DAS
Plant Height	Measuring tape from base to flag leaf tip (cm)	Bi-weekly	21, 35, 49, 63 DAS
Leaf Colour (SPAD)	SPAD chlorophyll meter on 3rd leaf from top	Bi-weekly	21, 35, 49, 63 DAS
Visual Pest Damage Score	1-9 scale visual assessment per plot	Bi-weekly	21, 35, 49, 63 DAS
Maize Grain Yield	Harvest, shell, weigh and adjust to 12.5% MC (t/ha)	Once at harvest	~120 DAS

DAS = Days After Sowing; MC = Moisture Content; SPAD = Soil Plant Analysis Development index.

3.5.1 Pest Population Density

All individual pests counted by direct visual methods on five randomly selected and permanently tagged plants per plot at each assessment date (21, 35, 49, 63 DAS) were used to determine pest

population density. Counts were made from 07:00 to 10:00 when insects are less mobile, during the cooler morning hours. All leaves abaxial and adaxial, leaf whorls, stems and developing ears were inspected for hidden pests like fall armyworm larvae, on both sides of each sample plant.

Field guides for maize pests in sub-Saharan Africa were used to identify pest species to the genus level, and counts of the different categories of pests were recorded (aphids, armyworm larvae and other foliar pests). The population density was presented as the mean number of pests/plant/plot. The values from the 5 plants sampled per plot were averaged to produce 1 value for each plot for statistical analysis.

3.5.2 Plant Health Indicators

3.5.2.1 Plant Height

Same 5 plants that were tagged for pest counting were used for plant height measurement at 21, 35, 49 and 63 DAS. A graduated measuring tape was used to measure height from the soil surface to the top of the last completely expanded leaf (vegetative stages) and to the tip of the flag leaf (reproductive stages). All measurements were made to the nearest centimetre. Five plants were sampled in each plot, and the plant height was averaged to give an average plant height for the plot which was used for all subsequent statistical analysis. The total crop vigor and the extent of growth inhibition caused by pests can be measured by plant height.

3.5.2.2 Leaf Color (Chlorophyll Content)

Chlorophyll content was estimated on the leaves using a chlorophyll meter (SPAD-502, Konica Minolta, Japan) as a measure of nutrition and physiological state of the plants. Readings were taken on the middle portion of the third fully expanded leaf from the top of each of the five tagged plants per plot at each assessment date. Each leaf was sub-read three times and the average value was used as a single SPAD value for each plant. The plot mean SPAD value was

obtained from the 5 sampled plants. SPAD values are dimensionless numbers, which are positively correlated with the amount of chlorophyll in the leaf, and lower SPAD values are associated with chlorosis or damage caused by pests.

3.5.2.3 Visual Pest Damage Severity Scores

Visual damage severity was scored on a modified 1-9 scale based on visual foliar damage in maize scoring protocol from the International Maize and Wheat Improvement Center (CIMMYT). The various types of leaf damage, degree of yellowing, tearing of leaves, boring of stems, and ear damage as outlined in Table 3.4 below are incorporated into each of the score categories. Two trained enumerators independently scored the plots and the final plot score was the average of the two. Whole-plot assessments were made at 21, 35, 49 and 63 DAS to reflect the overall severity of pest damage within the plot, rather than per plant.

Table 3.4: Visual Pest Damage Severity Scoring Scale (Adapted from CIMMYT, 2004)

Score	Damage Level	Description
1	No Damage	Leaves are healthy and showing no visible damage by any pest; no visible pest damage on any part of the plant
3	Low Damage	Few feeding marks are visible in less than 25% of the leaf area, economic damage is negligible
5	Moderate Damage	Feeding damage occurs on 25-50% of leaf area; some leaves are yellowed or wilted.

7	High Damage	50-75% leaf area destruction; boring of stem or ear damage evident
9	Severe Damage	More than 75% tissue damage, imminent loss of plant or ears

Scores recorded as whole numbers only. Final plot score = mean of two independent assessor scores.

