

**SUPPRESSIVE EFFECTS OF SUNFLOWER
(*HELIANTHUS ANNUUS* L.) ON LOCAL RAIN-FED
WEEDS IN ZAMBIA**

BY

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DECLARATION

I, Tamala Tonga Kambikambi, declare that this dissertation represents my own work and that it has not been previously submitted for a degree at this or any other University.

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APPROVAL

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DEDICATION

This is in memory of my mum and dad for the faith they had in me. I also dedicate it to my daughters Manda and Musonda.

ACKNOWLEDGEMENTS

I wish to graciously acknowledge with a deep sense of devotion and thanks my supervisors Professor Olusegun A. Yerokun, Professor Samuel Banda, Dr. David M. N. Mbewe and especially the main one Dr. Mick. S. Mwala for their guidance and unfailing support during the entire period of this work.

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My most sincere gratitude goes to my family especially my two daughters Manda and Musonda who were always there for me. They escorted me to my experimental plots, spurred me on when I was on my last wind and generally just supported me and inspired me to accomplish this task.

Lastly but not the least, to God almighty! May He's name continue to be praised for being the ever present companion in all I do.

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ABSTRACT

One of the constraints to crop productivity is weed infestation. Options in weed management are varied and can be associated with high costs unaffordable by small-scale farmers. Biological weed management through allelopathy presents an attractive option. Sunflower has been reported to possess allelopathic effects. This study was hence initiated with the aim of establishing the weed suppressive potential of sunflower linked to its allelopathic activity with the following strategic objectives: to evaluate weed infestation under different sunflower varieties with maize used as the control; to determine effects of season, location and time of sampling on allelopathic activity measured as weed infestation; and to determine the effects of weeds on yield of the two crops. The study was conducted over two growing seasons at two locations using a Randomized Complete Block Design (RCBD) arrangement with four replications. Six local sunflower varieties (Chongwe, Milika, Saona, Record, PAN7352 and PAN7371) were grown with two local maize varieties (MRI455 and MRI514) included as control, using standard cultural practices. Data were collected on weed diversity and density, weed biomass and crop yield. These data were subjected to Analysis of Variance (ANOVA) with mean separation done using the Least Significant Difference (LSD) method. Multivariate analysis through Principal Component Analysis (PCA) and Cluster Analysis were conducted for the three-way interactions. ANOVA results revealed significant differences for weed density within a season varied across location and time of sampling under both sunflower and maize. The amount of weed biomass that grew under different varieties varied by season, location and time under sunflower and to a greater extent under maize. Weed biomass within location significantly varied across seasons and time of sampling under sunflower and to a lesser degree under maize. Sunflower yields varied significantly between seasons and between locations while maize yields did not. Maize yields however were significantly influenced by the significant interaction between season x location. Both crops had significant variety x season x location interaction. Results for PCA showed the differences in the two crops and within each crop through loading separately for the different principal components. Cluster Analysis revealed the level of similarities between the two crops and within each crop separately through the centroid linkages and the Euclidean distances separating them. These results showed that sunflower varieties interacted with weeds differently from the maize varieties and that both weed density and weed biomass under sunflower were lower than those observed under maize. Further, crop yields for sunflower were marginally lower than the optimum for sunflower as compared to those of maize which were appreciably lower due to the weeds. In conclusion, the study established that indeed there was weed suppression by some of the local sunflower varieties and deduced that this was probably due to the involvement of allelopathy in the interference competition the crop was engaged in with weeds. Weed intensity was higher in maize than in sunflower and this intensity was affected by location, season and time of sampling. On average, sunflower yielded better in the presence of weeds than maize. No varietal differences for weed suppression and yield were observed under maize but these were observed in sunflower and from this the cost incurred by the sunflowers in allelochemical production was deduced. The study recommended that sunflower can be encouraged as an alternative crop for small holder farming since it will grow with reduced weed pressure and lessen the weeding requirement. Breeders should consider the potential cost of allelochemical production on plant metabolic processes so that they can come up with sunflower varieties that have high allelopathic activities without compromising the overall crop yield. Further research in this field is also recommended.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 The problem of weeds

There are numerous definitions of weeds. All of them deal with their impact on human activities in one way or another. Broadly defined, weeds are considered as “*plants growing in places, where they are not wanted*” and rather where another plant is desired to grow. If weeds are defined as “plants growing where they are not wanted”, then clearly, weeds have existed as long as humans have been around not to want them. Some plant species are particularly well adapted to environments disturbed by humans. However, these weeds are more than just anthropocentric entities, and overtime, they have become appreciated also as biological and ecological entities worthy of serious study (Harlan and deWet, 1965; Harper, 1959) and because despite best efforts to manage weeds, they continue to interfere with crop production (Tranel and Horvath, 2009).

Weeds have grown among cultivated crops from the time that systems of food production were developed. They compete with the crops and are a large economic and environmental cost to crop production (Kong, 2010; Broz, 2006; Olofsdotter *et al.*, 2002; Kohli *et al.*, 2001; Parish, 1990). These costs are reflected in the amount of manual labour, tillage and herbicides used to control the weeds. For instance, small scale farmers in the developing countries spend more than 40% of their time on weed control (Akobundu, 1987). Labrada (1992) reported up to 60% labor time spent on weed control in Africa. It is further estimated that even in well managed fields, the competitive effects of weeds result into loss of about 10% of agricultural production (WSSA, 2006). In cases where weed control is not done throughout the season, production losses can increase to 45 – 95% (Chung *et al.*, 2003). In the specific case of Zambia, average losses in production due to weeds of up to 30% have been reported, while complete crop loss can be experienced under heavy weed infestation (Vernon, 1983). Kong (2010) reported that the economic losses that are caused by weeds globally cost billions of dollars every year. This confirms that weeds remain one of the major constraints to agricultural production (Cousens and Mortimer, 1995).

1.2 Weed problem in the Zambian context

The agricultural sector is mainly dominated by millions of small holder farmers in Zambia. Production is very low due to many challenges that include biological weed threats, poor soil fertility, and low use of inputs among other factors. Interventions are therefore needed to

enhance productivity of these small-scale farmers as this would be a useful step towards the sustenance of Zambia's agricultural production as well as poverty alleviation efforts.

Although, there is very little information on weeds in Zambia, Vernon (1983) reported more than 400 plant species found as weeds in the arable lands of Zambia. Fortunately, only some of them are regarded as important; these include *Nicandra physalodes*, *Amaranthus* spp., *Galinsoga parviflora*, *Bidens pilosa*, *Datura stramonium*, *Acanthospermum* spp., *Commelina* spp., *Cyperus* spp., *Cynodon dactylon*, *Eleusine indica*, *Digitaria milaniana*, *Rottboellia conchinchinensis*, *inter alia*. He further reported that these weeds interfere with crops by competing for moisture, carbon dioxide, nutrients and light, which reduces yield quantity and quality (Vernon, 1983).

1.3 Weeds, weed management and control

Weeds are naturally occurring plants in agricultural lands. Consequently, any newly opened forest land has its characteristic weeds. Changes in weed flora and species richness are a result of multiplication of existing weeds and the introduction of new ones into the habitat. Weeds are, however, not crop specific and hence crops will grow with the complement of endemic weeds in the area where they are grown and be affected by them. Therefore, no viable crop production can be practiced without adequate measures of managing them.

Weed management aims at reducing the negative effect of weeds on crop production. A longer term strategy for obtaining a reduced weed plant density is to promote gradual depletion of the soil seed-bank (Bastiaans *et al.*, 2008). Ecologically based weed management relies heavily on a greater integration of cultural, mechanical and biological control tactics than conventional weed management. As such, management outcomes are more dependent on biotic interactions among the crop, weed and methods of management.

Weed control on the other hand relies on the removal or suppression of unwanted plants, so that they cause no (economic) damage. Control efforts are generally directed towards seedlings in the period just prior to, or shortly after, crop establishment since controlling seedlings is often far easier than killing or removing taller and more developed weed plants. Weed plants emerging during later stages of crop development are often considered less important, as their relative competitive ability is too weak to cause a major reduction in the production of the current crop (Bastiaans *et al.*, 2008).

One control method that is in use is biological control. It has already been used successfully as a practical and economically affordable weed control method in many situations (Shiraishi *et al.*, 2002; Caamal-Maldonado *et al.*, 2001). Biological control options are receiving a lot of attention because of their potential to maintain sustainability in agriculture and for the protection of natural resources. One area with potential for biological control of weeds is the use of allelopathic effects of both weeds and plant crops (Kruse *et al.*, 2000). This method has received new interest because it is an environmentally compatible method of weed control which does not

cause pollution. This is because the mechanisms rely upon allelopathic reactions which specifically target weeds.

Allelopathy, the chemical interaction which occurs when different plant species grow in close vicinity of each other or with plant residues, can cause inhibition, or promote growth (Kong, 2010; Tet-Vun and Ismail, 2006; Khanh *et al.*, 2005; Kobayashi, 2004; Wu *et al.*, 1999; Rice, 1984). This phenomenon permits ecological weed management (Tabaglio *et al.*, 2008; Kruse *et al.*, 2000; Alsaadawi, 1987; Rice, 1984; Putnam *et al.*, 1983). Such an allelopathy-based weed management technique is being developed for sustainable agriculture in low-input crop farming systems that are prevalent throughout China and other Asian countries (Kong, 2010). Kobayashi (2004) and Kohli *et al.* (1998) also reported that allelopathy is a novel approach to keeping the environment safe and developing sustainable agriculture with the latter showing that the exploitation of allelopathy in plant agricultural practice as tool for weed control helps to reduce weeds, prevent pathogens and enrich soils.

Although allelopathy has long been recognized to influence plant-plant interactions in natural communities (Milchunas *et al.*, 2011), it is only the discovery that it can be a viable component of crop/weed interference that prompted the idea of exploiting this phenomenon to manage weeds. Putnam and Duke (1974) first proposed the possibility of utilization of allelopathic crops to suppress weed growth in agricultural sites, and described the potential utilization of rotational crops, intercrops, or cover crops for practical weed control. Weston and Duke, (2003) and Weston, (1996) indicated that strategies to use allelopathy for weed control could comprise the use of phytotoxic crop residues or mulches, as well as phytotoxins released by intact roots of living crop plants. The latter is often denoted by the term “crop allelopathy” and considered the most promising approach to exploit allelopathy in annual crops (Duke *et al.*, 2005).

There are many crop species known to possess allelopathic activities. The key is to identify these crop species and varieties and recommend a cropping system that will incorporate their use in the farming systems available. Some of the crop species that have been investigated for allelopathic activities include alfalfa (*Medicago sativa* L.), barley (*Hordeum vulgare* L.), clovers (*Trifolium* spp. and *Melilotus* spp.), oats (*Avena sativa* L.), pearl millet (*Pennisetum glaucum* (L.) R. Br.), rice (*Oryza sativa* L.), rye (*Secale cereale* M. Bieb.), sorghums (*Sorghum* spp.), sunflower (*Helianthus annuus* L.), sweetpotato (*Ipomea batatas* (L.) Lam.) and wheat (*Triticum aestivum* L.) (Kruse *et al.*, 2000).

Sunflower, *Helianthus annuus* L., is a member of the Asteraceae family, a large and successful family of flowering plants occurring throughout the world with a few species of economic importance (Weiss, 1983). It is a tall, erect, unbranched, coarse annual with a distinctive large golden head. The seeds are often eaten or crushed for their oil (Heisler, 1986; Weiss, 1983). It is one of the major annual crops grown for its edible oil in the world (Kaya *et al.*, 2006; Knowles, 1978) and contains unsaturated fatty acids with no cholesterol and is hence in demand (Amala-

Balu *et al.*, 2005). In Zambia, it is also an important rotation crop (Mwala, 1997) and is recommended for inclusion in conservation and other local farming systems.

Sunflower's allelopathic potential has been reported by Kato *et al.* (2005), Semidey (1999) and Robinson (1978). Rice (1984) observed that there was a striking pattern of how herbaceous weeds were distributed around sunflower plants. It was also reported that sunflower plots tended to have fewer weeds and the weeds that were present had lower biomass even in the absence of herbicide applications (Semidey, 1999; Morris and Parish, 1992; Leather, 1987). Therefore, sunflower offers potential for biological weed control through the production and release of allelochemicals from living and decomposing plant materials (Weston, 1996).

1.4 Statement of the Problem

The use of allelopathy for weed control has received a great deal of attention elsewhere but not in Zambia. This work hence sought to explore that possibility. Sunflower was chosen among the many known allelopathic crops because it is a well known and commonly grown crop in Zambia with several commercially available varieties.

1.5 Objectives

1.5.1 Overall objective

To establish the weed suppressive potential of sunflower linked to its allelopathic activity

1.5.2 Specific objectives

- i) To evaluate weed infestation under different sunflower varieties with maize used as the control;
- ii) To determine the effects of season, location and time of sampling on allelopathic activity as measured by weed infestation; and
- iii) To determine the effects of weeds on yield of the two crops.

1.6 Hypotheses

1.6.1 Research hypothesis

Some sunflower varieties cultivated in Zambia can suppress weed growth using allelopathic effects.

1.6.2 Statistical hypotheses

H_0 : Zambian sunflower varieties do not possess allelopathic effects suitable for weed control

H_a : Zambian sunflower varieties possess allelopathic effects suitable for weed control

CHAPTER TWO

2.0 CONCEPTUAL FRAMEWORK

2.1 Towards finding sustainable weed management

Since the advent of agriculture, humans have encountered plants that have frustrated their goal to manage their environment. Today, we call the plant pests that interfere with agriculture “weeds”. Weeds pose an important biological constraint to crop productivity and the economic losses that are caused by weeds globally cost billions of dollars every year (Pimentel *et al.*, 2001).

The concept of sustainable agriculture is a relatively recent response to the decline in the quality of the natural resource base associated with modern agriculture (McIsaac and Edwards, 1994). The concept of sustainability although controversial and diffuse due to existing conflicting definitions and interpretations of its meaning is useful because it captures a set of concerns about agriculture which are conceived as a the result of co-evolution of socioeconomic and natural systems (Reijntjes *et al.*, 1992). Therefore, deeper understanding of agricultural systems will open doors to new management options more in tune with the objectives of a truly sustainable agriculture and an ecological approach to agriculture involving the strengths of natural ecosystem into agro-ecosystems (Magdoff, 2007).

2.1.1 Weeds and Crop-Weed interactions

Weeds are an important constraint in agricultural production systems (Oerke, 2006). Acting at the same trophic level as the crop, weeds capture a part of the available resources that are essential for plant growth (Gupta, 2004). Inevitably, leaving weeds uncontrolled will lead to considerable reductions in crop yields. Attempts to control them so far have met with only limited success (Kong, 2010). Figure 2.1 shows that these weeds interact with crops. In a crop-weed interaction, attention is given to the fundamental understanding of the processes governing the interaction (Maxwell and Luschei, 1987) as well as the utilization of this knowledge for improved weed management.

2.1.2 Weed Management and Control

Weed management is the ability to manipulate weeds so that they do not interfere with man’s efficient use of his environment. In relation to agricultural activities, weed management refers to how weeds are manipulated so that they do not interfere with the growth, development and

economic yields of crops. Weed control on the other hand refers to those actions that seek to restrict the spread of weeds, and destroy or reduce their population in a given location. Weed management encompasses all aspects of weed control including prevention of spread, together with those land use practices and modifications in the crop habitat that interfere with the weed's ability to adapt to its environment. In Figure 2.1, weed management is flowing out of crop-weed interactions, signifying that there are some interactions that can be exploited in managing these weeds. The development of some management and control strategies could be done in such a way as to strive toward a future of sustainable agriculture.

2.1.2.1 Biological weed control

Biological control of weeds involves using any organism to reduce or eliminate the detrimental effects of weed populations (Ghosheh, 2005) and meanwhile, host specificity is the primary criterion by which scientists and regulators judge the risk of releasing biological control organisms into new environments (Goeden, 1999; Lym, 1998; Hess, 1994).

Biological weed control is one of the components of weed management (hence its flowing out of weed management in Figure 2.1) and its objective is not to eradicate but to reduce and regulate weed populations below economic injury levels. Biological weed control is a selective, environment-friendly process, utilizing host-specific control agents towards targeted weeds that prevent damage to non-target crops or native plants (Pleban and Strobel, 1998; Bewick, 1996; Rosenthal *et al.*, 1989).

Biological control gained considerable momentum in the 1970s (Charudattan and Dinoor, 2000). Generally, biological control of weeds is practiced through either the classical or augmentative approaches. The classical approach is an ecological approach that involves initial inoculation of weed population with self-sustaining agents (Sheley *et al.*, 1998; Zimdahl, 1993) while the augmentative or inundative approach utilizes bioherbicidal annual application of endemic or foreign agents similar to herbicide application (Goeden, 1999). One measure under augmentative biological control is the use of allelopathy (Lovett, 1991) which involves the synthesis of plant bioactive compounds known as allelochemicals that are capable of acting as natural pesticides (Dayan *et al.*, 2009; Macais *et al.*, 2007). In Fig 2.1, biological control of weeds is flowing out of weed management before it flows into allelopathy since the latter is a facet of biological control.

One interaction that has been reported among biological organisms is amensalism. This is an interaction where one species suffers while the other interacting species experiences no effect. It is of particular interest to weed scientists if the species that is not suffering is the crop. A form of amensalism that has been observed in crop-weed situations is allelopathy. In Fig 2.1, amensalism has been shown as an important crop-weed interaction, whose trophic interactions via a specific means (allelopathy) can lead to sustainable agriculture and ultimately, improved crop production.

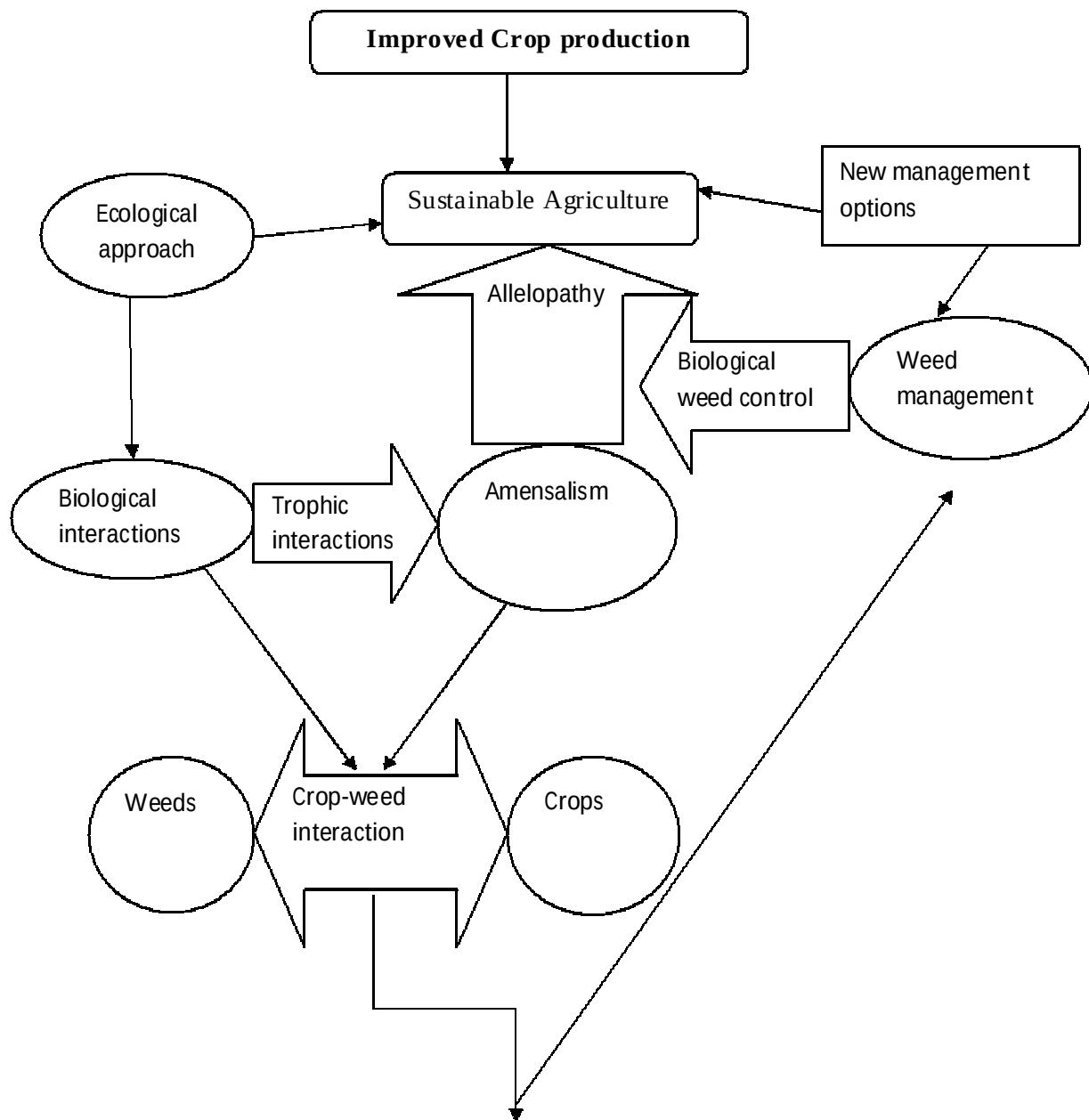


Figure 2.1: Conceptual framework of the study

The exploitation of allelopathic traits of an allelopathic crop may be advantageously taken into consideration for weed suppression, theoretically permitting significant input reductions for weed management.

The discovery that allelopathy can be a viable component of crop-weed interference prompted the idea of exploiting this phenomenon to manage weeds (Farooq *et al.*, 2010). Strategies to this goal comprise the use of phytotoxic crop residues or mulches, as well as phytotoxins released by intact roots of living crop plants (Weston and Duke, 2003; Weston, 1996). The latter is considered the most promising approach to exploit allelopathy in annual crops (Duke *et al.*, 2008; Duke *et al.*, 2005) and was explored in this study.

CHAPTER THREE

3.0 LITERATURE REVIEW

3.1 Crop-weed interactions

3.1.1 Biological interactions

Biological interactions result from the fact that organisms in an ecosystem interact with each other. In the natural world, no organism is an autonomous entity isolated from its surroundings. It is part of its environment, rich in living and non-living elements all of which interact with each other in some fashion. An organism's interactions with its environment are fundamental to the survival of that organism and the functioning of the ecosystem as a whole. In ecology, biological interactions are the relationships between two or more species in an ecosystem. These relationships can be categorized into many different classes of interactions based either on the effects or on the mechanisms of the interaction. The interactions between these species vary greatly in these aspects as well as in duration and strength. Species may meet once in a generation or live completely within another. Effects may range from one species eating the other, to both living together with mutual benefit. The interactions between species need not be through direct contact. Due to the connected nature of ecosystems, species may affect each other through intermediaries such as shared resources or common enemies.

Burkholder (1952) described a wide range of possible interactions that may occur among plants as shown in Table 3.1 below.

Table 3.1: Possible biological interactions among populations of living organisms

No.	Type of interaction	Species		General outcome of interaction
		1	2	
1.	Neutralism	0	0	None of the populations is affected
2.	Competition (direct interference type)	-	-	Direct inhibition of one species by the other e.g. one species produces toxins that inhibit growth of the other species
3.	Competition (resource use type)	-	-	Indirect inhibition when common resource is in short supply
4.	Amensalism	0	-	One population is inhibited, the other is unaffected
5.	Parasitism	+	-	One population, the parasite, generally smaller benefits at the expense of the other (the host)
6.	Predation	+	-	Predator, (generally larger), destroys the smaller prey population
7.	Commensalism	+	0	The commensal benefits while the host is unaffected
8.	Protocooperation	+	+	Interaction is favorable to both but it is not obligatory
9.	Mutualism	+	+	Obligatory interaction favorably affecting both populations

0 = no significant interaction; - = population is inhibited; + = growth, survival or otherwise the population is benefitted

Source: Burkholder, 1952.

Not all the biologically possible types of interactions are applicable to crop-weed associations. Only three of them are. These are parasitism, competition and amensalism (Akobundu, 1987) that involve situations where the crop has negative effects. Predation does not feature in the realm of crop-weed interactions.

3.1.2 Crops and weeds

Whenever a crop is seeded, weeds will also appear. Weeds compete with crops for moisture, light and nutrients, and uncontrolled weeds can stunt crop growth. If only a few weeds are present, yield losses may be small, but heavy weed infestations can cause complete crop failure. The level of yield loss depends not only on the infestation, but also the composition of weed flora. Weeds may also interfere with harvest operations, making the process less efficient. In cases where perennial weeds become established, the land may not be suitable any more for crop production (Gupta, 2004). Weed interference with crops may result from competition or allelopathy (Mallik and Tesfai, 1988).

3.1.3 Parasitism

Parasitism is a relationship where one species, the parasite, benefits at the expense of the other, the host. A parasitic plant is an angiosperm that directly attaches to another plant via a haustorium (Nickrent and Musselman, 2004). Approximately 1% of all angiosperms are parasitic (Kuijt, 1969). A small percentage of these parasitic species infest agricultural crops and cause serious problems for farmers in many parts of the world (Musselman *et al.*, 2001; Parker and Riches, 1993). By far the most economically damaging parasites are *Striga* and *Orobanche* species. *Striga* species are a major pest throughout semi-arid Africa and parts of Asia. They mainly attack cereal crops such as maize, sorghum and pearl millet, but one species *Striga gesnerioides*, attacks legumes. *Orobanche* spp. is a major pest of legumes and vegetables in the Mediterranean basin, Eastern Europe, parts of the former Soviet Union, India and China (Parker and Riches, 1993).

Parasitic weed problems are, to a large extent, the product of demographic and economic pressures where the crisis of sustainability is stretched leading to changes in cropping systems such as loss of natural fallows. Further, parasitic weed problems are just one element in a syndrome of decline in over-stressed agro-ecosystems; so it stands to reason that a series of inter-linked measures are required to reverse the downward spiral of yields and soil fertility (SP-IPM, 2003).

3.1.4 Competition

Competition is defined as the relationship between two or more plants in which the supply of a growth factor falls below their combined demand (Aldrich, 1984). Two types of competition are

identified; resource and interference. Resource competition involves direct acquisition of a growth factor (resource) with no interaction between the adversaries beyond depriving them of that resource (Schoener, 1983). The success of a strategy for resource competition does not depend directly on the state of a competitor, only on the state of the resource. Resource competition can maintain diversity if availability varies in time or space (Chesson, 2000) and if trade-offs exist in the ability to acquire the resource when it is abundant or rare (Stewart and Levin, 1973).

In contrast, strategies for interference competition target competitors themselves, rather than a resource (Park, 1962). Interference competition thus often requires additional activities to those needed for resource competition and the success of a strategy for interference competition depends on the state of the competitor (Amarasekare, 2002) such as that via allelopathy (Molisch, 1937) or indirect interspecific interference via abiotic or biotic modification of plant derived soil. For example, the mechanisms facilitating the invasion of exotic plants, resulting in the displacement of indigenous flora, are often cited as direct or indirect resource and interference competition (Amarasekare, 2002; Williamson, 1996).

3.1.5 Amensalism

Amensalism is a type of plant interaction in which growth of one plant species is affected while the other plant species is not adversely affected (Aldrich, 1984). A type of amensalism where a given plant species releases a chemical that adversely affects the growth of another plant species that shares a habitat with it is called allelopathy.

3.1.5.1 Allelopathy

Allelopathy is a phenomenon observed in many plants that release chemicals into the near environment either from their aerial or underground parts in the form of root exudation, leaching by dews and rains, and volatilization or decaying plant parts. The released chemical compounds into the environment act on other organisms, such as weeds, other plants, animals and microorganism, by inhibitory or excitatory ways. These chemicals may accumulate and persist for a considerable time, thereby imparting significant interference on the growth and development of neighboring weeds and plants (Putnam and Duke, 1974). Allelopathy also involves the interaction among plants, fungi, algae and bacteria with the organisms living in a certain ecosystem, interactions that are mediated by the secondary metabolites produced and exuded into the environment. Intraspecific allelopathy has also been postulated where

autotoxicity occur when a plant species releases chemical substances that inhibit or delay germination and growth of the same plant species (Putnam, 1985).

Consequently, allelopathy is a multidisciplinary science where ecologists, chemists, soil scientists, agronomists, biologists, plant physiologists and molecular biologists offer their skills to give an overall view of the complex interactions occurring in a certain ecosystem. As a result of these studies, applications in weed and pest management are expected in such different fields as development of new agrochemicals, cultural pest control methods, developing of allelopathic crops with increased weeds resistance etc. (Macais *et al.*, 2007).

Numerous instances of allelopathy have been observed across diverse taxonomic groups including plants (Callaway and Aschehoug, 2000), marine invertebrates (Jackson and Buss, 1975), bacteria (Adams *et al.*, 1979), and yeast (Starmer *et al.*, 1987). Birkett *et al.* (2001) also reported that the effects of allelopathy have been observed in all classes of plants and also microorganisms. The success or failure of allelopathic strategies is thought to depend on the frequency of toxin producers, environmental structure, the cost associated with toxin production, the effect of a toxin on competitor growth, as well as the relative importance of interference competition and resource competition (Frank, 1994). These first two factors have been investigated experimentally by Chao and Levin (1981), who showed that the fate of an interfering competitor can depend critically on its frequency. Interfering bacteria that produced an anti-competitor toxin were allowed to compete against bacteria that were sensitive to the toxin and did not produce it. Toxin producers grew more slowly than sensitive strains because of the costs associated with toxin production, but in certain conditions the interfering strain could invade.

Among the plants, numerous of them have been reported to possess inhibitory effects on the growth and population of neighboring or successional plants by releasing allelopathic substances into the environment (Einhellig, 1996; Inderjit, 1996; Putnam and Tang, 1986). For example, hairy vetch (*Vicia villosa*) (Fujii, 2001), Mexican sunflower (*Tithonia diversifolia*) (Tongma *et al.*, 2001), itch grass (*Rottboellia conchinchinensis*) (Kobayashi *et al.*, 2008), alfalfa (*Medicago sativa*) and kava (*Piper methysticum*) (Xuan *et al.*, 2003) showed promising results for weed control. Several other cases of highly suppressive crops are reported in the literature, and include both annual and perennial crops such as alfalfa (*Medicago sativa* L.), buckwheat (*Fagopyrum esculentum* Moench.) (Xuan and Tsuzuki, 2004), black mustard (*Brassica nigra* L.) (Xuan *et al.*, 2004), and sunflower (*Helianthus annuus* L.) (Azania *et al.*, 2003; Leather, 1983), and the sensitivity of cereals seeded after this crop has largely been documented (Leather, 1983).

The challenge remains as to which allelopathic plants should be selected. The preliminary requirements in determining which plants should be collected for screening include:

- i) The plants that have less natural weed density in their canopy and surroundings compared with the other plants in their ecosystem (Xuan *et al.*, 2005);

- ii) The plants that are traditionally used as medicinal plants because of their bioactive natural product content. This is because previous results have confirmed that it is easier to screen allelopathic plants from medicinal plants than other plants (Laosinwattana *et al.*, 2009; Batish *et al.*, 2007; Fujii *et al.*, 2003).

Macaïs *et al.* (2007) proposed that the following guidelines should fit any reported case of allelopathy:

- i) Plant dominance/distribution/frequency cannot be explained solely on the basis of physical/biotic factors;
- ii) The allelopathic plants (donors) should synthesize and release into the environment chemicals that must be or become bioactive;
- iii) Soil permanence and concentrations should be high enough to produce effects on the germination and/or growth of neighboring plants, bacteria or fungi;
- iv) Uptake by the target plant and evidence of the detrimental/beneficial effects caused by the chemical(s).

Decomposition of plant residues has been observed to release secondary metabolites that exhibit phytotoxic effects on other plants (Kohli *et al.*, 2001; Mason-Sedun, 1986; Rice, 1984). The potential phytotoxicity is dependent on numerous factors that together govern the rate of residue decomposition, the net rate of active allelochemicals production and the subsequent degrees of phytotoxicity. These factors could be basically classified into three main categories:

- i) Amount and composition of plant residues;
- ii) The environment in which plant residues are decomposing; and
- iii) Management practices.

Each category consists of factors having definite and specific meaning, i.e., residue type and quantity are factors in the category of plant residues; temperature, moisture, aeration, soil texture, inorganic ions, and pH are environmental factors; while decomposition time, residue placement, and weathering are factors classified in management practices.

Allelopathic crops, when used as cover crops, mulch, smother crops, intercrops or green manures, or grown in rotational sequences, can combat biotic stresses such as weed infestation, insect pests and disease pathogens and additionally build up fertility and organic matter status of soil, thereby reducing soil erosion, and improve farm yields (Jabran *et al.*, 2007; Khanh *et al.*, 2005). Therefore, allelopathy may be exploited profitably in many ways.

Allelopathic crops or crop by-products offer the potential for integrated weed management, which is particularly attractive as an environmentally responsible opportunity for pest management (Belz, 2007). Allelopathic cover crops have also proven beneficial, especially in no-tillage crop systems, by reducing weed populations (Blum *et al.*, 2002). Allelopathic crop species gained attention for their ability to reduce weed species growth in crop agriculture

settings (Singh *et al.*, 2003). Since varietal differences of crops against weeds were discovered in the 1970s, research groups worldwide have identified several crop species possessing potent allelopathic interference mediated by root exudation of allelochemicals with rice, wheat, barley and sorghum attracting most attention (Belz, 2007). Selection for superior genotypes with allelopathic potential has been carried out in several field crops, and evidence has accumulated that crop cultivars differ significantly in their ability to inhibit the growth of certain weed species. The identification of cultivars with high allelopathic activity and the transfer of such a characteristic into modern cultivars could restore a property that has inadvertently been lost during the process of breeding for higher growth rate and yield. Once the allelopathic genes have been located, a breeding program could be initiated to transfer the genes into modern cultivars to enhance their allelopathic activity for weed suppression, thereby reducing over-reliance on herbicides (Wu *et al.*, 1999).

In depth understanding of the mechanisms of allelopathic interference in cropping systems can develop new, environmentally safe strategies for sustainable agriculture (Kong *et al.*, 2006). Further implications of allelopathy could use germplasm of allelopathic plants to select for improved cultivars providing season-long weed suppression, thus requiring fewer herbicide applications (Weston, 1996). With environmental fate of pesticides atop public concern, allelopathy will likely gain additional attention now and in the future. Allelopathy has been accepted as a viable option in recent years, for reducing herbicide use to obtain eco-friendly and cost-effective weed control (Farooq *et al.*, 2010; Jamil *et al.*, 2009; Jabran *et al.*, 2007; Khanh *et al.*, 2005).

3.2 Allelopathy research

3.2.1 Research efforts

Past research focused on germplasm screening for elite allelopathic cultivars and the identification of the allelochemicals involved. Based on this, traditional breeding efforts were initiated in rice and wheat to breed agronomically acceptable, weed-suppressive cultivars with improved allelopathic interference. Later on, molecular approaches have elucidated the genetics of allelopathy by QTL mapping which associated the traits in rice and wheat with several chromosomes and suggested the involvement of several allelochemicals.

Potentially important compounds that are constitutively secreted from roots have been identified in several crop species. Biosynthesis and exudation of these metabolites follow a distinct temporal pattern and can be induced by biotic and abiotic factors. The current state of knowledge suggests that allelopathy involves fluctuating mixtures of allelochemicals and their metabolites as regulated by genotype and developmental stage of the producing plant, environment,

cultivation and signaling effects, as well as the chemical or microbial turnover of compounds in the rhizosphere.

Functional genomics is being applied to identify genes involved in biosynthesis of several identified allelochemicals, providing the potential to improve allelopathy by molecular breeding. The dynamics of crop allelopathy, inducible processes and plant signaling have gained growing attention. Future research should, however, also consider allelochemical release mechanisms, persistence, selectivity and modes of action, as well as consequences of improved crop allelopathy on plant physiology, the environment and management strategies. Creation of weed-suppressive cultivars with improved allelopathic interference is still a challenge, but traditional breeding or biotechnology should pave the way (Belz, 2007).

Another characteristic of past crop allelopathy research efforts has been a one-sided view of the phenomenon, focusing only on the crop and its phytotoxins rather than any interaction. The genetic improvement of allelopathic traits was considered an essential pre-requisite for the practical application of crop allelopathy for weed control, and thus most emphasis was laid on the development of commercial weed-suppressive cultivars with improved allelopathic activity. For this purpose, large screenings were initiated to identify highly efficient allelopathic donor plants that could be used in breeding programs and to identify the active allelochemicals. However, under field conditions, allelopathy does not occur independently of other mechanisms of plant interference; and therefore, the interference outcome of a cultivar is a combined effect of allelopathy and competitive ability (Olofsdotter *et al.*, 1999).

Field experiments offer the possibility to overcome three main drawbacks of laboratory and glasshouse tests. First, they test if toxic substances accumulate at sufficient concentrations or if they persist long enough in natural soils to inhibit the growth of other plants. Second, toxic effects are tested on coexisting species that can vary in their sensitivity to allelochemicals. Third, they permit exploration of spatio-temporal patterns of the variation in allelochemical effects (Jose and Gillespie, 1998; Zackrisson and Nilsson, 1992). The ecological importance of any given allelochemical compound is likely to be highly dependent on its spatio-temporal variability in natural communities.

Allelopathy is mediated by many different types of compounds called allelochemicals, with different sites and modes of biochemical actions (Zeng *et al.*, 2001; An *et al.*, 1993). These allelochemicals can be utilized for weed control as they can suppress plant growth and regulate species diversity in the natural habitat of the producer plant (Kokalis-Burelle and Rodriguez-Kabana, 2006; Weston, 2005; Hirai, 2003).

3.2.3 Use of crop residues

Allelopathic compounds released from cover crop residues during decomposition can reduce both emergence and growth of weeds. Allelochemicals can be released either through leaching, decomposition of residues or volatilization (Inderjit *et al.*, 2001; Duke *et al.*, 2000; Chou, 1999; Wardle *et al.*, 1992; Quasem and Hill, 1989). Kohli *et al.* (2001) and Takeuchi *et al.* (2001) stipulated that these chemicals may reach the receiver plants in various ways, including leaching from plant foliage, exudation from the roots, and decomposition of dead residues of the donor plant. To achieve consistent results in the field from the use of cover crop residues, it is important to understand the mechanisms involved (Diab and Sullivan, 2003).

Weed suppressive effects of cover crop residues have been explained by different mechanisms including initial low nitrogen availability following cover crop incorporation (Kumar *et al.*, 2008; Liebman and Mohler, 2001; Dyck and Liebman, 1994), mulch effects (Mohler, 1996; Mohler and Teasdale, 1993; Mohler and Callaway, 1991), stimulation of pathogens or predators of weed seeds (Gallandt *et al.*, 2005; Davis and Liebman, 2003; Conklin *et al.*, 2002; Carmona and Landis, 1999; Kremer, 1993), and allelopathy (Chou, 1999; Weston, 1996).