3.5.3 Maize Grain Yield

Maize grain yield was assessed at physiological maturity, some 120-125 DAS after the moisture content of the grain had reached around 30-35% stable and the black layer had formed at the bottom of the kernel. To prevent border effects, the harvest was taken from the net plot area, which was two rows of plot area on each side of the plot. Ears from the net plot were hand harvested, counted and weighed. A sub-sample of 10 ears per plot was taken at random and the following data were recorded: weight of grain, weight of cob, and shelling percentage.

The moisture content of grain was measured in a 200 g sub-sample of freshly shelled grain from each plot with a portable digital grain moisture meter (DICKEY-john GAC 2500, USA). This formula was used to adjust yield to 12.5% moisture.

Adjusted Yield (t/ha) = [Fresh grain mass (kg) × (100 – Actual MC%)] / [(100 – 12.5) × Net plot area (m^2)] × 10,000

The yield was reported in tonnes per hectare (t/ha) for comparison with regional and national maize yield standards. Yield component data was collected as supplementary data, harvest index, ear weight.

3.6 Statistical Analysis

Data collected were all analysed by analysis of variance (ANOVA) suitable to the Randomized Complete Block Design (RCBD) approach using GenStat statistical software. The F-test revealed significant difference among treatments at $p \leq 0.05$ and these means were compared with Fisher's Least Significant Difference (LSD) test at 5% probability. For the temporal data (repeated measures across assessment dates), mean comparisons were made using repeated measures ANOVA, to account for the within plot correlation of measurements over time.

CHAPTER FOUR

RESULTS

4.1 Pest Population Density

There were significant differences in treatment at every sampling time. At 21 DAS, P = 0.01 and from 35 DAS onwards, P < 0.001. The untreated control had the most pests throughout the sampling period (T4). Neem oil (T1) had the least pest infestation throughout the trial with 1.426 insects/plant at 63 DAS. The intermediate values were obtained for insecticidal soap (T2) and garlic extract (T3) at 63 DAS with values of 1.803 and 1.867 respectively.

Table 4.1: Effect of organic pesticide treatments on pest population density (insects/plant) across sampling dates

Treatment	21 DAS	35 DAS	49 DAS	63 DAS
Neem Oil	2.841^{c}	2.4^{c}	1.613^{c}	1.426^{c}
Insecticidal soap	2.923^{b}	2.388^{b}	2.028^{b}	1.803^{b}
Garlic extract	2.962^{b}	2.733^{b}	2.113^{b}	1.867^{b}
Control	3.59^{a}	4.476^{a}	4.963^{a}	5.102^{a}
Grand Mean	3.079	2.999	2.679	2.549
P-value	0.01	0.001	0.001	0.001

SED	0.2005	0.2602	0.2231	0.1697
LSD	0.4369	0.567	0.486	0.3698
CV%	10.3	13.7	13.2	10.5

Means in the same column followed by the same letter are not significantly different at $p \leq 0.05$

4.2 Plant Health Indicators

4.2.1 Plant Height (cm)

A marginally significant treatment effect was recorded at 21 DAS ($P = 0.013$), with highly significant differences emerging from 35 DAS onwards ($P \leq 0.001$). Neem oil (T1) produced the tallest plants at all sampling dates, reaching 198.8 cm at 63 DAS. Insecticidal soap (T2) followed closely at 195.2 cm at the same date. The untreated control (T4) consistently produced the shortest plants, recording 165.9 cm at 63 DAS.