One approach to understanding the allelopathic effects of cover crop residues is to separate soil effects occurring during the growth of cover crops from residue effects occurring after incorporation. This is so because allelopathy in the soil is a complicated phenomenon that is affected by soil conditions, growth conditions of the donor and receiver plants and climatic conditions. Allelochemicals in the soil are adsorbed on soil solids, and metabolized by chemical and biological reactions during the movement in the soil (Duke *et al.*, 2000; Wardle *et al.*, 1992; Qasem and Hill, 1989). This behavior is affected by various soil factors, such as soil physical (texture, moisture), chemical (inorganic ions, organic matter), and biological (microorganisms) properties, which affect the phytotoxic activity in soil (Kobayashi, 2004; Inderjit, 2001).

Inderjit *et al.* (2001) reported that the application of plant residues to the soil were closer to field conditions than the application of aqueous extracts, as seen from a case study on allelopathy. Kobayashi (2004) pointed out that the phytotoxic activity of allelochemicals is affected by soil factors, usually leading to a decrease in their activity that is much less than that obtained in non-soil conditions.

3.2.4 Testing allelopathy and its challenges

Experimental approaches to study allelopathy are complicated by the many possible interaction effects that can occur in the field, including indirect effects of plant allelochemicals on microorganisms and the microbial degradation of plant allelochemicals to less or more toxic

substances (Inderjit, 2005; Weidenhamer and Romeo, 2004). Experimental designs for the study of allelopathic interactions remain an area of active critique, with measurement of allelochemicals concentrations in soil being particularly problematic (Weidenhamer, 2007, 1996; Inderjit and Callaway, 2003).

An issue of concern voiced out by researchers working on allelopathy is that field experiments to prove the presence of allelopathic effects are difficult if not impossible to design and conduct. On the other hand, many laboratory bioassays do not adequately predict the growth responses observed at field scale. In fact, it is difficult to design a bioassay that can be used profitably to examine growth responses uniformly across all species. Therefore, when assessing allelopathic potential, phytotoxicity and growth response should potentially be evaluated through the use of multiple experiments and bioassay systems. Despite the problems in studying and defining allelopathic activities, modes of action of allelochemicals, and their interactions in natural settings, important progress has been made to support the further use of allelopathy in agroecosystems for weed management (Weston, 1996).

The majority of past crop allelopathy research has focused on rice, where the shortage of labor for hand weeding and water for flooding led to a rapid increase in herbicide use. The associated evolution of herbicide resistance and social and environmental problems are repeatedly stated as reasons for the need to exploit allelopathy as an alternative weed management option in rice (Duke *et al.*, 2005; Gearly *et al.*, 2003; Olofsdotter, 1998).

3.2.4.1 *Allelopathy research in sunflower*

Sunflower is listed among the species that exhibit strong allelopathic activity towards both weeds and crops (Azania *et al.*, 2003; Batish *et al.*, 2002; Waller and Einhellig, 1999; Semidey, 1999; Leather, 1983; Schon and Einhellig, 1982). The allelopathic potential of sunflower has been well studied (Weston and Duke, 2003), with many allelochemicals identified that are responsible for the inhibitory action. Leather (1987) showed that weed suppression by sunflower was as effective as using herbicides S-ethyl dipropyl carbomothioate (EPTC) in sunflower fields.

Macaïs *et al.*, (1999) and Leather (1983a) showed great genotypic differences in allelopathic activity among 13 and 26 genotypes of sunflower, respectively. Sunflower is suppressive against quite a broad range of weeds which is a desirable character for application in practice (Azania *et al.*, 2003; Macaïs *et al.*, 1999; Leather, 1983a). Sunflower is known for synthesis of allelochemicals of great variation in chemical structure and activities, which might serve as templates for “natural herbicides” synthesis differing in chemical structure and mode of action (Macaïs *et al.*, 1999). The positive effects of sunflower allelopathy on the succeeding crop are also reported (Semidey, 1999). Nikneshan *et al.*, (2011) in their study to evaluate the herbicidal potential of sunflower cultivar leaf extracts against two broad-leaf weeds, two narrow-leaf weeds

and two crops under bioassay laboratory conditions found that the allelopathic properties of some sunflower cultivars can affect noxious weed species such as *Hordeum spontaneum* and *Lolium rigidum* in wheat and *Amaranthus retroflexus* in safflower.

The allelopathic potential of sunflower against weeds under field conditions was clearly demonstrated in a 5-year field study in which weed density and ground cover were reduced on plots with sunflower treatment when compared to control plots (Leather 1983a, b). In another study, the reduction in germination and growth of *Amaranthus retroflexus* L. was reported by Hall *et al.*, (1983). Reduced growth and yield has been reported in some crops planted in sunflower fields (Bogatek *et al.*, 2006) and yields of some crops following sunflower were lower than normal, possibly because of inadequate nutrition and chemical inhibition (Kamal and Bano, 2008). Bashir *et al.*, (2012), in their study to investigate the effect of incorporation of sunflower residue on growth and yield of two rice and two wheat varieties grown thereafter observed that the adverse effects of sunflower residue incorporation on rice and the subsequent wheat crop could be reduced by cultivation of allelopathic tolerant varieties. In their study on allelopathic activity of sunflower on growth of bambara groundnut, Batlang and Shushu (2007) found that results suggested that sunflower contains allelochemicals that have strong inhibitory effect on growth, especially flowering and nodulation of bambara groundnuts. Ohno *et al.* (2001) showed that germinating seeds of sunflower exude substances that displayed allelopathic activity. Azania *et al.* (2003), Leather (1983a, b) and Irons and Burnside (1982) noticed that in general, sunflower root exudates are less effective than leaf and stem leachates.

Laboratory experiments conducted to evaluate the allelopathic effects of water extracts of sunflower on the germination and seedling growth of rice, *Trianthema portulacastrum*, *Dactyloctenium aegyptium* and *Eleusine indica* showed that sunflower water extracts caused maximum reduction in root length of *T. portulacastrum* (Mubeen *et al.*, 2012). Awan *et al.*, (2009) also found that sunflower water extracts are very useful in allelopathic control of weeds in different crops and that this weed control strategy is environment friendly and reduced the cost of production. Sunflower leaf extracts caused reduction in radical and hypocotyls length of mustard seedlings (Bogatek *et al.*, 2006; Wardle *et al.*, 1991). Sedigheh *et al.* (2010) observed that sunflower parts significantly inhibit germination of *Solanum nigrum* L. According to Oracz *et al.* (2007) allelopathic material from sunflowers can influence the antioxidant systems in target plants, causing cell-membrane permeability and cellular damage, reducing the target plants' ability to germinate and causing a gradual loss of seed vigor.

Sunflower has been reported to be rich in terpenoids, particularly sesquiterpenoids (Macais *et al.*, 2002) which have been found to have a wide range of biological activities including potential allelopathy (Macais *et al.*, 2002; Harborne, 1993). Macais *et al.* (2002) isolated 125 natural allelopathic compounds that are phytotoxic towards many plants from different sunflower cultivars. More than 200 natural allelopathic compounds have been isolated from different cultivars of sunflower (Kamal and Bano, 2009). Vyvyan (2002) reported that heliannuols, terpenoids and flavonoids are the most important allelopathic compounds isolated from

sunflowers. An annuionone isolated from aqueous extract of sunflower (cv. Suncross-42 leaves), (Anjum and Bajwa, 2005) reduced the growth of all five selected weed species: *Phalaris minor* Retz., *Chenopodium album* L., *Coronopsis didymus* (L.), *Medicago polymorpha* L. and *Rumex dentatus* L. Ohno *et al.*, (2001) isolated a species selective allelopathic substance, sundiversifolide, exuded from germinating sunflower seeds, suggesting that allelopathy occurs only during seed germination. In that study, the inhibitory activity changed during the seed germination process.

CHAPTER FOUR

4.0 MATERIALS AND METHODS

4.1 Methodology

4.1.1 Site

Field experiments were conducted at the Field Station of the School of Agricultural Sciences, University of Zambia (15°23'S, 28°20'E and 1,225m above sea level) and the University of Zambia's research farm at Liempe (15°23'S, 28°28'E and 1,155m above sea level) in Chongwe district in the 2008/09 and 2009/10 rain-fed seasons. The soils at the Field Station are classified as fine loamy mixed isohyperthermic oxic paleusalf while those at Liempe are classified as fine loamy mixed isohyperthermic oxic kandiustalf. Monthly weather parameters for both sites in the two seasons are shown in Appendix 1.

4.1.2 Layout and treatments

A Randomized Complete Block Design (RCBD) was set up with four replications. Plots, 5 m x 5 m were set up in seven rows 75 cm apart with 20cm intra row spacing and one plant left per station. This translated to a plant population of 60,000 plants per hectare equivalent. One and a half (1.5) meters was allowed between plots while blocks (replications) were laid 2 m apart. The field layout is illustrated in Appendix 2.

Treatments were assigned to the plots at random using random numbers in Little and Hills (1978) and comprised six different sunflower varieties (Saona, Milika, Chongwe, Record, PAN7371 and PAN7352) and two maize varieties (MRI514 and MRI455).

4.1.3 Crop husbandry

The soils were ploughed to a depth of 20cm using conventional means and disced to obtain a fine tilth. Basal dressing fertilizer was applied at 200 kg ha⁻¹ using Compound D (10:20:10) to supply 20 kg N, 16 kg P (40 kg P₂O₅) and 16.6 kg K (20 kg K₂O), and top dressing using Urea (46% N) at 100 kg ha⁻¹ to supply 46 kg N, was applied four weeks after planting as per local

recommendations (Mwala, 1997). Weeding was done in the third, sixth and ninth week after assessment of weed density and diversity in all plots. Harvesting was done at maturity.

4.1.4 Data collection

Proxy data to indirectly pointing toward allelopathic effects was collected.

- i) Weed density and diversity was determined within four 0.25 m² quadrats on a transect at mid-plot at 3, 6 and 9 weeks after planting (WAP).
- ii) Weed biomass was obtained by uprooting all weeds from each quadrat and drying them in an oven at 60°C for 48 hours.
- iii) Seed weight (yield) for both sunflower and maize were determined. For sunflower, the heads were harvested at petal drop stage (Kaya *et al.*, 2004) by cutting off the heads of the sunflower from the stalk. The heads were then moved to the shed for drying at room temperature. When the heads were dry enough, they were threshed separately for each plot and seeds weighed. A 100 g sample was drawn from each harvest plot for moisture content determination. Using the determined moisture content, data was corrected to 8%. For maize, the same process was followed except that the cobs were harvested at black layer maturity (Makonnen and Bauman, 1976) and the determined moisture content was corrected to 12.5%. The correction was done using the relationship:

$$Q = 8(12.5) \times M/W \text{ where}$$

Q is the seed weight (g) at 8 (12.5)% moisture content;

M is the weight of seed sample at a given moisture content in g; and

W is the percent moisture content of the seed weight.

Yield was then expressed in kg ha⁻¹ equivalent.

4.1.5 Statistical analysis

Data for weed density, weed biomass and harvest were analyzed using ANOVA and mean separation was done using the Least Significant Difference (LSD). This assumed that errors were normally and independently distributed with mean zero and constant variance s^2 . Model

adequacy was tested using the primary diagnostic tools based on the residuals as outlined in Montgomery (1991).

Data was further subjected to correlation analysis in order to determine the association of various variables with each other.

Multivariate analysis through Principal Component Analysis (PCA) was done for orthogonal transformation of linearly uncorrelated variables while cluster analysis was also conducted in order to determine the relationships among the different varieties in such a way that those placed in the same group were more similar to each other than those in other groups.

CHAPTER FIVE

5.0 RESULTS

5.1 Weed Diversity and Density

5.1.1 Weed Diversity

A total of thirty-eight weeds were recorded in these field trials (Appendix 3.1) of which fifteen were widespread in both locations. The first flush of weeds emerged in the first two weeks of planting and later developed along side the crops. This resulted in about 40% weed cover in maize compared to about 25% for sunflower just before the first weed count at three weeks after planting (3 WAP). After six weeks, the figures had gone up to about 50% and 30% for maize and sunflower respectively. Data collected at 9 weeks after planting showed a reduction in weed cover to about 30% and 15% in maize and sunflower, respectively.

5.1.2 Weed density in sunflower and maize crops

Table 5.1 shows the analysis of variance for weed density at the two locations over two seasons and across three sampling times, separated by crop and also pooled for the crops. Full ANOVA tables are in Appendix 3.2.

Table 5.1: Summary of crop specific and combined Analysis of Variance for weed density grown at two locations, Field Station and Liempe Farm over two seasons 2008/9 and 2009/10, Lusaka Province

Source	Sunflower			Maize			Sunflower + maize		
	df	F _{calc}	Sign	df	F _{calc}	Sign	df	F _{calc}	Sign
Replication	3	1.42	ns	3	0.62	ns	3	1.52	ns
Variety	5	1.90	ns	1	0.15	ns	7	1.67	ns
Season	1	1.60	ns	1	1.69	ns	1	0.69	ns
Location	1	8.23	ns	1	32.57	*	1	10.78	*
Time	2	5.17	ns	2	9.80	*	2	9.34	*
Variety*Season	5	1.01	ns	1	0.02	ns	7	1.35	ns
Variety*Location	5	1.04	ns	1	0.01	ns	7	0.90	ns
Variety*Time	10	1.39	ns	2	2.54	ns	14	1.35	ns
Season*Location	1	22.03	*	1	10.59	*	1	29.30	*
Season*Time	2	5.94	*	2	4.48	*	2	8.48	*
Location*Time	2	1.86	ns	2	0.23	ns	2	1.87	*
Variety*Season*Loc	5	1.92	ns	1	0.85	ns	7	1.83	ns
Variety*Season*Time	10	0.98	ns	2	1.51	ns	14	0.95	ns
Variety*Location*Time	10	1.05	ns	2	2.08	ns	14	1.07	ns
Season*Location*Time	2	10.03	*	2	16.02	*	2	17.44	*
Error / Pooled error	205			71			296		

Location and time of sampling were important because:

- i) Location was used as a proxy for soil differences as the two sites had different soil types; and
- ii) Time of sampling gave the progressive nature of the weed problem as the critical period for weeding of both crops was roughly between 3 and 9 W AP.

Under maize, single factors locations and time of sampling were significantly different for weed density. Similar results were observed under combined analysis. However, since the interactions involving these two factors were also significant, no further explanations are done for them. Under sunflower, no single factor exhibited significant differences for weed density.

Significant interactions were also detected between season x location, and between season x time of sampling for sunflower, maize and combined analyses. The combined analyses also showed significant interactions between location x time of sampling. The only three-way interaction that showed significance was season x location x time for all the three analyses. Under sunflower, significant interactions were detected in both the two-way and three-way interactions, similarly in both crops and for the combined analyses.

5.1.2.1 Effects due to season x location under sunflower and under maize

Significant interactions between season x location were observed under maize, sunflower and in the combined analysis. Mean separation for this two-way interaction are shown in Table 5.2.

Table 5.2: Interaction effects of season x location for weed density (No. m⁻²)

Location	Season	
	S1	S2
Field Station	114.18	25.56
Liempe Farm	69.36	58.48
LSD _{a0.05}	19.37	

Means for this interaction showed that at the FS, there were more weeds in S1 (114.18 weeds m⁻²) than in S2 (25.56 weeds m⁻²) while at LF, although there were more weeds in S1 (69.36 weeds m⁻²) than in S2 (58.48 weeds m⁻²), it was by a smaller margin and they were not significantly different from each other. At the FS, the decrease was by 346.7% while at LF, the decrease was only by 10.6%.

5.1.2.2 Effects due to season x time of sampling across the two crops

Means for season x time of sampling interaction when considered across the two crops are shown in Table 5.3.

Table 5.3: Interaction means for season x time of sampling weed density (No. m⁻²)

Time of sampling	Season	
	S1	S2
T1 (3WAP)	96.53	80.11
T2 (6WAP)	43.13	77.48
T3 (9WAP)	69.95	34.17
LSD _{a0.05}	24.16	

In S1, all the three times of sampling were significantly different from each other with T1 (3 WAP, 96.53 weeds m⁻²) having the highest weed density and T2 (6 WAP, 43.13 weeds m⁻²) having the least. In S2, T1 (80.11 weeds m⁻²) and T2 (77.48 weeds m⁻²) were not significantly different from each other but they were then both significantly different from T3 (9 WAP, 34.17 weeds m⁻²). The change in weed density in S1 was negative quadratic while in S2 it was negative linear as shown in Figure 5.1.

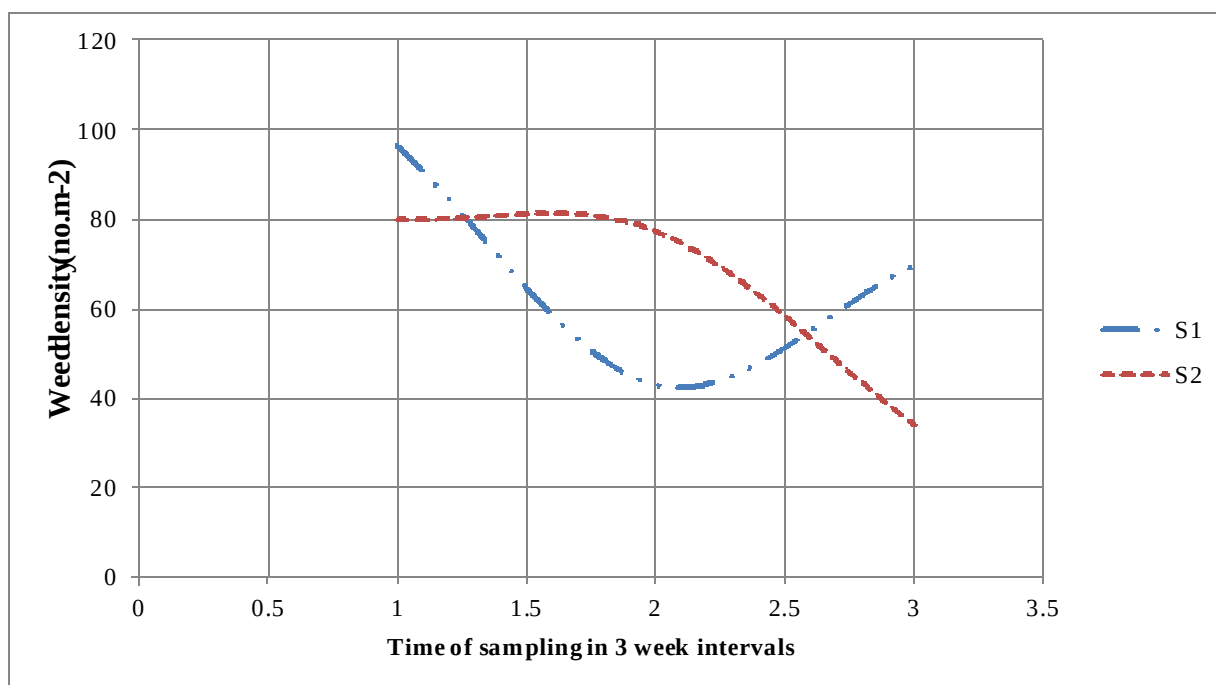


Figure 5.1: Interaction means for season x time of sampling weed density (No. m⁻²)

5.1.2.3 Effects due to the three-way interaction season x location x time for the two crops

The Principal Component Analysis (PCA) conducted for the three-way interaction season x location x time of sampling showed that PC1 was very strong for T1 (0.442) in both seasons, T2 in S1 (0.470) and T3 in S2 (0.440). Although T3 in S1 also showed strong PC1 (0.393), it was not as strong as the earlier four interactions; while T2 in S2 showed very strong PC3 (Table 5.4). This is evident in Figure 5.2 since the former four lines loaded quite closely to each other while the last two loaded at a larger distance from the first four and even then, were far apart from each other.

Table 5.4: Principal components for the 3-way interaction season x location x time of sampling

Interaction	PC1	PC2	PC3
S1T1	0.442	0.330	0.303
S1T2	0.470	0.373	0.067
S1T3	0.393	-0.477	-0.408
S2T1	0.442	-0.086	-0.571
S2T2	0.201	-0.711	0.564
S2T3	0.440	0.106	0.306

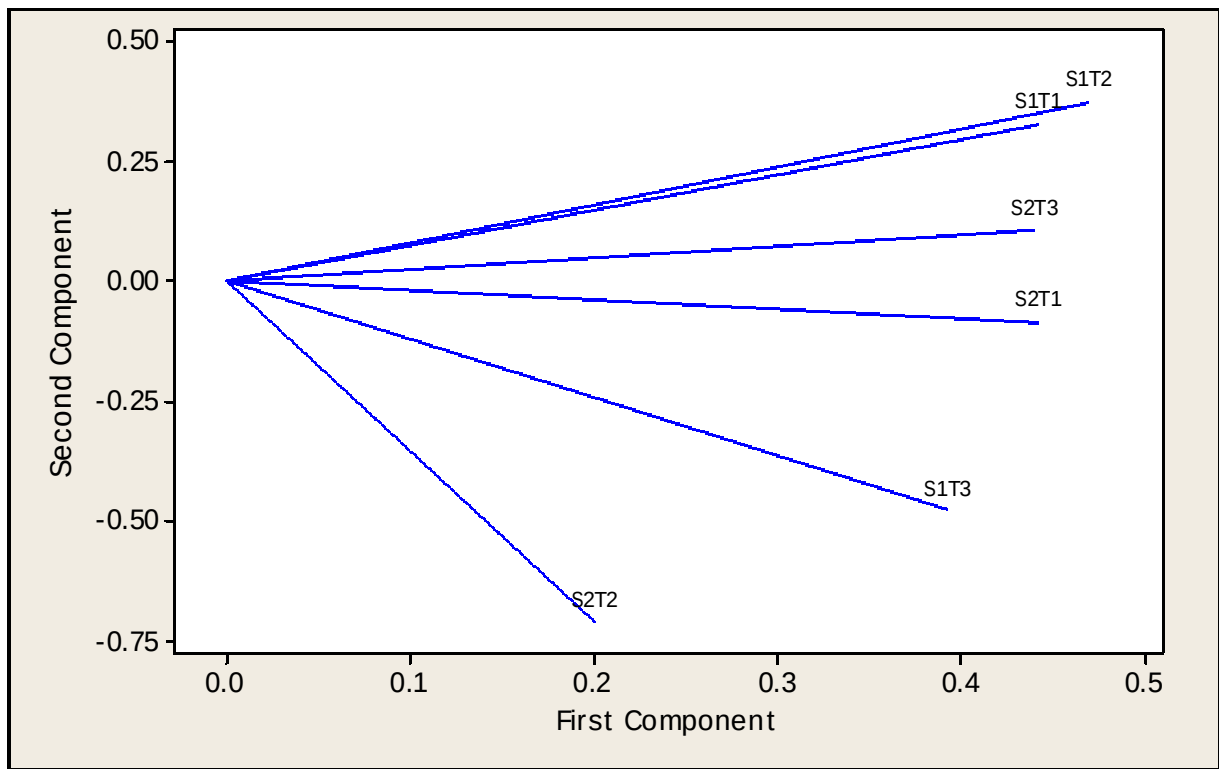


Figure 5.2: Loading plot for the three-way interaction for Location x Season x Time of sampling

5.2 Weed Biomass

5.2.1 Weed biomass in sunflower and maize crops

Table 5.5 shows the analysis of variance for weed biomass at the two locations over two seasons and across three sampling times, separated by crop and also pooled for the crops. Full ANOVA tables are in Appendix 3.3.

Table 5.5: Summary of crop specific and combined across crops Analysis of Variance for weed biomass grown at two locations, Field Station and Liempe Farm over two seasons 2008/9 and 2009/10, Lusaka Province

Source	Sunflower			Maize			Sunflower + maize		
	df	F _{calc}	Sign	df	F _{calc}	Sign	df	F _{calc}	Sign
Replication	3	1.78	ns	3	0.40	ns	3	1.60	ns
Variety	5	2.9	ns	1	1.92	ns	7	0.91	ns
Season	1	3.79	ns	1	0.89	ns	1	1.58	ns
Location	1	0.03	ns	1	0.40	ns	1	0.09	ns
Time	2	13.74	*	2	20.08	*	2	48.10	*
Variety*Season	5	3.65	*	1	0.71	ns	7	2.99	*
Variety*Location	5	4.52	*	1	5.61	*	7	4.10	*
Variety*Time	10	3.41	*	2	4.81	*	14	3.51	*
Season*Location	1	35.04	*	1	0.12	ns	1	30.00	*
Season*Time	2	4.92	ns	2	3.06	ns	2	4.14	ns
Location*Time	2	23.02	*	2	12.24	*	2	32.40	*
Variety*Season*Loc	5	2.17	ns	1	1.49	ns	7	2.96	*
Variety*Season*Time	10	2.64	*	2	1.03	ns	14	2.30	*
Variety*Location*Time	10	2.22	*	2	2.24	ns	14	2.19	*
Season*Location*Time	2	6.25	*	2	4.34	*	2	8.82	*
Error / Pooled error	178			71			245		

Significant differences were observed between time of samplings under sunflower, maize and when sunflower and maize data were combined. However, since interactions involving this factor were also significant, it was not explained further.

Amongst the interactions, the following was discerned: Significant interactions were observed under sunflower alone and sunflower plus maize analysis for variety x season, variety x location, variety x time, and season x location. Under maize alone, significant interactions were observed for variety x location, variety x time and location x time. Significant three-way interactions were observed for season x location x time under maize only. Under sunflower significant interactions

were for variety x season x time, variety x location x time and season x location x time. Significance was observed for the same interaction effects under combined analysis in addition to variety x season x location effects.

5.2.1.1 Effects due to variety x season

In S1, Milika had the least weed suppressive capacity (highest weed biomass of 24.34 gm⁻²) which was not significantly different from Record (22.56 gm⁻²), Saona (18.87 gm⁻²) and Chongwe (18.66 gm⁻²) but was significantly different from PAN7371 (16.64 gm⁻²) and PAN7352 (14.47 gm⁻²), (Table 5.6). Record was not significantly different from Saona, Chongwe and PAN7371 but was significantly different from PAN7352. These four varieties which had the highest weed suppressive capacity (Saona, Chongwe, PAN7371 and PAN7352), were not significantly different from each other.

Table 5.6: Interaction variety x season means for weed biomass (gm⁻²)

Variety	Season	
	S1	S2
Record	22.56	13.46
Milika	24.34	14.38
Saona	18.87	12.23
Chongwe	18.66	13.37
PAN7371	16.64	17.97
PAN7352	14.47	27.62
MRI514	24.40	20.96
MRI455	23.06	23.85
LSD _{a0.05}	6.64	

In S2, PAN7352 had the least weed suppressive capacity (highest weed biomass of 27.62 gm⁻²) which was significantly different from the other five varieties. These varieties had better weed suppressive capacity [with weed densities of Record (13.46 gm⁻²), Milika (14.38 gm⁻²), Saona (12.23 gm⁻²), Chongwe (13.37 gm⁻²) and PAN7371 (17.97 gm⁻²)] and were then not significantly different from each other.

Across the seasons for each individual variety, Saona, Chongwe and PAN7371 showed no significant differences in weed suppressive capacity between the two seasons. Record and Milika had significantly better weed suppressive capacity in S2 than in S1 while the opposite was observed for PAN7352. A negative and strong correlation was found between the two season ($r = -0.7$).

The two maize varieties had high weed biomass in both seasons consistently.

5.2.1.2 Effects due to variety x location for the two crops

Under both maize and sunflower significant interactions for variety x location were observed and Table 5.7 presents the effects.

At the FS, Milika had the least weed suppressive capacity (highest weed biomass of 21.02 gm⁻²) with PAN7352 having the highest weed suppressive capacity. The weed biomass of these two varieties was significantly different from each other (PAN7352 weed biomass 13.98 gm⁻²). No significant differences were observed among the rest of the varieties of sunflower and maize in the study; [Record (17.65 gm⁻²), Saona (14.52 gm⁻²), Chongwe (19.16 gm⁻²), PAN7371 (19.41 gm⁻²), MRI514 (17.25 gm⁻²) and MRI455 (19.26 gm⁻²)] at the FS.

An assessment of the two crops individually, the sunflowers had a grand mean weed biomass of 17.62 gm⁻² while the maize weighed in at 18.26 gm⁻². Therefore, the maize had a numerically higher weed biomass than the sunflowers. Further, the range in the maize was only 2.01 while for the sunflowers it was 7.08. Hence among the sunflowers, there were varieties with high weed suppressive capacity and some with low weed suppressive capacity. For maize, both of them had low weed suppressive capacity.

Table 5.7: Interaction variety x location means for weed biomass (gm⁻²)

Variety	Location	
	Field Station	Liempe Farm
Record	17.65	18.37
Milika	21.02	17.71
Saona	14.52	16.58
Chongwe	19.16	12.88
PAN7371	19.41	15.20
PAN7352	13.98	28.11
MRI514	17.25	23.40
MRI455	19.26	15.70
LSD _{a0.05}		6.64

At LF, the two crop varieties had almost similar weed suppressive capacity except sunflower variety PAN7352 and maize variety MRI514 which had significantly lower weed suppressive capacities (highest weed biomass of 28.11 gm⁻² and 23.40 gm⁻², respectively) compared to the other crop varieties. The best weed suppressive capacity was observed with sunflower variety Chongwe (12.88 gm⁻²), though not significantly different from the other varieties in the study.

With the results from the two-way interaction variety x location, there was absence of consistency of weed suppressiveness amongst the varieties in the study with the FS being conducive for weed suppression by one sunflower variety and LF favoring another sunflower

variety along with a maize variety, probably due to the differences in soil types of the two locations. Correlation analysis showed that there was a fairly strong and negative relationship between the location of $r = -0.6$.

5.2.1.3 Effects due to variety x time for the two crops

Significant interactions for variety x time of sampling were observed for weed biomass and the effects are presented in Table 5.8.

At T1 (3WAP), Milika and MRI514 had the least weed suppressive capacity (highest weed biomass of 32.98 gm^{-2} and 33.91 gm^{-2} , respectively); though not significantly different from each other or from that of Saona (25.97 gm^{-2}). Milika and MRI514 were then significantly different from Record (23.46 gm^{-2}), Chongwe (23.03 gm^{-2}), PAN7371 (20.57 gm^{-2}), PAN7352 (20.23 gm^{-2}) and MRI455 (22.07 gm^{-2}). The sunflower varieties Record, Chongwe, PAN7371 and PAN7352 together with the maize variety MRI455 were not significantly different from each other. PAN7371 and PAN7352 had the highest weed suppressive capacity at this time of sampling though not significantly different from the other varieties in the study.

At T2, PAN7352 had the least weed suppressive capacity (highest weed biomass of 32.20 gm^{-2}), significantly different from all the other varieties. These other varieties [Record (19.41 gm^{-2}), Milika (16.16 gm^{-2}), Saona (12.90 gm^{-2}), Chongwe (14.58 gm^{-2}), PAN7371 (17.82 gm^{-2}), MRI514 (14.68 gm^{-2}) and MRI455 (16.38 gm^{-2})] were then not significantly different from each other. Saona had the highest weed suppressive capacity at this time of sampling,

At T3, no significant differences were observed among all the treatment means for all the varieties although Saona again had lowest weed biomass, translated as highest weed suppressive capacity and MRI455 had the least weed suppressive capacity.

Table 5.8: Interaction variety x time means for weed biomass (gm^{-2})

Variety	Time of sampling		
	T1 (3WAP)	T2 (6WAP)	T3 (9WAP)
Record	23.46	19.41	11.16
Milika	32.98	16.16	8.95
Saona	25.97	12.90	7.79
Chongwe	23.03	14.58	10.44
PAN7371	20.57	17.82	13.53
PAN7352	20.23	32.20	10.71
MRI514	33.91	14.68	12.37
MRI455	22.07	16.38	13.98
LSD _{a,0.05}		8.14	

5.2.1.4 Effects due to season x time

Season x time interaction effects are shown in Table 5.9.

In S1, T1 (3 WAP), had significantly higher weed biomass (28.25 gm^{-2}) than both T2 (15.17 gm^{-2}) and T3 (14.82 gm^{-2}) which were themselves not significantly different from each other. In S2, no significant differences were observed between T1 (22.31 gm^{-2}) and T2 (20.87 gm^{-2}) but these two were then significantly different from T3 (7.42 gm^{-2}) which had the lowest weed biomass. At T1 and T3, there was significantly higher weed biomass in S1 than in S2 while the opposite was observed at T2.

Table 5.9: Interaction season x time means for weed biomass (gm^{-2})

Season	Time of sampling		
	T1 (3WAP)	T2 (6WAP)	T3 (9WAP)
S1	28.25	15.17	14.82
S2	22.31	20.87	7.42
LSD _{a,0.05}	4.07		

In S1, an exponential relationship was discerned while in S2, an inverse exponential relationship existed among the three times of sampling. The correlation coefficient between the two seasons was 0.6.

5.2.1.5 Effects due to season x location

This source of variation was significant under sunflower only and when the analysis was across the two crops.

Interaction effects for season x location are shown below (Table 5.10).

Table 5.10: Interaction season x location means for weed biomass (gm^{-2})

Season	Locations	
	Field Station	Liempe Farm
S1	22.28	16.54
S2	13.28	20.45
LSD _{a,0.05}	3.32	

At the FS, significant reduction (40.4%) in weed biomass was observed from S1 to S2 while at LF, a significant increase of 19.1% was observed. Whereas at the FS, S1 had higher weed

biomass than S2, this was opposite for LF where S2 had higher weed biomass than S1 (Figure 5.3). The magnitude of the difference was higher at the FS than at LF.

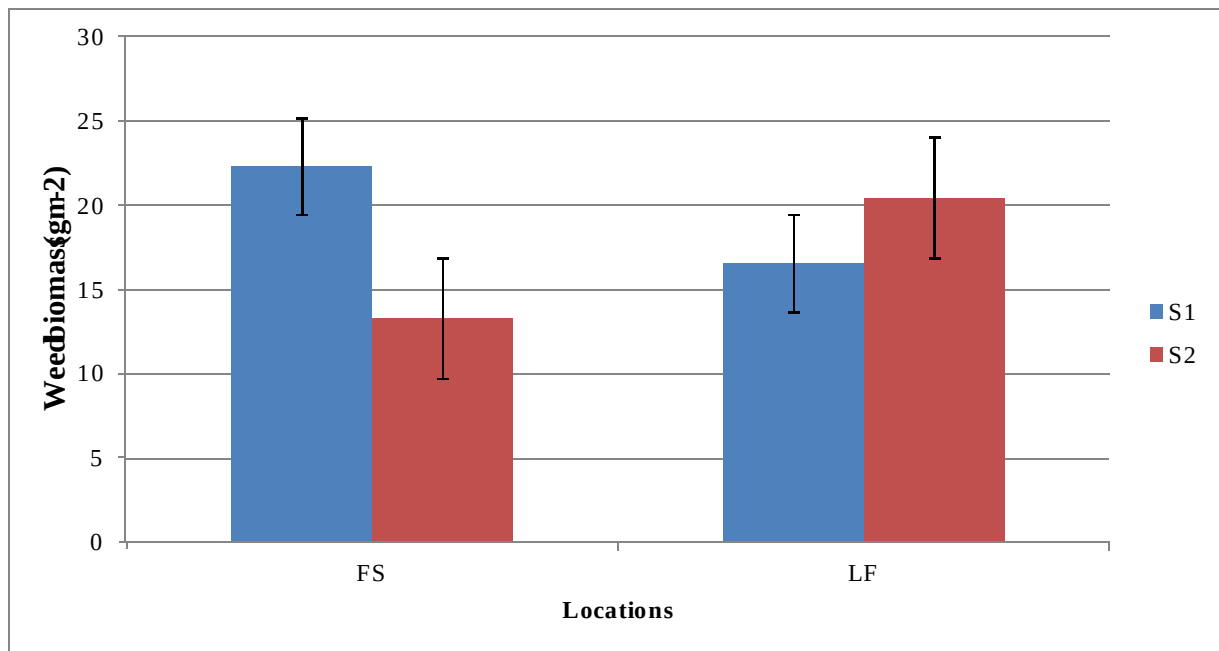


Figure 5.3: Spatial differences between seasons within each location for weed biomass

5.2.1.6 Effects due to variety x season x time of sampling for sunflower

This source of variation was significant under sunflower and when analysis was across the two crops and the outcomes are illustrated in Figure 5.4.

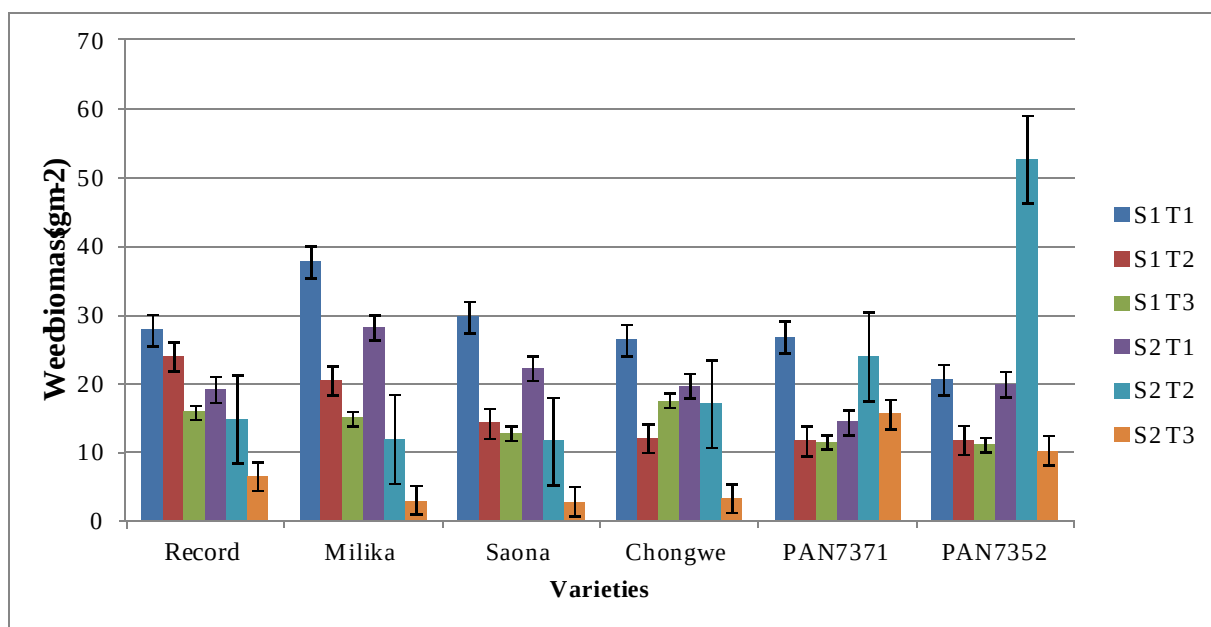


Figure 5.4: Relationship for the 3-way interaction variety x season x time for weed biomass (gm^{-2})

Principal Component Analysis was conducted for this 3-way interaction and the results showed that PC1 was very strong for Record (0.449), Milika (0.483), Saona (0.494) and Chongwe (0.477). For PAN7371 the strongest component was PC3 at 0.738 while for PAN7352, the strongest was PC2 (0.742) [Table 5.11].