Table 4.2: Effect of organic pesticide treatments on plant height (cm) across sampling dates

Treatment	**21 DAS**	**35 DAS**	**49 DAS**	**63 DAS**
Neem Oil	32.36^{a}	69.78^{a}	143.7^{a}	198.8^{a}
Insecticidal soap	32.98^{a}	69.16^{a}	138.9^{b}	195.2^{a}
Garlic extract	31.32^{a}	64.18^{b}	137.8^{b}	191.7^{ab}
Control	27.92^{b}	58.1^{c}	116^{c}	165.9^{c}
Grand Mean	31.14	65.3	134.1	187.9

P-value	0.013	0.001	0.001	0.001
SED	1.365	2.082	3.08	3.36
LSD	2.974	4.535	6.7	7.31
CV%	6.9	5	3.6	2.8

Means in the same column followed by the same letter are not significantly different at $p \leq 0.05$

4.2.2 Percentage Leaf Damage (%)

There was no significant treatment effect on percentage leaf damage at 21 and 35 DAS (P=0.478 and P=0.068 respectively). All the three botanicals had significant less damage than the control 6.808%, P=0.001. At 49 DAS garlic extract recorded significantly lower leaf damage at 5.774% than neem oil 6.012% and insecticidal soap 6.161%. leaf damage decreased over time in all botanical treatments but increased slightly in the control.

Table 4.3: Effect of organic pesticide treatments on percentage leaf damage (%)

Treatment	**49 DAS**	**63 DAS**
Neem Oil	6.012^{b}	5.716^{b}
Insecticidal soap	6.161^{b}	5.812^{b}
Garlic extract	5.774^{a}	5.548^{b}
Control	6.808^{c}	7.047^{c}

Grand Mean	6.189	6.031
P-value	0.001	0.001
SED	0.1996	0.1952
LSD	0.4349	0.4252
CV%	5.1	5.1

Means in the same column followed by the same letter are not significantly different at $p \leq 0.05$

4.3.3 Visual Pest Damage Severity Score

There was no significant treatment effect on visual pest damage severity score at 21 DAS (P=0.804). All organic treatments significantly reduced damage scores compared to the untreated control at 35, 49 and 63 DAS (P=0.001). Damage scores declined progressively from 35 to 63 DAS in all botanical treatments while the control remained consistently high.

Table 4.4: Effect of organic pesticide treatments on visual pest damage severity scores across sampling dates

Treatment	35 DAS	49 DAS	63 DAS
Neem Oil	1.856[a]	1.744[a]	1.555[a]
Insecticidal soap	2.011[a]	1.807[a]	1.666[a]
Garlic extract	1.943[a]	1.678[a]	1.55[a]
Control	2.744[b]	2.758[b]	2.676[b]
Grand Mean	2.138	1.997	1.862
P-value	0.001	0.001	0.001
SED	0.0683	0.1022	0.1744
LSD	0.1488	0.2226	0.3799
CV%	5	8.1	14.8

Based on the range test at $p \leq 0.05$, means followed the same letter on the same column are not different from each other

4.3 Maize Grain Yield

There was a highly significant treatment effect on yield mass of grain (P=0.001). Neem oil recorded the highest yield mass (2.153 t/ha), followed by insecticidal soap (2.045 t/ha) and untreated control recorded the lowest yield mass (1.532 t/ha).

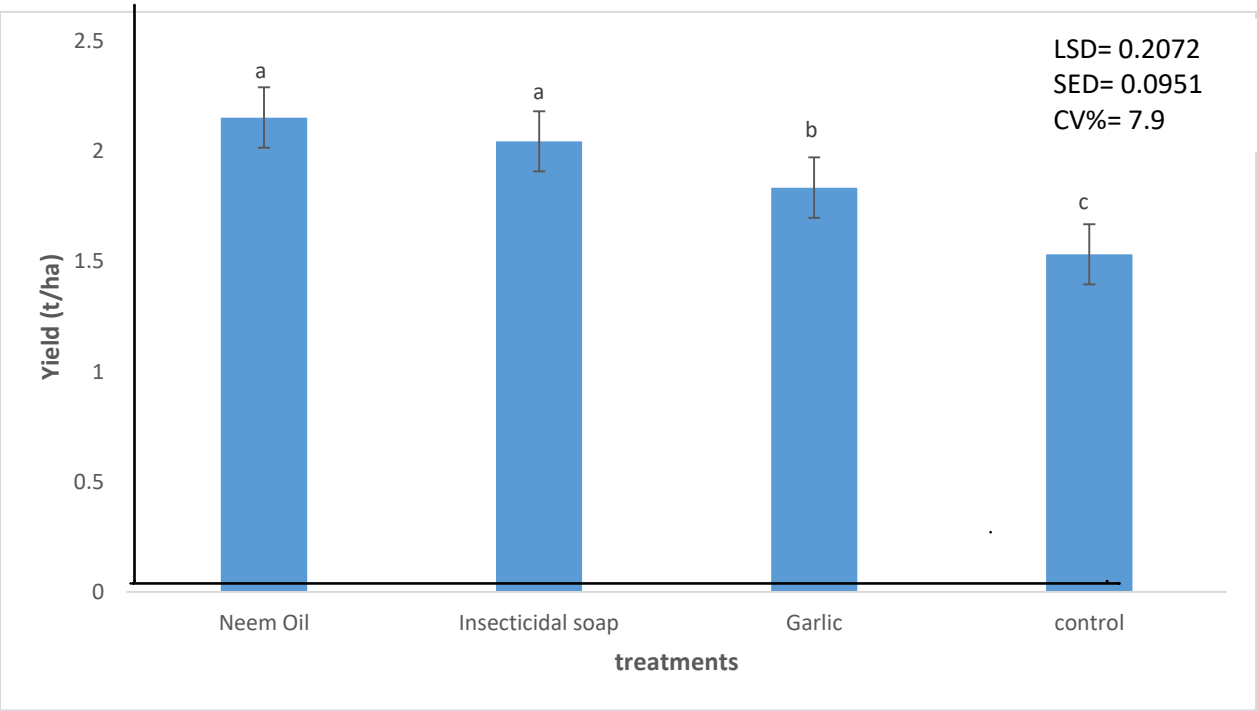


Fig 4.1: Effects of organic pesticide treatments on grain yield mass. Means followed by the same letter are not significantly different at $p \leq 0.05$

CHAPTER FIVE

Discussion

5.1 Effect of Organic Pesticides on Pest Population Density

The findings showed that densities of pests were significantly lower than the untreated control in all three treatments of organic pesticides during the study period. The untreated control had the highest pest density in each sampling date, and also the lowest density of pests throughout all sampling dates for neem oil (Table 4.1).

The effectiveness of neem oil is consistent with the results of Dougoud et al. (2019) who found that neem products effectively decreased fall armyworm populations by 45–68% in all maize production systems in Africa. The activity of neem oil could be explained by the presence of azadirachtin and other bioactive limonoids with these activities, namely as antifeedants, growth regulators, repellents and oviposition deterrents. Neem compounds is different from contact pesticides which only kill the insects on contact, it works on several stages of insect development thus controlling both current and future pest populations.

Insecticidal soap and garlic extract also contributed significantly in pest reduction as compared to control, but not as much as neem oil. The moderate effectiveness of this insecticidal soap can be attributed to its contact mode of action where direct contact with pests is needed for the insecticidal soap to kill them. Insecticidal soap cannot control concealed insect pests like fall armyworm larvae in maize whorls because of the lack of residual activity (Lawson, 2007).

Garlic extract also decreased the insect population, as observed by Ogah et al. (2017) garlic has insecticidal and repellent activities that help to control maize pests. The production of volatile sulphur compounds in garlic are likely to have inhibited feeding and oviposition, and thus reduced establishment of pests. The relatively low performance, however, may be attributed to the quick breakdown of active components under the high temperatures typical of semi-arid environments during application.

The increase in pest numbers in untreated control confirms that active pest management is crucial for maize production. In the absence of intervention, pest populations continued to increase in the plots and even surpassed the findings in treated plots indicating that maize pests can increase rapidly in favorable environmental conditions and inflict heavy crop damage as reported by Chikosi et al. (2020).

5.2 The height of plants from the impact of organic pesticides

Significant treatment effects were observed on plant height from 35 DAS onwards. Neem oil gave the tallest plants during the whole study period, followed closely by insecticidal soap and garlic extract, whereas the untreated control had the shortest plants throughout the study period (Table 4.2).