Table 5.11: Principal Components for the 3-way interaction variety x season x time for weed biomass (gm^{-2})

Variety	PC1	PC2	PC3
Record	0.449	-0.235	-0.179
Milika	0.483	-0.212	0.084
Saona	0.494	-0.130	0.063
Chongwe	0.477	0.056	-0.297
PAN7371	0.287	0.574	0.738
PAN7352	0.108	0.742	-0.570

The above explanation was evident in the loading plot (Figure 5.5) where the four varieties (Record, Milika, Saona and Chongwe) loaded closely together. The two PAN varieties were very far from the earlier four varieties and thereafter, far apart from each other indicating the separate loadings as articulated earlier.

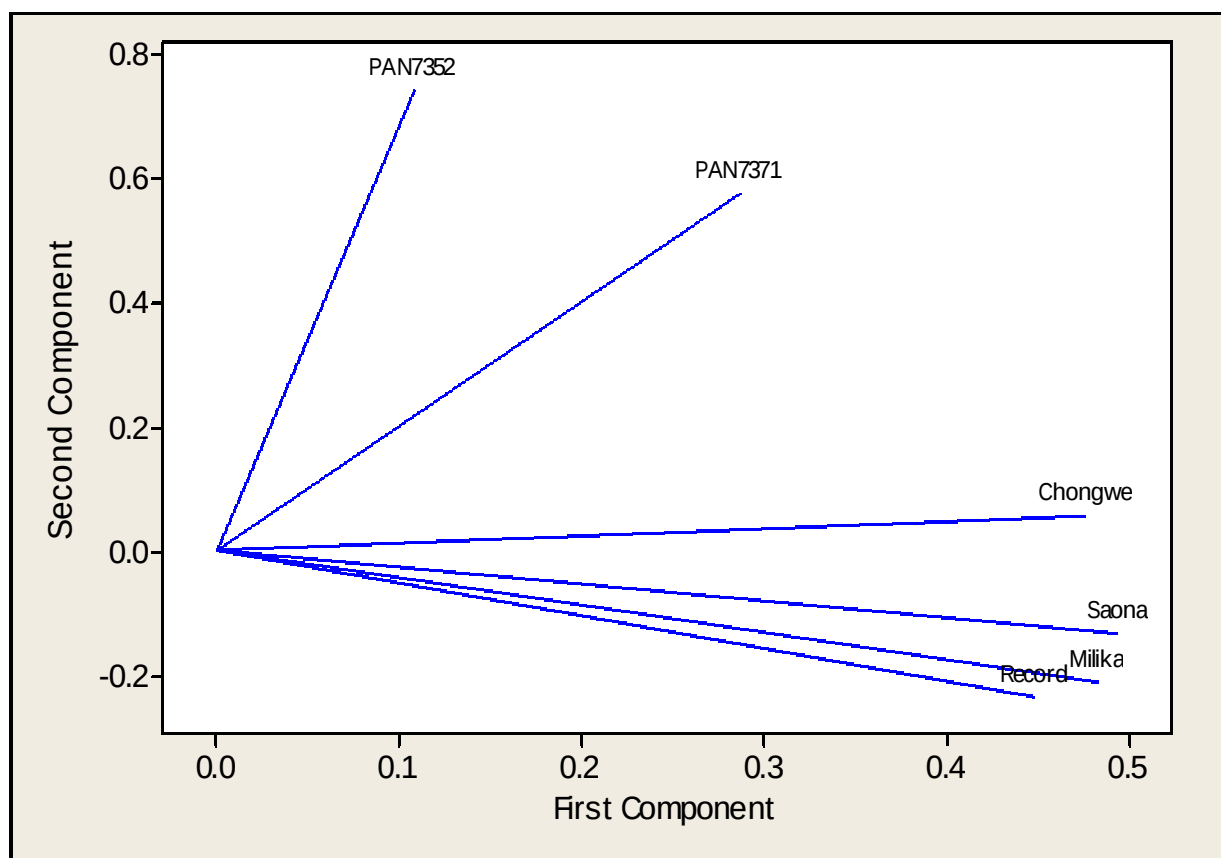
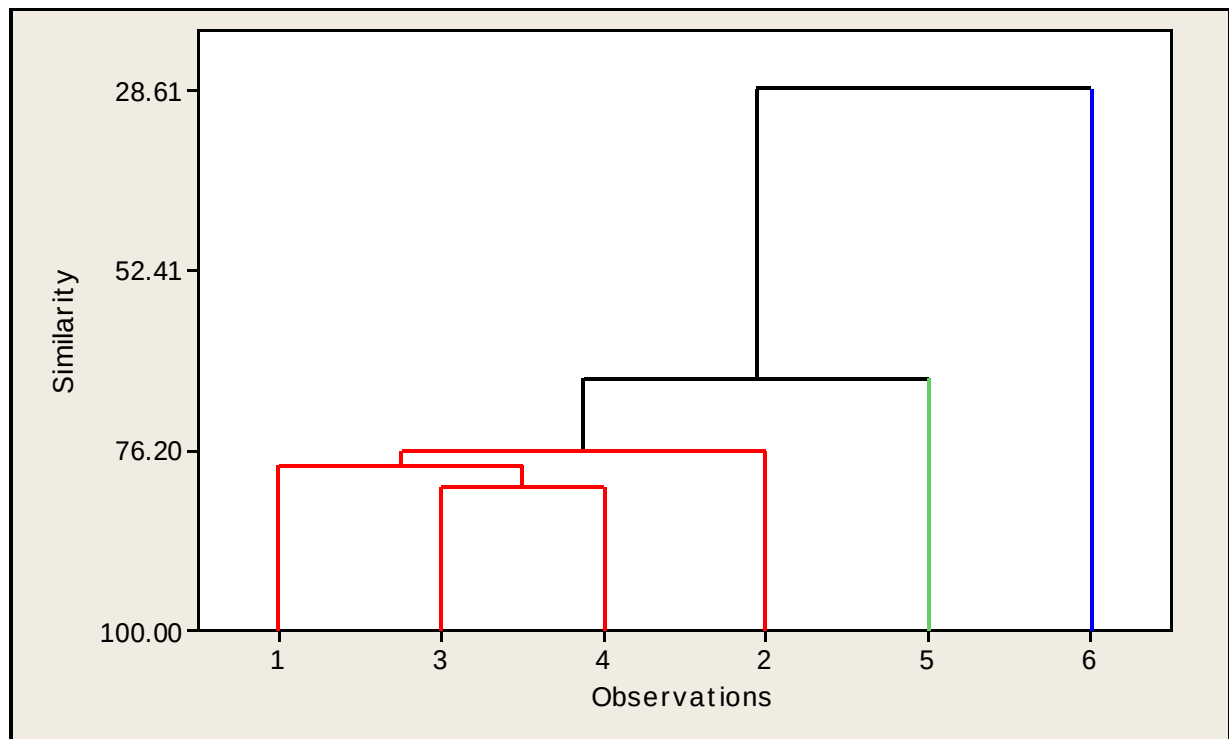


Figure 5.5: Loading plot for the 3-way interaction variety x season x time of sampling

The PCA results were further corroborated by cluster analysis where Record (1), Saona (3), Chongwe (4) and Milika (2) in the dendrogram with centroid linkage and Euclidean distance were closely linked together (Figure 5.6) while 5 (PAN7371) and 6 (PAN7352) are quite distant from the other four varieties and more remotely connected to them.

The most closely related varieties were Saona and Chongwe which had a similarity of 81.1% and were separated by a Euclidean distance of 8.77. Record had a similarity of 78.3% with Saona/Chongwe combination and was separated from them by a Euclidean distance of 10.09. Milika had a similarity level of 76.3% to the Saona/Chongwe/Record combination and was separated from them by a Euclidean distance of 11.02. The Saona/Chongwe/Record/Milika combination had a 66.8% similarity level with PAN7371 and was separated from it by a Euclidean distance of 15.4. Finally, PAN7352 was separated from Saona/Chongwe/Record/Milika by a Euclidean distance of 33.21 and had a similarity level of only 28.6%.



Key: 1=Record, 2=Milika, 3=Saona, 4=Chongwe, 5=PAN7371, 6=PAN7352

Figure 5.6: Dendrogram with centroid linkages and Euclidean distances for the 3-way interaction variety x season x time of sampling

The above show that there was a close similarity among Record, Milika and Saona. Chongwe also had a close relationship to these three but was slightly more different from them. The two PAN varieties (PAN7352 and PAN7371) were then very different from these four varieties and not very similar to each other.

5.2.1.7 Effects due to variety x location x time of sampling for sunflower

This source of variation was significant for sunflower and the combined analysis.

Interaction means for sunflower for the three-way interaction variety x location x time are shown in Figure 5.7.

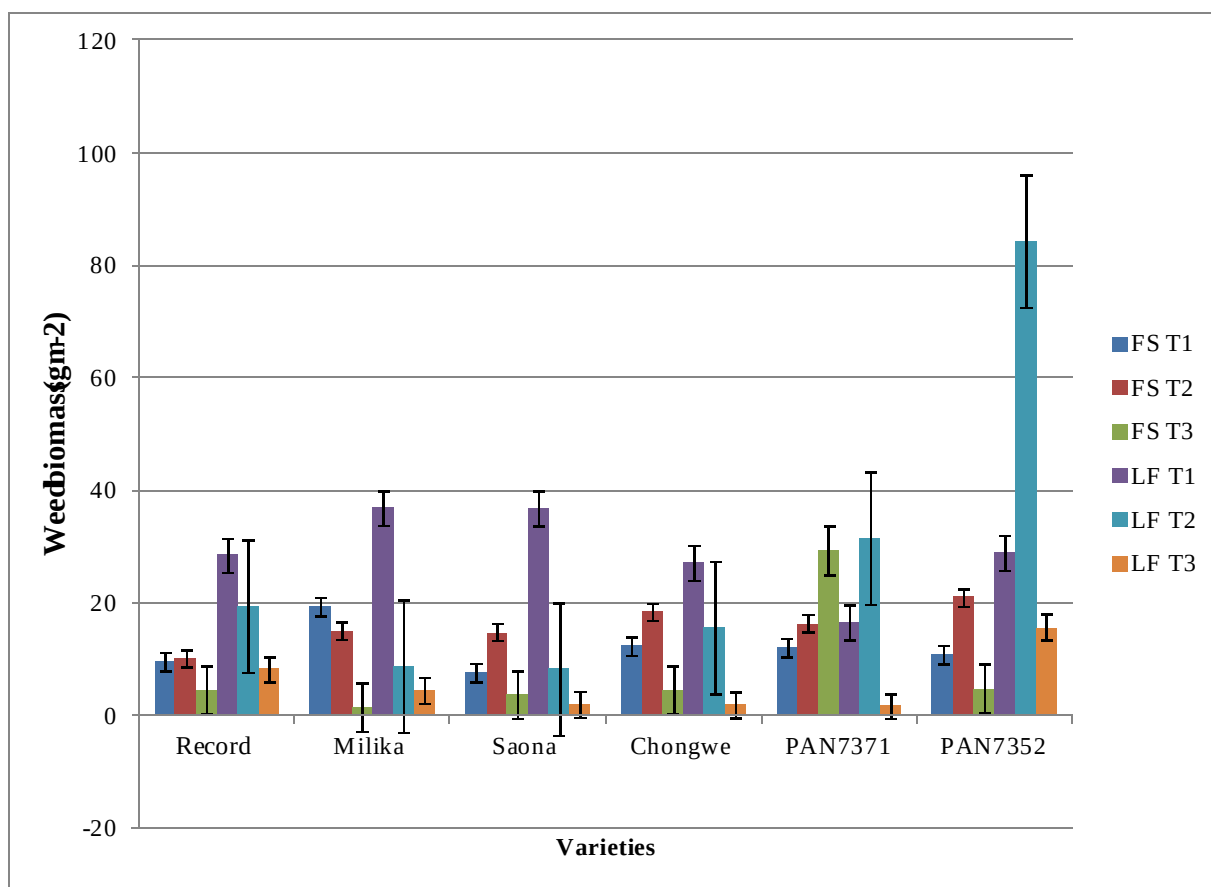


Figure 5.7: Relationship for the 3-way interaction variety x season x time for weed biomass (gm^{-2}) for the six sunflower varieties

When Principal Component Analysis was conducted for this 3-way interaction, the results revealed that PC1 was strongest for Record (0.492), Milika (0.470), Saona (0.492) and Chongwe (0.501). For the two PAN varieties, PC2 was the strongest (0.669 for PAN7371 and 0.642 for PAN7352) [Table 5.12].

Table 5.12: Principal components for the three-way interaction variety x location x time of sampling for the six sunflower varieties

Variety	PC1	PC2	PC3
Record	0.492	0.108	0.285
Milika	0.470	-0.307	-0.064
Saona	0.492	-0.185	-0.203
Chongwe	0.501	0.014	-0.159
PAN7371	0.070	0.669	-0.701
PAN7352	0.199	0.642	0.597

The above is illustrated in the loading plot (Figure 5.8) where the four varieties (Record, Chongwe, Saona and Milika) loaded closely together. PAN7371 and PAN7352 both loaded far from the earlier four varieties; however, they were closer to each other, corroborating their closer loading.

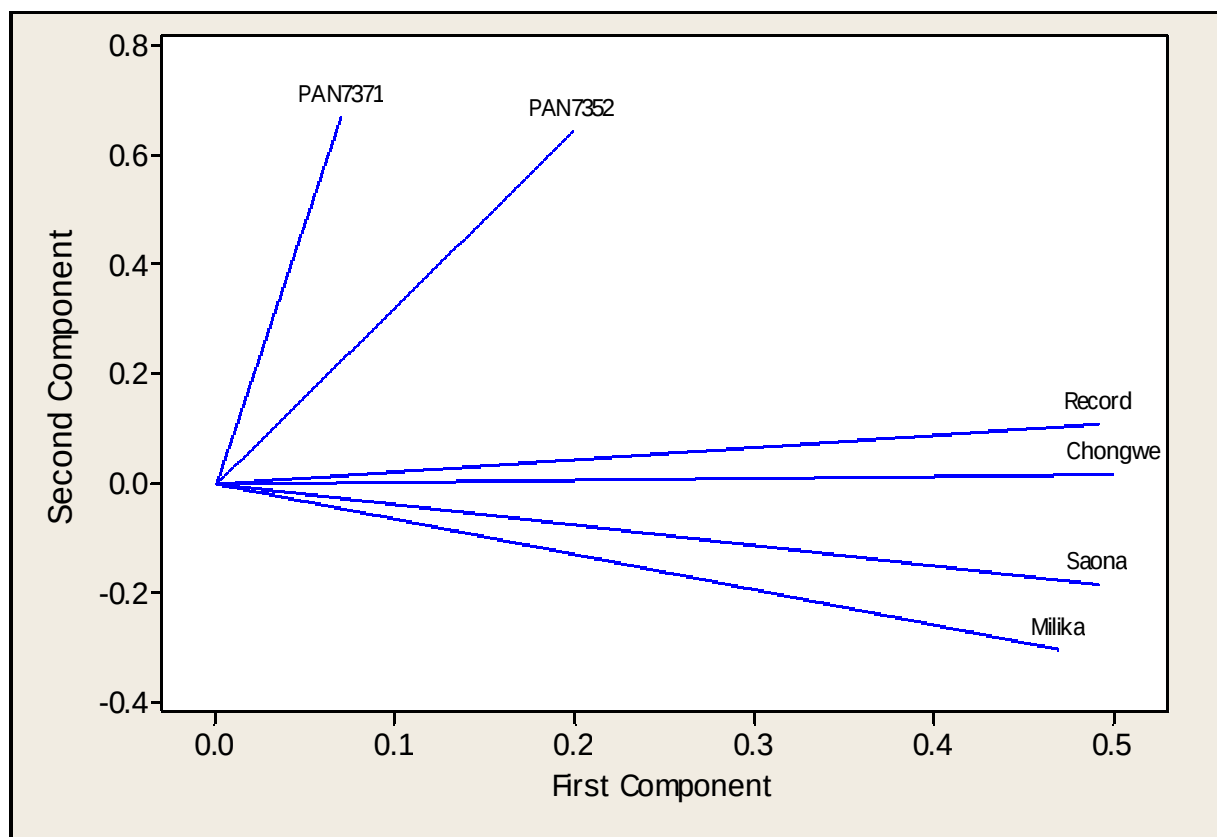
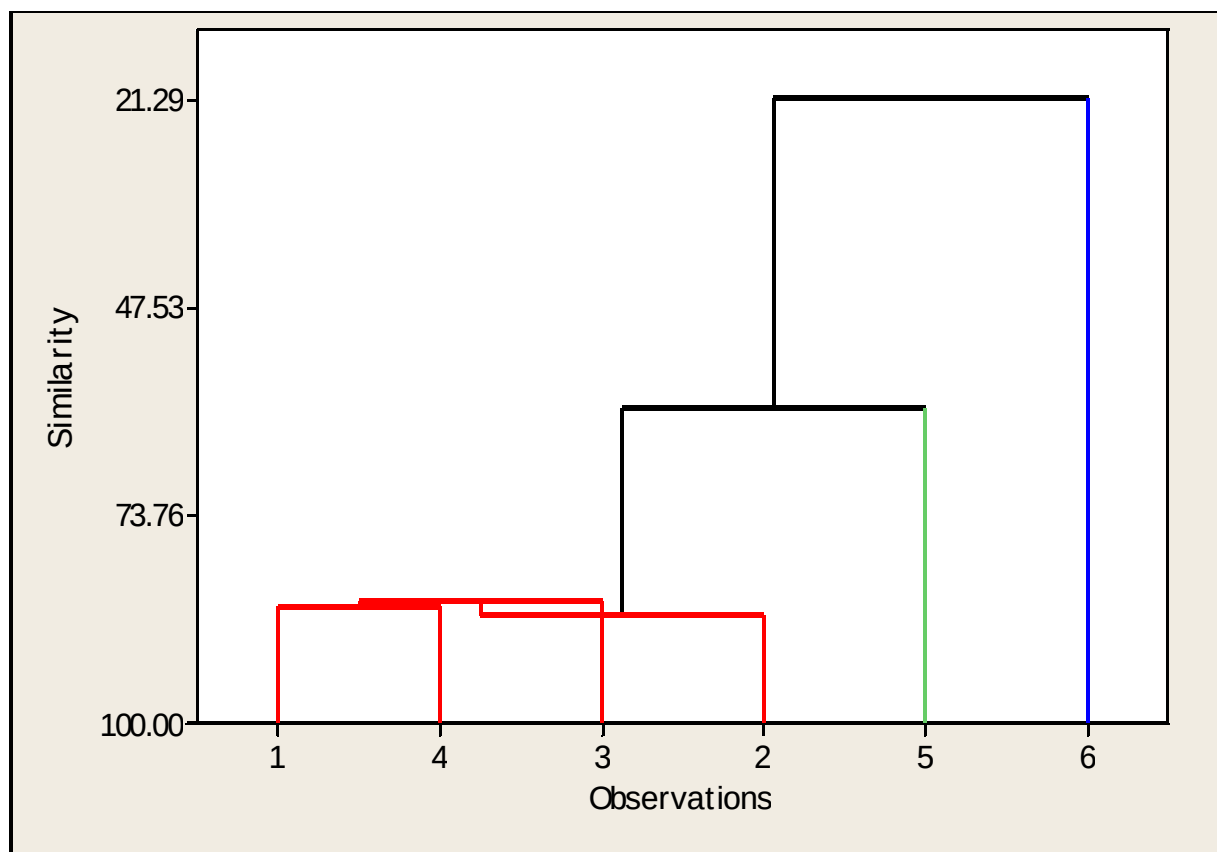


Figure 5.8: Loading plot for the 3-way interaction variety x location x time of sampling for the six sunflower varieties

These PCA results are further corroborated by cluster analysis where Record (1), Chongwe (4), Saona (3) and Milika (2) in the dendrogram with centroid linkage and euclidean distance (Figure 5.9) were closely linked together. However, 5 (PAN7371) and 6 (PAN7352) are quite distant from the other four varieties and only remotely connected to them. Even the linkage between the two PAN varieties was not as close as that of the earlier four varieties.