Increased plant height in treated plots may be attributed to less pest attack. This reduced feeding injury reduced the plant's resources that had to be used to recover from stress. The results corroborate Hruska and Gould (1997) who found that pests limit the growth of maize by injuring the apical meristem and decrease the photosynthetic leaf area.

Plants treated with neem oil had the highest growth in comparison with the least pest density observed in the same treatment. It implies that other than direct pest suppression effects,

increased vigor of plants was directly correlated with effective pest suppression. Reduced incidence of pests enhanced vegetative growth relationships have also been reported for maize systems where pest management interventions were effective in ensuring that plants were not exposed to pests during critical growth stages.

The marked decrease in plant height in the untreated control is a combined effect from feeding by the pests during the season. The degree of insect damage being continuous was probably affecting photosynthetic capacity, nutrient assimilation and overall plant development with stunted growth. In Zaka District with its semi-arid climate, plant growth is already constrained by moisture stress and further growth reductions are caused by pests.

5.3 The effect of organic pesticides on percentage leaf damage

There was no significant treatment difference during the early growth phase but significant difference was observed at 49 and 63 DAS. All the organic treatments recorded significantly less percentage leaf damage than the untreated control at 49 DAS, with garlic extract showing the least damage (Table 4.3).

Slower treatment differences may be due to the relatively low pest pressure in the early establishment of the crop. However, more differences between treatments emerged as the pest populations grew as the crop aged. This is in line with what Mgoo et al. (2020) observed that the effects of pest management increases with increasing pest numbers throughout the growing season.

The lower leaf damage observed under garlic extract could be due to the high repellent activity of garlic extract, which could have deterred feeding of the foliar pests. Sulphur compounds

derived from garlic have also been found to disrupt the insect host location behavior and feeding activity, thereby decreasing damage to plant tissues.

Leaf damage was reduced in all treatments with organic pesticides versus the control, with pest suppression resulting in better protection of the crop. The untreated control on the other hand had progressive leaf damage over time, which suggests continued pest feeding activity. The results confirm Prasanna et al. (2021) who claimed that pest attack may result in significant losses of leaf tissues in maize and also lower photosynthetic efficiency.

5.4 The effects of organic pesticides on visual pest damage severity scores

The data indicated that in the 35 days after sowing (DAS) onwards the organic pesticide treatments caused significant reductions in the severity scores of the visual estimates of the level of pest damage. The neem oil, insecticidal soap and garlic extract all gave significantly lower damage scores compared to the untreated control (Table 4.4).

The decrease in the severity of the damage indicates the effectiveness of treatments in controlling the pest populations prior to the development of severe feeding injury. Reduced damage scores mean plants are healthy with more functioning leaf area and less interference with plant physiological processes. This result is corroborated by Sola et al. (2014) and Mgoo et al. (2020) who reported strong correlation between decreased pest infestation and decreased damage ratings of maize.

There were no significant differences among the three organic pesticide treatments, despite the differences in numbers of pests. This indicates that the three treatments were effective in keeping the pests at levels below economic injury. For a farmers' point of view, this result suggests that they can attain a satisfactory level of control with any of the organic pesticides tested.

The damage rating was consistently high with the control treatment, thus verifying the negative impact of unmanaged pest problems. The feeding damage caused by persistent feeding may have resulted in a decrease in plant growth and hence in grain yield.

5.5 The effect of organic pesticides on maize grain yield

The best measure of the economic return of pest management interventions is maize grain yield. The result showed that the effect of the treatment on grain yield was very significant; the highest grain yield was obtained from neem oil (2.153 t/ha), followed by insecticidal soap (2.045 t/ha) and garlic extract. The untreated control yielded the least amount of 1.532 t/ha (Figure 4.1).

The superior performance in terms of grain yield following neem oil treatment is well matched with its efficacy in decreasing densities of pests and keeping the plants healthy. This result corroborates with the previous studies by Ogah et al. (2017) and Dougoud et al. (2019) which found that significant yield improvements have been achieved as a result of neem based pest management interventions.

The increased yields obtained in the treated plots indicate the importance of proper pest control in maintaining photosynthesis, biomass accumulation and allocation of assimilates to grain production. Minimized losses due to leaf destruction, stem damage and nutrient depletion as a result of reduced pest pressure throughout the growing season.

Insecticidal soap and garlic extract gave slightly lower yields than neem oil but they both were significantly better than the untreated control. This indicates that semi-arid maize production systems can benefit from yield in terms of the use of organic pesticides. The results also indicate that there is scope for increasing farm productivity for resource constrained farmers using locally available organic pest management techniques.

The low yield of the untreated control is the result of all the negative effects on plant growth and grain formation due to the pest infestation. This yield loss has been reported by Chikosi et al. (2020) who reported significant maize losses in unmanaged fields in Zimbabwe.

CHAPTER SIX

Conclusions and Recommendations

6.1 Conclusion

- From the results of this study it is observed that under the semi-arid conditions of Zaka District, the density of maize pests was significantly reduced by using organic pesticide than the untreated control. The organic pesticide treatments with neem oil produced the lowest pest population densities, throughout the study period. Organic pesticide applications had a beneficial effect on plant health with increases in plant height and decreases in both percentage leaf damage and visual pest damage severity scores. All organic pesticide treatments were significantly superior to the untreated control in improving maize grain yield, which showed their potential in improving productivity within smallholder maize production systems. Neem oil generated the maximum yield of grain, reflecting its effectiveness in suppressing pests and thus creating an improvement in crop performance and productivity. Also, insecticidal soap and garlic extract showed good pest management and yield advantage and could be used as alternative to neem oil when it is not available. The study validates the potential for the use of organic pesticides in maize production in Zimbabwe's semi-arid region within integrated pest management programmes.

6.2 Recommendations

To farmers

- To use neem oil with preference as an organic pesticide for maize pest management, which is more efficient in reducing pest population and boosting grain yield.
- Where neem oil is not available or cost of neem oil is high, consider insecticidal soap and garlic extract.
- Organic pesticides should be used early in the crop growth cycle, before populations of pests have reached damaging levels.
- Use organic pesticides in combination with other IPM strategies (field sanitation, proper planting time, crop rotation, and destruction of crop residues) to make use of organic pesticides more effective.
- To Researchers
- Critically assess the economic cost-benefit analysis of neem oil, insecticidal soap and garlic extract in farming by small farmers.
- Study of Integrated Pest Management (IPM) using organic pesticides and biological control agents.
- Compare the effectiveness of organic pesticides under various maize varieties and agro-ecological regions in Zimbabwe.
- Conduct research on the best rates and intervals for applying organic pesticides in an arid environment to optimize effectiveness and profitability for farmers.
- To Policymakers
- The promotion of locally available organic pest management technologies should be encouraged as part of the efforts of the government and development agencies towards climate smart agriculture.

- There should be neem tree policy which promotes farming and conservation of neem trees in rural communities and farmers for better access to neem-based products.
- Investments should be put into farmer education programmes which encourage environmentally friendly pest control measure.

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Appendix

Appendix 1: Analysis of variance

Variate: Pest_population_denisity_at_21_D

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.1426	0.0357	0.35	
Block.*Units* stratum					
Treatment	3	1.7783	0.5928	5.90	0.010
Residual	12	1.2065	0.1005		
Total	19	3.1275			

Appendix 2: Analysis of variance

Variate: Pest_population_denisity_at_35_D

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.3671	0.0918	0.54	

Block.*Units* stratum					
Treatment	3	14.9181	4.9727	29.37	<.001
Residual	12	2.0316	0.1693		
Total	19	17.3168			

Appendix 3: Analysis of variance

Variate: Pest_population_denisity_at_49_D

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.6343	0.1586	1.27	
Block.*Units* stratum					
Treatment	3	35.4958	11.8319	95.11	<.001
Residual	12	1.4929	0.1244		
Total	19	37.6231			