Record and Chongwe had a similarity level of 85.2% and were separated by a Euclidean distance of 11.52. Record/Chongwe and Saona had a similarity of 84.68% and were separated by a Euclidean distance of 11.93. Saona and Milika had the highest similarity, 86.4% and were separated by a Euclidean distance of only 10.58. PAN7371 had a similarity of 60.4% with Record/Chongwe/Saona/Milika combination and was separated from them by a Euclidean

distance of 30.87. Lastly, PAN7352 was separated by a 61.29 Euclidean distance from Record/Chongwe/Saona/Milika and had a similarity level of only 21.3%.



Key: 1=Record, 2=Milika, 3=Saona, 4=Chongwe, 5=PAN7371, 6=PAN7352

Figure 5.9: Dendrogram with centroid linkages and Euclidean distances for the 3-way interaction variety x location x time of sampling

5.2.1.8 Effects due to season x location x time of sampling for both crops

Interaction means for season x location x time are shown in Figure 5.10.

At the FS in S1, T1 (30.72 gm⁻²) and T3 (25.83 gm⁻²) had significantly higher weed biomass than T2 (10.30 gm⁻²). The two, T1 and T3 were then not significantly different from each other. At the same location in S2, no significant differences were observed between T1 (14.36 gm⁻²) and T2 (16.53 gm⁻²) and between T2 (16.53 gm⁻²) and T3 (8.94 gm⁻²) but there were significant differences observed between T1 and T3. S1 showed a quadratic relationship while S2 had an inverse quadratic relationship.

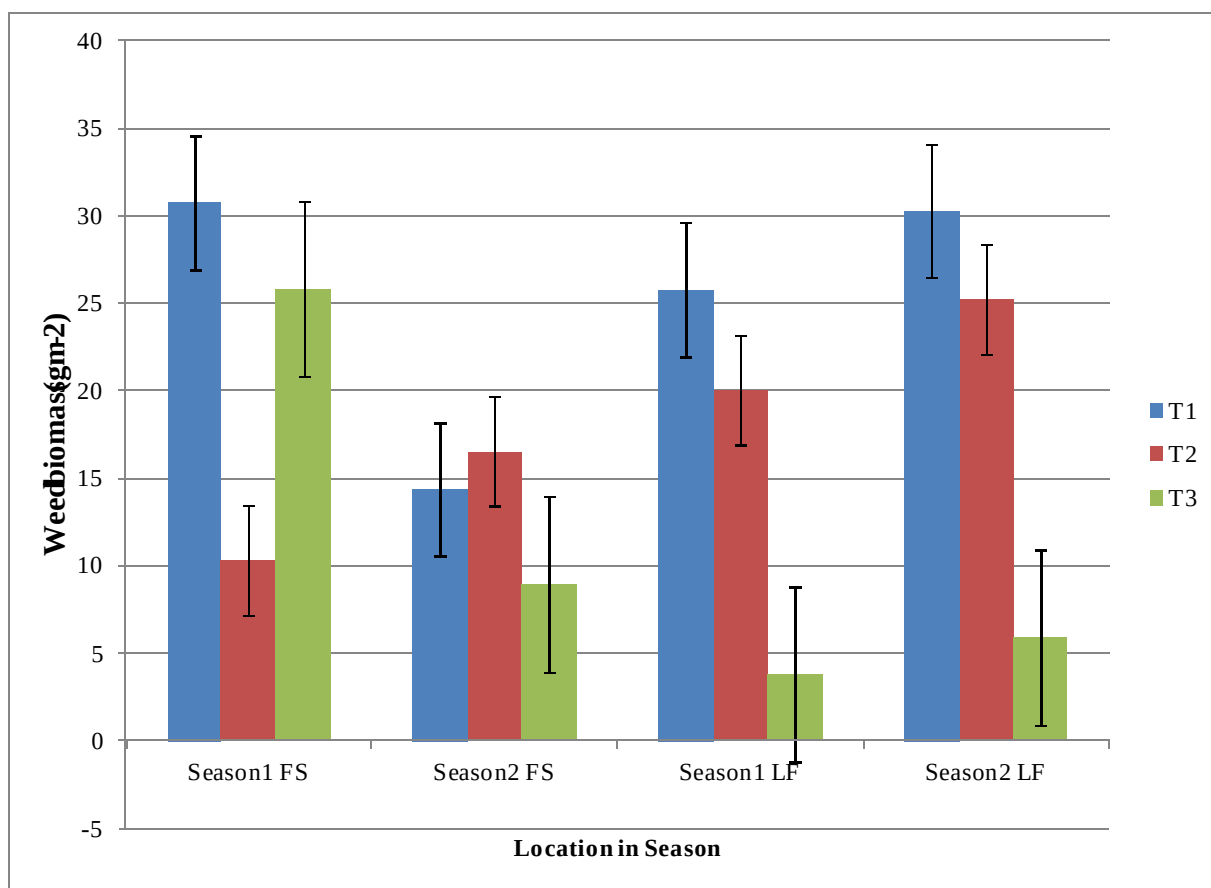


Figure 5.10: Interaction season x location x time means for weed biomass (gm^{-2}) for the six sunflower and two maize varieties

At LF in both S1 and S2, no significant differences were observed between T1 (25.78 and 20.03 gm^{-2} , respectively) and T2 (30.25 and 25.21 gm^{-2} , respectively) but the two were then both significantly different from T3 (3.80 and 5.89 gm^{-2} , respectively).

5.2.1.9 Effects due to variety x season x location for both crops

The PCA revealed that PC1 was strongest for sunflower varieties Record (0.474), Milika (0.405) and Saona (0.478) and the maize variety MRI514 (0.407). PC2 was strongest for sunflower variety Chongwe (0.428) and maize variety MRI455 (0.470) while PC3 was strongest for the two sunflower PAN varieties, PAN7371 (0.734) and PAN7352 (0.518) [Table 5.13].

Table 5.13: Principal components for the three-way interaction variety x season x location for the six sunflower and tow maize varieties

Variety	PC1	PC2	PC3
Record	0.474	0.157	-0.002
Milika	0.405	0.330	-0.111
Saona	0.478	0.054	-0.203
Chongwe	0.318	0.428	0.250
PAN7371	0.159	-0.343	0.734
PAN7352	-0.110	0.488	0.518
MRI514	0.407	-0.322	-0.151
MRI455	-0.280	0.470	-0.232

These results are illustrated in the loading plot (Fig 5.11) where the four sunflower varieties Milika, Record, Saona and Chongwe loaded closely to each other while the two PAN varieties PAN7371 and PAN7352 loaded in opposite directions (almost 180° apart) as did the two maize varieties MRI514 and MRI455.

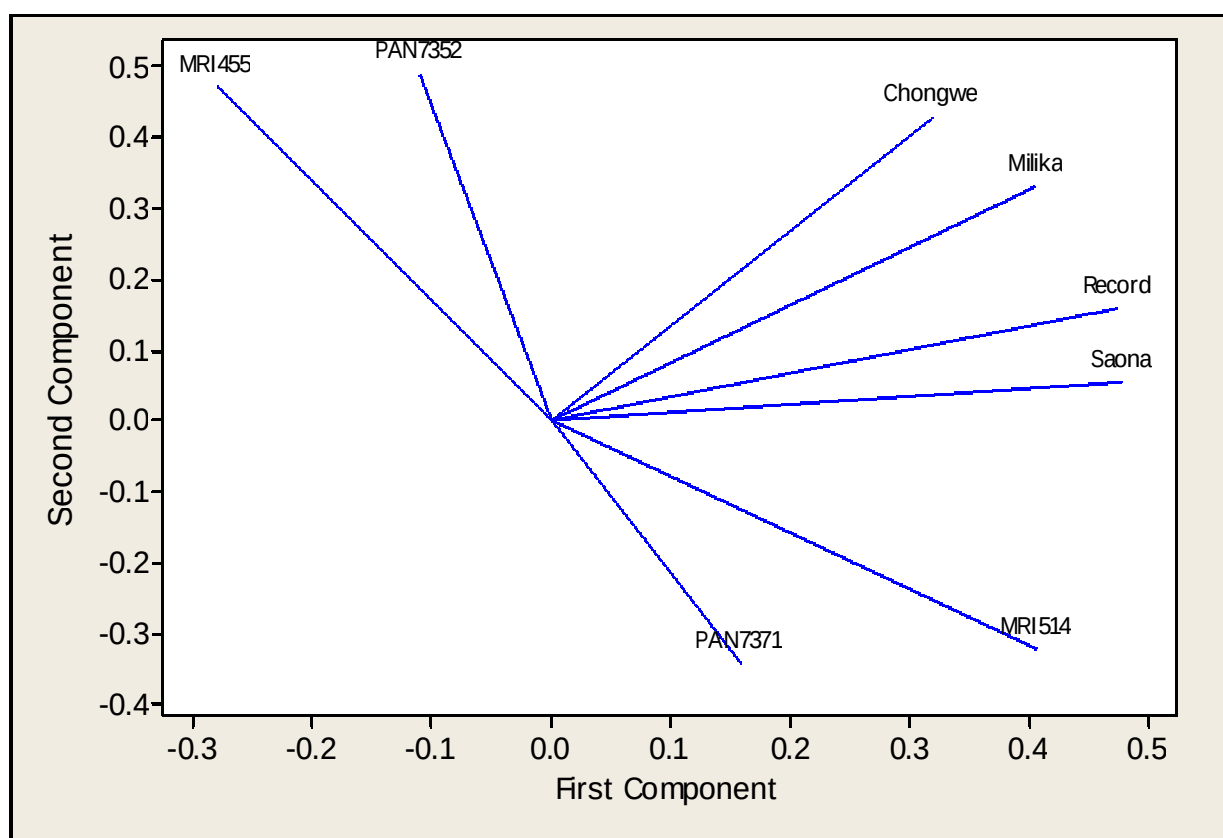
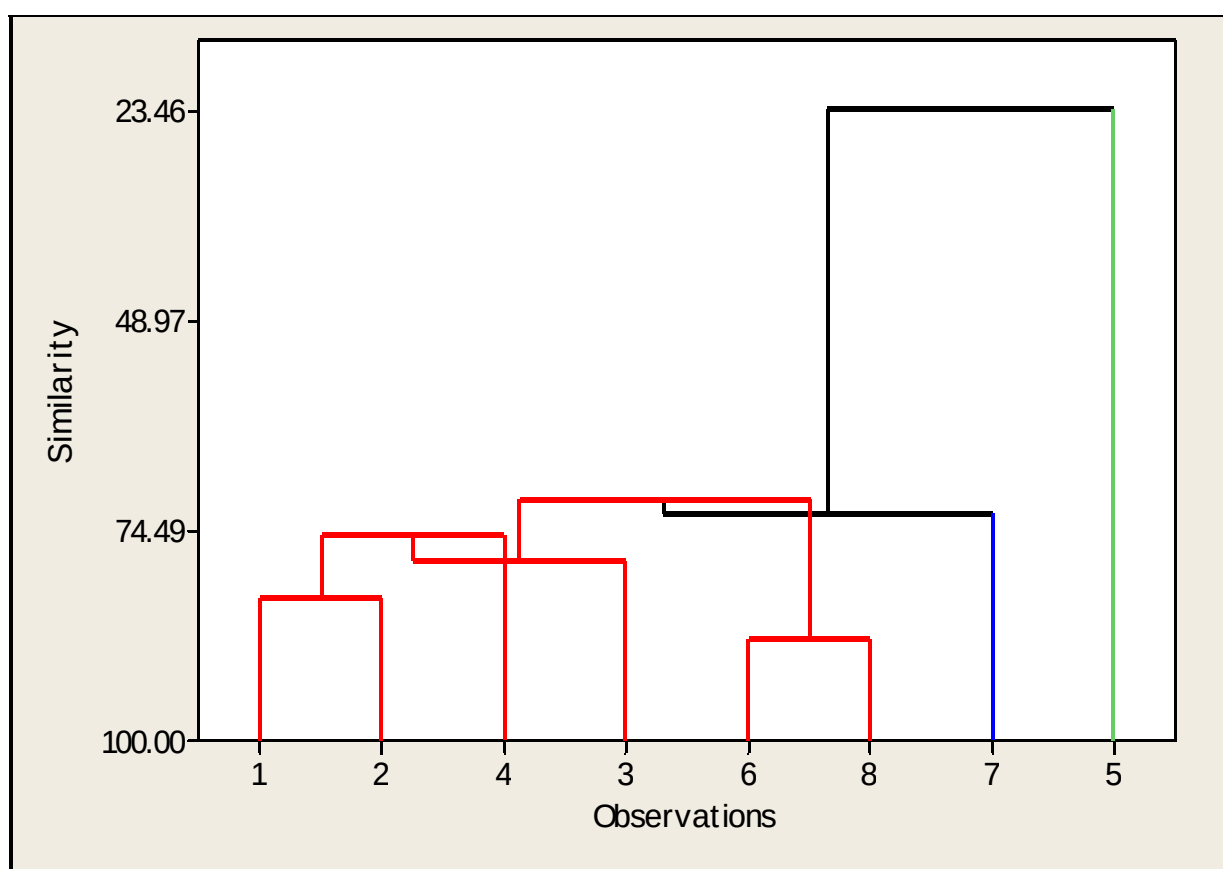


Figure 5.11: Loading plot for the 3-way interaction variety x season x location for the six sunflower and tow maize varieties

These PCA results are further corroborated by cluster analysis (Figure 5.12) where the four sunflower varieties, Record, Milika, Chongwe and Saona are closely linked. The Euclidean distance between Record and Milika was 5.28 with a similarity level of 82.6%. The Euclidean distance between Record and Milika and Chongwe and Saona was 7.54 with a similarity level of 75.2%. Thereafter, a close similarity of 87.8% was observed between PAN7371 and MRI455 with a Euclidean distance of 3.71. The sunflower variety PAN7352 had the furthest distance from its counterparts (23.27) and the lowest similarity (23.5%). The maize variety MRI514 had a Euclidean distance of 8.41 from Record and similarity of 72.3%.



Key: 1=Record, 2=Milika, 3=Saona, 4=Chongwe, 5=PAN7371, 6=PAN7352, 7=MRI514, 8=MRI455

Figure 5.12: Dendrogram with centroid linkages and Euclidean distances for the 3-way interaction variety x season x location

5.3 Crop Yield

5.3.1 Yield in sunflower and maize crops

Table 5.14 shows the analysis of variance for crop yield at the two locations over two seasons separated by crop and also pooled for the crops. Full ANOVA tables are in Appendix 3.4.

Table 5.14: Summary of crop specific and combined across crops Analysis of Variance for crop yield grown at two locations, Field Station and Liempe Farm over two seasons 2008/9 and 2009/10, Lusaka Province

Source	For sunflower only			For maize only			For both crops		
	df	Fcalc	Sign	df	Fcalc	Sign	df	Fcalc	Sign
Replication	3	75.70	*	3	2826	*	3	255.64	*
Variety	5	0.00	ns	1	7.25	ns	7	11.16	*
Variety*Replication	15								
Season	1	12.67	*	1	1.90	ns	1	0.05	ns
Season* Replication	3								
Location	1	54.90	*	1	1.27	ns	1	1.15	ns
Location* Replication	3								
Variety*Season	5	1.02	ns	1	4.87	ns	7	3.10	*
Variety*Season*Rep	15								
Variety*Location	5	1.20	ns	1	3.14	ns	7	1.83	ns
Variety*Location*Rep	15								
Season*Location	1	20.80	*	1	11.22	*	1	24.51	*
Season*Location*Rep	3								
Variety*Season*Loc	5	4.08	*	1	555.7	*	7	43.33	*
Error				67			277		
Pooled error	210								
TOTAL	287			95			383		

From Table 5.14, it can be observed that under maize, only two sources of variation were significant namely the 2-way interaction season x location and the 3-way interaction variety x season x location. Under sunflower, season and location as single factors were significantly different for yield. However, since interactions involving the two were also significant, no

further explanation was made for the single factor effects. Further, significant interactions were detected between season x location and among variety x season x location. The combined analyses showed significant differences for varieties, significant interactions between variety x season, and between season x location. The combined analysis also showed significant interaction among variety x season x location.

5.3.1.1 Effects due to variety x season for combined analysis

Table 5.15 shows the mean yields for the interaction variety x season and the proportion of potential yield achieved.

In S1, Milika had the least deviation from its potential yield of 1,500 kg ha⁻¹ of only 13% while Chongwe had the highest deviation of 86%. Only Saona yielded fairly highly in this season, deviating by 26% from the potential. The remaining three sunflower varieties deviated from the potential yield quite significantly by 42%, 50% and 35% for Record, PAN7371 and PAN7352, respectively. The two maize varieties MRI514 and MRI455 only yielded 22% and 23% of their potential yields respectively.

Table 5.15: Crop yield means (kg ha⁻¹) for the interaction variety x season for the six sunflower and two maize varieties and % of potential yield achieved

Variety	Season			
	S1	% of potential	S2	% of potential
Record	873.71	58	771.10	51
Milika	1311.64	87	1223.23	82
Saona	1111.17	74	668.65	45
Chongwe	203.50	14	35.75	2
PAN7371	753.36	50	492.96	32
PAN7352	985.76	65	421.20	28
MRI514	1347.19	22	2715.99	45
MRI455	1350.14	23	2014.79	34
LSD _{a,0.05}	175.72			

In S2, the two maize varieties yielded significantly higher than in S1 but still only achieved to yield 45% and 34% of their yields, respectively. Among the sunflowers, only Milika yielded very well (82% of its potential) while the remaining sunflower varieties yield 51%, 45%, 2%, 32% and 28% of their potential yields for Record, Saona, Chongwe, PAN7371 and PAN7352, respectively.

Across the two seasons for each individual variety S1 (Figure 5.13) revealed the following: all sunflower varieties had higher yields in S1 than in S2. However, the differences between the two

seasons varied. Record and Milika had minimal differences between the two seasons; declines of 11.7 and 6.7%, respectively from S1 to S2. These were followed by PAN7371 and Saona whose declines were 34.6 and 39.8%, respectively. PAN7352 and Chongwe had very significant declines from S1 to S2 of 57.3 and 82.4%, respectively. The two maize varieties both yielded significantly higher in S2 than S1. MRI514 yielded over double in S2 what it yielded in S1 while MRI455 yielded 49.2% higher in S2 than in S1. A strong positive correlation coefficient of 0.78 was found between the two seasons.