Appendix 4: Analysis of variance

Variate: Pest_population_denisity_at_63_D

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.33433	0.08358	1.16	
Block.*Units* stratum					
Treatment	3	44.00891	14.66964	203.75	<.001
Residual	12	0.86398	0.07200		
Total	19	45.20721			

Appendix 5: Analysis of variance

Variate: Plant_height_at_21_DAS

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	40.357	10.089	2.17	

Block.*Units* stratum					
Treatment	3	76.374	25.458	5.47	0.013
Residual	12	55.879	4.657		
Total	19	172.610			

Appendix 6: Analysis of variance

Variate: Plant_height_at_35_DAS

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	14.19	3.55	0.33	
Block.*Units* stratum					
Treatment	3	440.32	146.77	13.55	<.001
Residual	12	130.00	10.83		
Total	19	584.51			

Appendix 7: Analysis of variance

Variate: Plant_height_at_49_DAS

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	255.67	63.92	2.70	
Block.*Units* stratum					
Treatment	3	2284.95	761.65	32.19	<.001
Residual	12	283.96	23.66		
Total	19	2824.58			

Appendix 8: Analysis of variance

Variate: Plant_height_at_63_DAS

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	27.13	6.78	0.24	

Block.*Units* stratum					
Treatment	3	3337.34	1112.45	39.51	<.001
Residual	12	337.83	28.15		
Total	19	3702.30			

Appendix 9: Analysis of variance

Variate: Leaf_damage_at_21_DAS_1

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.11011	0.02753	0.52	
Block.*Units* stratum					
Treatment	3	0.14124	0.04708	0.88	0.478
Residual	12	0.64024	0.05335		
Total	19	0.89159			

Appendix 10: Analysis of variance

Variate: Leaf_damage_at_35_DAS_2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.12485	0.03121	0.33	
Block.*Units* stratum					
Treatment	3	0.86510	0.28837	3.09	0.068
Residual	12	1.12101	0.09342		
Total	19	2.11096			

Appendix 11: Analysis of variance

Variate: Leaf_damage_at_49_DAS_3

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.24111	0.06028	0.61	
Block.*Units* stratum					
Treatment	3	2.94121	0.98040	9.84	0.001
Residual	12	1.19512	0.09959		
Total	19	4.37744			

Appendix 12: Analysis of variance

Variate: Leaf_damage_at_63_DAS_4

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.20945	0.05236	0.55	
Block.*Units* stratum					
Treatment	3	7.05897	2.35299	24.71	<.001
Residual	12	1.14253	0.09521		
Total	19	8.41096			

Appendix 13: Analysis of variance

Variate: Damage_score_at_21_DAS_1

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	4.572	1.143	0.61	

Block.*Units* stratum					
Treatment	3	1.859	0.620	0.33	0.804
Residual	12	22.566	1.880		
Total	19	28.996			

Appendix 14: Analysis of variance

Variate: Damage_score_at_35_DAS_2

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.09395	0.02349	2.01	
Block.*Units* stratum					
Treatment	3	2.50495	0.83498	71.62	<.001
Residual	12	0.13989	0.01166		
Total	19	2.73879			

Appendix 15: Analysis of variance

Variate: Damage_score_at_49_DAS_3

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.

Block stratum	4	0.13964	0.03491	1.34	
Block.*Units* stratum					
Treatment	3	3.90695	1.30232	49.92	<.001
Residual	12	0.31306	0.02609		
Total	19	4.35965			

Appendix 16: Analysis of variance

Variate: Damage_score_at_63_DAS_4

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.31591	0.07898	1.04	
Block.*Units* stratum					
Treatment	3	4.46016	1.48672	19.56	<.001
Residual	12	0.91208	0.07601		
Total	19	5.68816			

Appendix 17: Analysis of variance

Variate: Grain_yield_t_ha

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	4	0.11757	0.02939	1.30	
Block.*Units* stratum					
Treatment	3	1.12221	0.37407	16.55	<.001
Residual	12	0.27119	0.02260		
Total	19	1.51097			