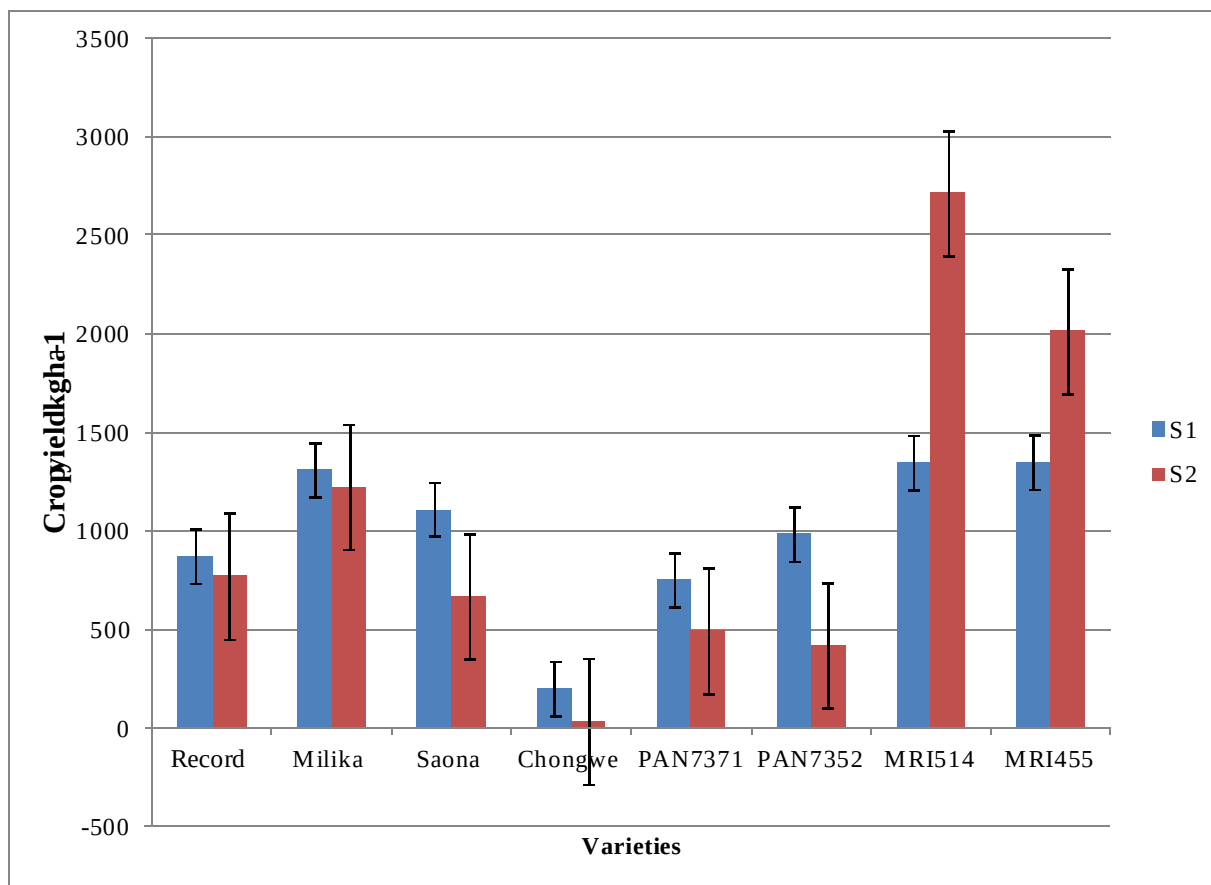


Figure 5.13: Crop yield means (kg ha^{-1}) for the interaction variety x season for the six sunflower and two maize varieties

5.3.1.2 Effects due to season x location for combined analysis

Table 5.16 shows the yield means for the interaction season x location.

The yields of the two locations were diametrically opposed. The FS had significantly higher yields in S1 ($1,173.99 \text{ kg ha}^{-1}$) than in S2 ($812.73 \text{ kg ha}^{-1}$) while LF had significantly higher

yields in S2 (1,273.19 kg ha⁻¹) than S1 (810.28 kg ha⁻¹). The decrease at the FS from S1 to S2 was 30.8% while the increase at LF was 36.4%.

Table 5.16: Interaction means (kg ha⁻¹) for the interaction season x location for crop yield

Season	Location	
	Field Station	Liempe Farm
S1	1173.99	810.28
S2	812.73	1273.19
LSD _{a,0.05}	87.86	

5.3.1.3 Effects due to the interaction variety x season x location

This three-way interaction was significant for all the analyses and its means are shown in Figure 5.14.

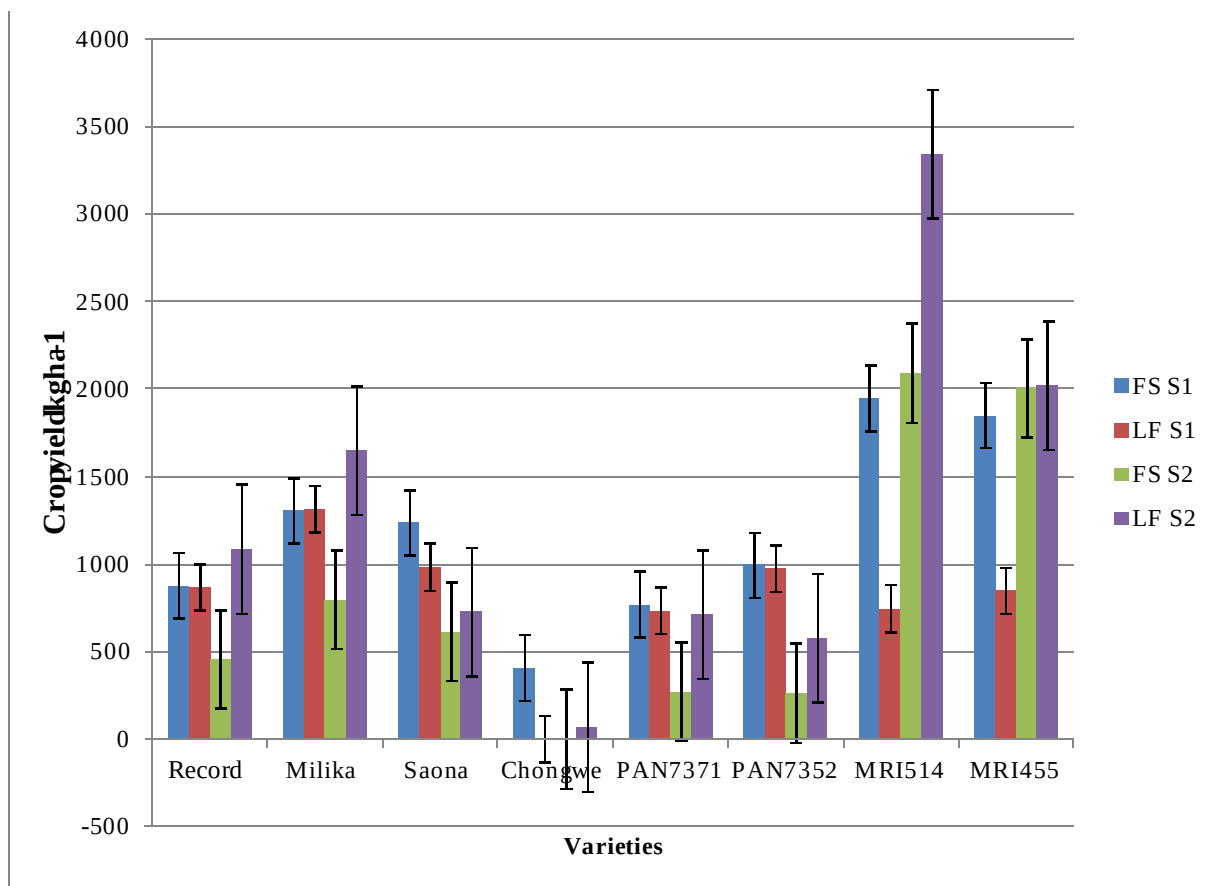


Figure 5.14: Yield (kg ha⁻¹) means for the three-way interaction variety x season x location for the six sunflower and two maize varieties

The PCA revealed that PC1 was strongest for five sunflower varieties [Record (0.378), Milika (0.352), Saona (0.408), PAN7371 (0.473) and PAN7352 (0.458)] while for Chongwe PC3 was the strongest (0.679). For the two maize varieties, PC2 was the strongest component [MRI514 (-0.639) and MRI455 (-0.495)] (Table 5.29).

Table 5.17: Principal components for the three-way interaction variety x season x location for the six sunflower and two maize varieties

Variety	PC1	PC2	PC3
Record	0.378	-0.338	-0.295
Milika	0.352	-0.367	-0.336
Saona	0.408	0.176	0.393
Chongwe	0.274	-0.130	0.679
PAN7371	0.473	-0.100	-0.107
PAN7352	0.458	0.200	0.058
MRI514	-0.109	-0.639	0.035
MRI455	-0.215	-0.495	0.412

The loading plot (Figure 5.15) illustrates the above. All the sunflower varieties loaded closely together, quite distantly from the maize varieties. Among the sunflowers, Saona and PAN7352 loaded exactly the same while Record and Milika loaded closely and Chongwe and PAN7371 also loaded closely.

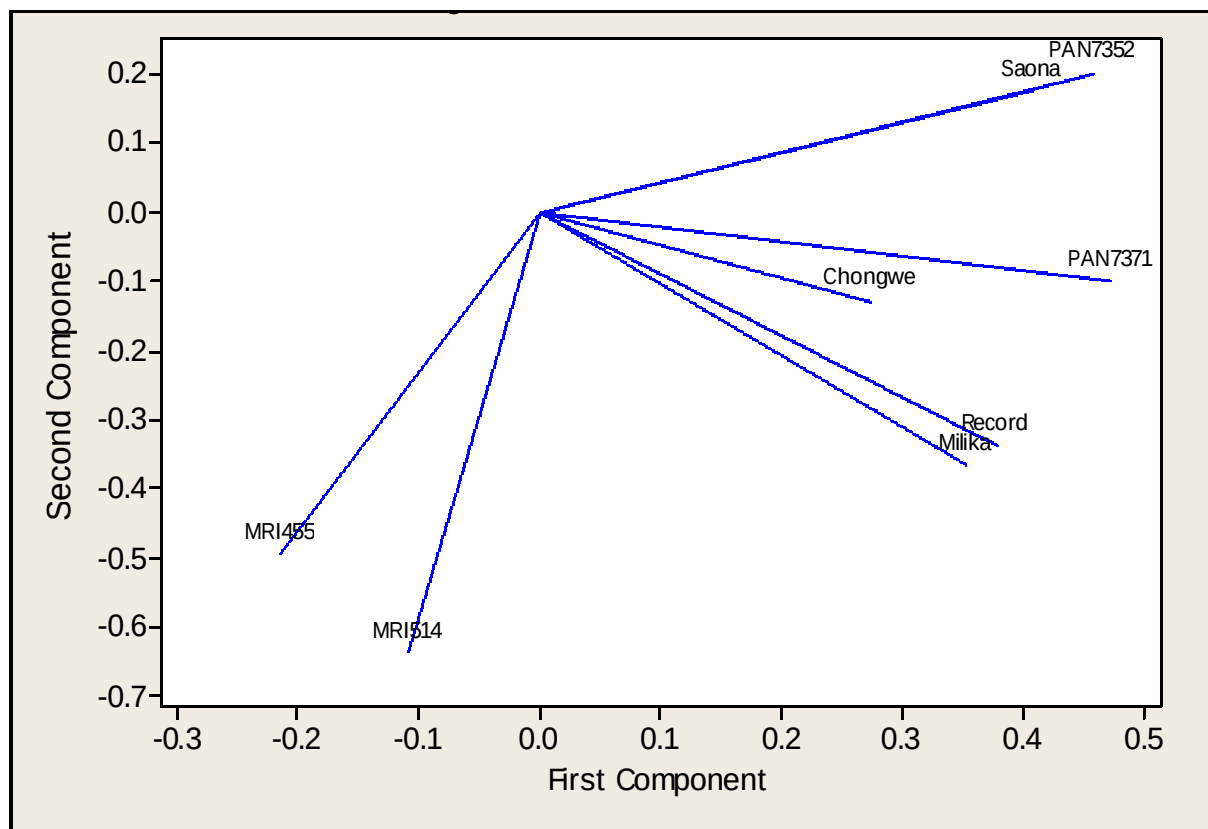
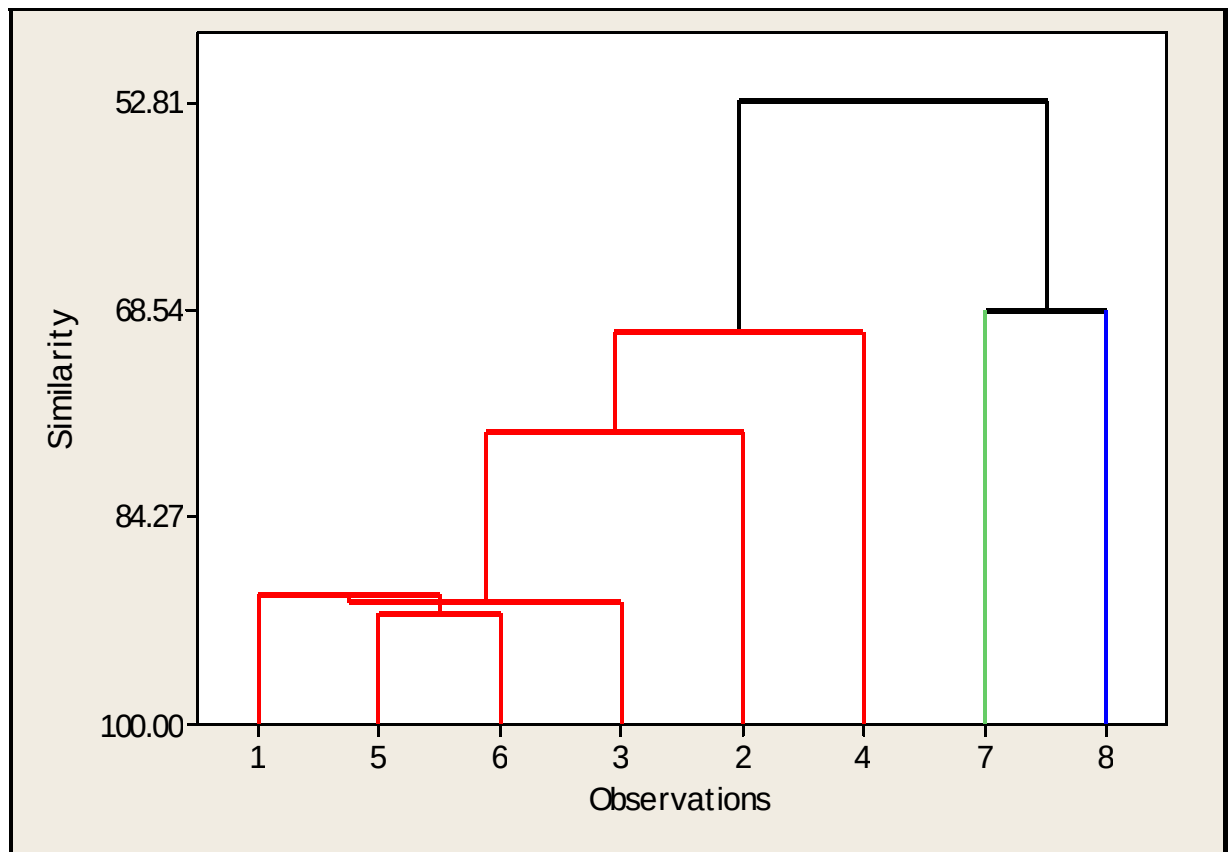


Figure 5.15: Loading plot for the 3-way interaction variety x season x location of sampling for the six sunflower and two maize varieties

These PCA results were further corroborated by cluster analysis (Figure 5.16) where the six sunflower varieties, Record, PAN7371, PAN7352, Saona, Milika and Chongwe were more closely linked to each other than to the two maize varieties. The maize varieties in turn were more closely linked to each other also.

Among the sunflowers, PAN7371 and PAN7352 have a similarity level of 91.6% with a Euclidean distance of 355.82. Record had a similarity level with these two of 90.1% and was separated from them by a Euclidean distance of 418.88. Saona was separated from the two PAN varieties by a Euclidean distance of 391.06 with a similarity level of 90.8%. Milika's similarity level to the two PAN varieties was 77.78% with a Euclidean distance of 1,257.28 while Chongwe had a similarity level of 68.7% with a Euclidean distance of 1,327.46. The two maize varieties had similarity level of 52.8% with the PAN varieties and a Euclidean distance of 2,000.72. Between the two of them, MRI514 and MRI455 had a similarity level of 68.7% with a Euclidean distance of 1,327.46.



Key: 1=Record, 2=Milika, 3=Saona, 4=Chongwe, 5=PAN7371, 6=PAN7352, 7=MRI514, 8=MRI455

Figure 5.16: Dendrogram with centroid linkages and Euclidean distances for the 3-way interaction variety x season x location for the six sunflower and two maize varieties

CHAPTER SIX

6.0 DISCUSSIONS

6.1 General

The two seasons were very different from each other although the meteorological data shows great similarities. Season 2 had a good rainfall distribution at both locations and was hence considered a normal year for agricultural production. Season 1 on the other hand had an erratic distribution so that there were no rains at the critical periods for crop growth and was hence considered a drought year viz-a-viz agricultural production. The differences thus observed between them can be attributed, in part, to that. No major pest problem or disease incidence of any consequence was encountered during both seasons.

The two locations are quite similar in that they both fall under agro-ecological region II of Zambia's zoning system and hence have fairly similar characteristics. However, their soils are quite different (fine loamy mixed isohyperthermic oxic paleustalf for the Field Station and fine loamy mixed isohyperthermic oxic kandiustalf for Liempe Farm) and this was the major reason for including them. This is because Kobayashi (2004) pointed out that the phytotoxic activity of allelochemicals is affected by soil factors, usually leading to a decrease in their activity.

The three times of sampling were included in order to determine the effects of the progressive nature of weed growth on the crops during the season. In crop interference, two aspects are key; the density of the weeds and the time when the weeds are interfering with crop growth. Hence, sampling the weeds at three different times during the growth of the crops helped to gain insights and make deductions on the time when the weeds were most damaging.

The choice of the two crops, sunflower and maize was based on two factors:

- i) The two crops have very similar agronomic practices recommended for them except that the amounts for fertilizers for sunflower are half those recommended for maize; and
- ii) Maize is not known to be allelopathic while sunflower is reported to have allelopathic potential.

Since sunflower is a late planted crop (usually planted in December or January), care was taken in the selection of maize varieties. Short season varieties were selected which could be planted at the same time as the sunflowers and mature at the same time (MRI514 and MRI455).

The sunflower varieties were selected at random, based mainly on availability. Nonetheless, these are their general characteristics: Record, Milika, Saona and Chongwe are open pollinated varieties (OPV) while PAN7371 and PAN7352 are hybrids. Among the OPVs, Record was an introduced variety from Tanzania, while Milika and Saona were locally bred varieties from the Zambia Research Institute and Chongwe was a fairly newly bred variety by a private company Maize Research Institute.

6.2 Weed diversity

The Field Station is an experimental station where research and some commercial activities are conducted. It is intensively used both during the rain-fed season as well as off-season with irrigation. Its weed flora is hence intense as weeds thrive all year round. The top five common weeds in the Field Station were *Cynodon dactylon*, *Bidens pilosa*, *Eleusine indica*, *Amaranthus hybridus* and *Cyperus* spp. Apart from *Cynodon dactylon*, the rest are listed to be among the top ten most common weeds in Zambia. The fields used at Liempe Farm on the other hand are non-irrigated and hence do not have the same intensity of weeds as those observed at the Field Station. The weed flora of the fields was typical of most dry land farmed areas of Region II. The annual weeds tend to die off during the dry season while the perennial ones over-winter in various perennating structures. The five major weeds there were *Amaranthus hybridus*, *Cynodon dactylon*, *Nicandra physalodes*, *Commelina benghalensis* and *Bidens pilosa*. It can be noted that *Eleusine indica* which is normally an annual weed did not act as one at the FS since it did not die off at the end of the rainy season due to presence of moisture but died off at LF. However, overall, the two locations had similar weed flora (Vernon, 1983).

There were more weeds in maize on average than in sunflower. This could be partly attributed to the allelochemicals released by sunflower which were not present in maize (Khanh *et al.*, 2005). Further, there were fewer weeds of certain species in sunflower than in maize. *Rottboellia conchinchinensis*, *Eleusine indica*, *Cyperus* spp., *Digitaria milanjiana*, *Nicandra physalodes* and *Bidens pilosa* were fewer in the sunflower plots than in the maize ones. These species could have been the ones that were more sensitive to the allelochemicals released by sunflower which allelochemicals were not present in the maize plots.

6.3 Weed density

Weed density within a season varied across location and time of sampling under both sunflower and maize. Anafjeh and Chaab (2012) postulated that the higher the weed density, the higher the competition between the crop and the weeds; with weeds usually getting an inordinate amount of

the growth requirements. Weed intensity was generally higher in maize than in sunflower as evidenced through the high weed density. This is probably because they had access to more growth resources and also due to the absence of allelochemicals. These findings agree with the postulations of Semidey (1999), Morris and Parish (1992) and Leather (1987) who reported that sunflower plots tended to have fewer weeds than plots with other crops. Cultivated sunflower has been shown to contain a series of heliannuols, which show more subtle effects and seem to be signals influencing the germination and growth of competitive seeds (Birkett *et al.*, 2001).

Weed density was different for the three times of sampling with T1 having the highest weed density and T3 having the least in S1 but T2 having the least in S2. This shows that at the beginning of the season, there were more weeds in the fields. As the season advanced, these reduced progressively in S1 but not in S2. The plausible explanations include the normal senescence of weeds but this does not hold water in S2 where T2 had significantly fewer weeds than in T1 and especially T3. Hence some weed suppressive activity can be deduced from these results and this is being attributed to the weed suppressive capacity of the sunflowers through allelopathy.

Season 2 was a normal year while S1 was a drought year which could explain the difference between the two. These seasonal variations portrayed the spatial variation of weed density in line with Uremis *et al.*, (1997). Further, this data set shows that seasonal differences will be experienced and it will be important to understand if what is actually happening in the season seems to enhance or decrease the weed suppressive activity, as the case may be (Knezevic *et al.*, 2002).

Locational differences were experienced where at the FS there were significantly more weeds in S1 than in S2 while no significant difference was observed at LF between the two seasons. This has been attributed to the differences in soil types between the two locations. Soils are a factor in allelopathy in that allelochemicals in the soils are adsorbed on soil solids and are metabolized by chemical and biological reactions during movement in the soil (Duke *et al.*, 2000; Wardle *et al.*, 1992; Quasem and Hill, 1989).

6.4 Weed biomass

In this study, the amount of weed biomass that grew under different varieties varied by season, location and time of sampling under sunflower and to a greater extent under maize. Also observed was that weed biomass within location significantly varied across seasons and time of sampling under sunflower but to a lesser degree under maize.

Plots with sunflower varieties had lower weed biomass than the maize plots. Differences were also observed within the sunflower varieties for weed biomass in the plots. Leather (1987)

conducted field studies to determine if season long weed control could be achieved by combining the use of a herbicide with the natural allelochemicals produced by cultivated sunflower and found that weed biomass was reduced equally in plots planted with sunflower, whether or not the herbicides applied.

Varietal differences across and within seasons were discerned indicating that varieties reacted differently temporally (Figure 6.1).

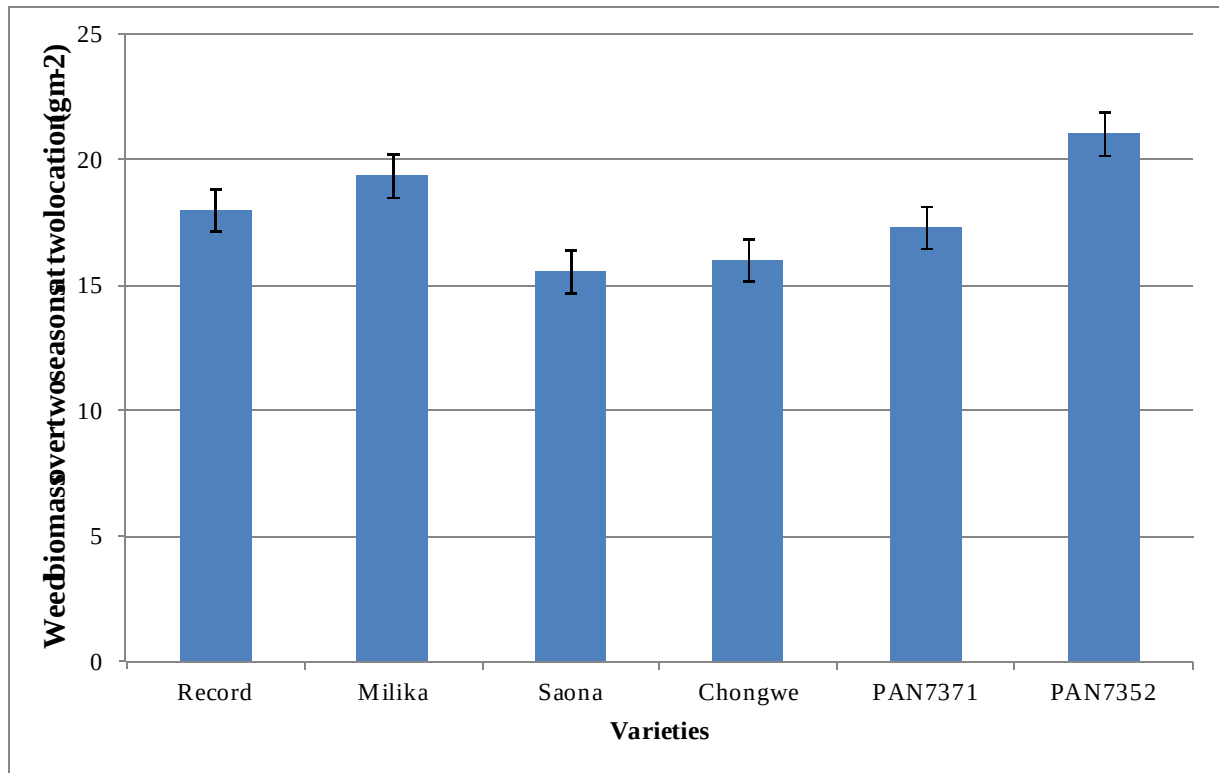


Figure 6.1: Weed biomass for the six sunflower varieties grown at two locations for two seasons.

Anjum *et al.*, (2005) reported that the expression of allelopathic effects by sunflower was highly dependent upon the particular variety. Macais *et al.* (1999) also reported that that sunflower showed great genotypic differences in allelopathic activity among the genotypes tested. Besides the growth habit of sunflower, which has broad leaves and is a faster growing crop that helped cover the inter row spaces faster than maize, also probably helped to suppress emerging weeds or emerged but small weeds. Wang *et al.*, (2006) explained that the growth habit of a crop and competing weed species are important determinants of crop-weed interference. The lower weed numbers in sunflower are probably due to both allelopathy as well as the growth habit of the plant. Olofsdotter *et al.*, (1999) also explained that under field conditions, allelopathy does not occur independently of other mechanisms of plant interference and that therefore, the interference outcome of a cultivar is a combined effect of allelopathy and competitive ability.

Allelopathic properties of plants can be utilized for weed control as allelochemicals suppress other plant growth in the natural habitat of the producer plant (Birkett *et al.*, 2001). Further, several authors conducted well designed field experiments and chemical analyzes to provide convincing evidence of allelopathy (Vivanco *et al.*, 2004; Bias *et al.*, 2003; Callaway and Aschehoug, 2000). While Milika accumulated the highest weed biomass in S1 and at the FS, extrapolated to being the least weed suppressive capacity, PAN7352 had the highest weed suppressive capacity in this season with the other four sunflower varieties being in between the two. However, in S2 and at LF, PAN7352 had the least weed suppressive capacity with Milika having high weed suppressive capacity in that season (Figure 6.2). The trend that was observed was that all the OPVs had higher weed suppressive capacity in S2, the normal year but not in the drought one S1. The exact opposite was observed for the two hybrids (PAN7371 and PAN7352) which had high weed suppressive capacity in the drought season S1 but not in the normal one.

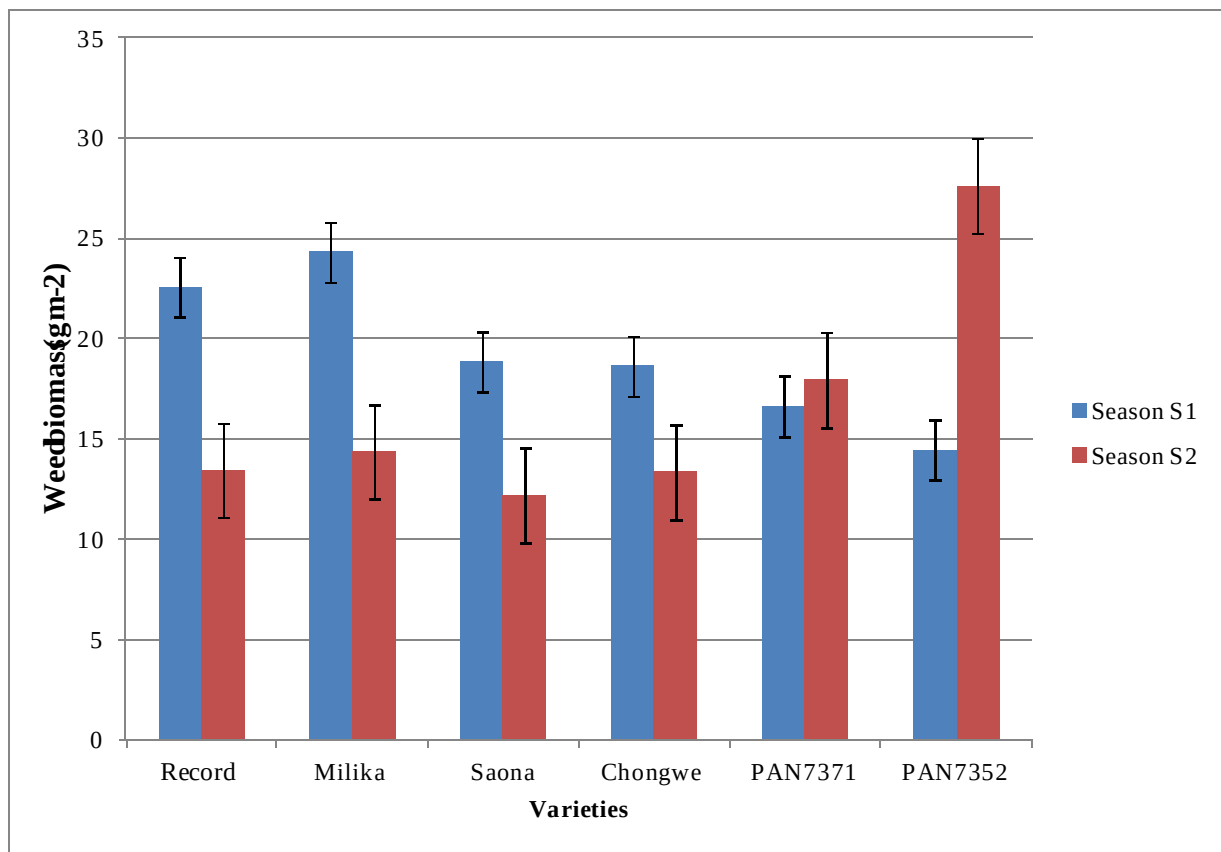


Figure 6.2: Spatial effects of the sunflower varietal weed biomass across the two seasons

Johnson *et al.* (2004) also found that weed patterns in two seasons differed significantly making it imperative for seasonal based differences. Literature also shows that allelopathic effects are not independent of stresses (Inderjit, 1995) such as high or low rainfall or temperature extremes that

are out of the ordinary. No two seasons are exactly the same due to the variations in these climatic factors. Rice (1974) confirmed that concentrations of allelochemicals increased when plants were under stress. Therefore, each season produced different stress levels and the plants as a consequence produced different concentrations of allelochemicals. These are then exhibited as varying allelopathic potential as a result of different seasons and this was observed in this study. Further, Pelegrini and Cruz-Silva (2012) observed seasonal variation in allelopathic potential of plants and Kalinova (2000) also showed that the influence of year on allelopathic activity of buckwheat was statistically significant. Similar postulations were made by Wu *et al.* (2000) on his study among wheat accessions.

Differences between the Field Station and Liempe Farm were most attributed to be due to the different soil types of these two locations. Figure 6.3 shows these differences.

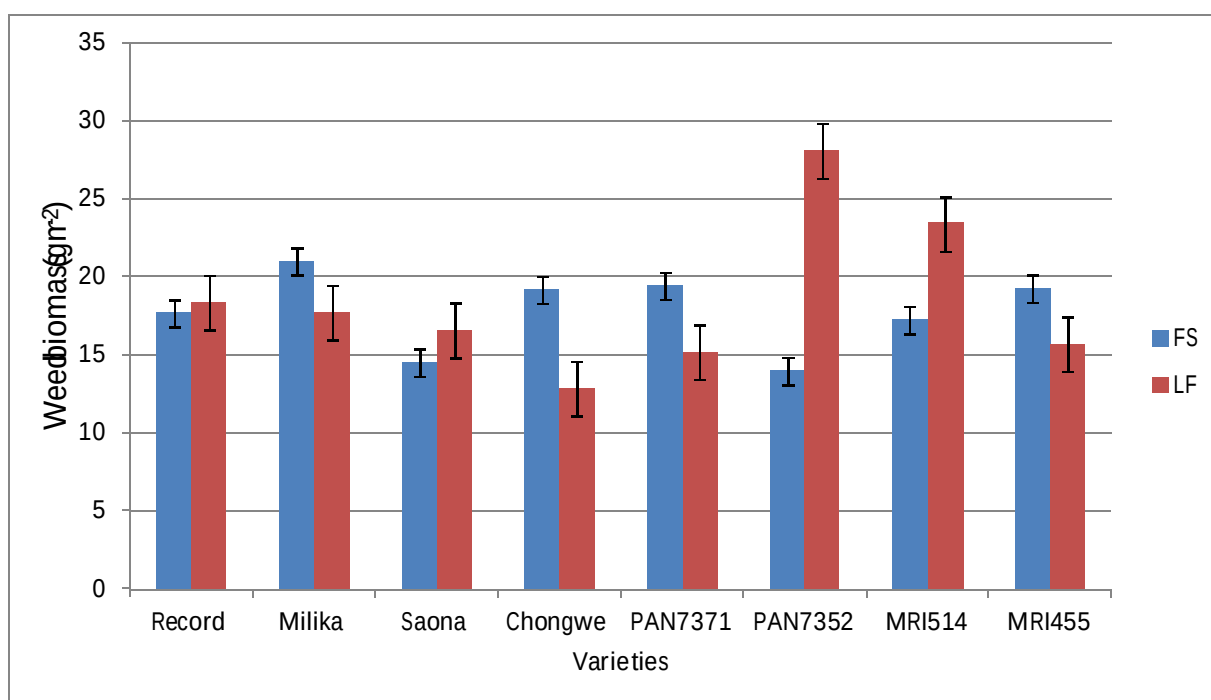


Figure 6.3: Spatial differences of weed biomass between the two locations for each variety

Allelopathy in the soil is a complicated phenomenon that is affected by soil conditions, growth conditions of the donor and receiver plants and climatic conditions. Allelochemicals in the soil are adsorbed on soil solids and metabolized by chemical and biological reactions during movement in the soil (Duke *et al.*, 2000; Wardle *et al.*, 1992; Quasem and Hill, 1989). This behavior is affected by various soils factors such as soil physical, chemical and biological properties which affect the phytotoxic activity in the soil (Inderjit, 2001). This usually leads to a

decrease in their activity (Kobayashi, 2004). In this study, no specific trend was discerned making it difficult to draw any inferences about the two locations and their attendant soil types.

Temporal differences were observed among the different varieties for time of sampling. While the two hybrid sunflowers (PAN7371 and PAN7352) varieties seem to have high weed suppressive capacity early in the season (low weed biomass at T1), they did not sustain this because at T2 PAN7352 had the highest weed biomass (higher than what they had at T1) showing that its weed suppressive capacity had been lost or that there might have been some excitory activity happening. The difference between T1 and T2 for PAN7371 was not significant just like that of the maize variety MRI455. This was not so for the other four sunflower varieties which had progressively lower weed biomass as the season progressed (Figure 6.4).

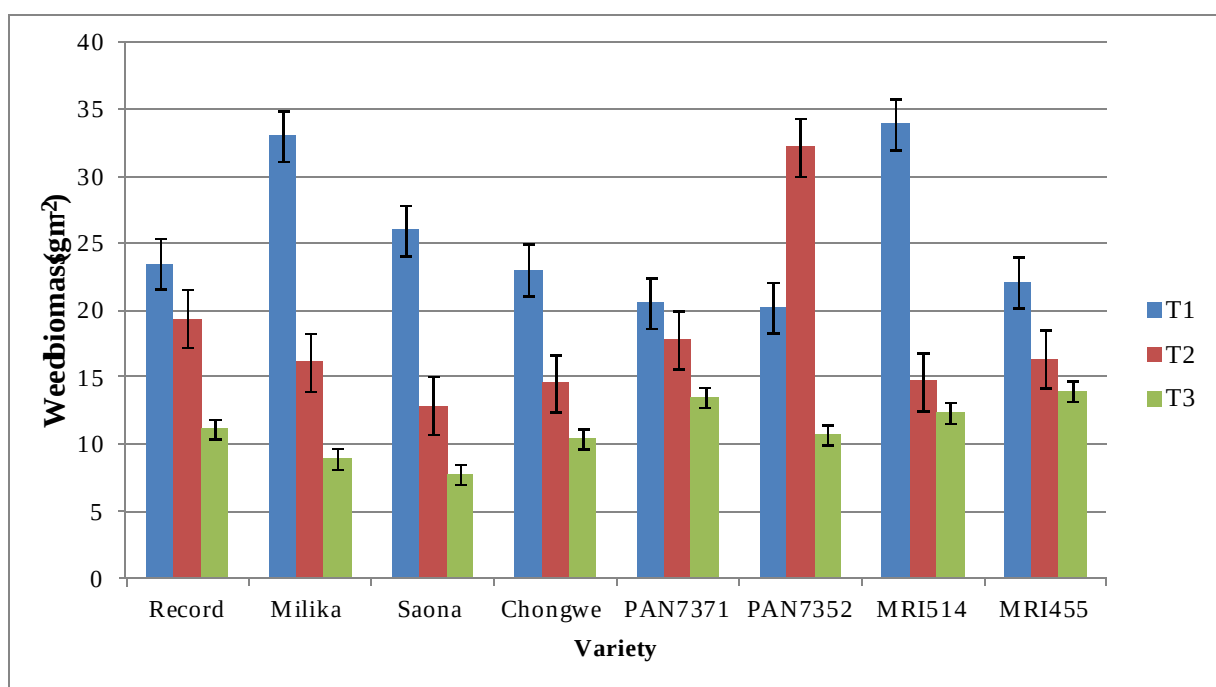


Figure 6.4: Temporal differences of weed biomass for the three times of sampling for each variety

Burgos *et al.*, (1999) and Reberg-Horton *et al.*, (2003) showed that weed suppressiveness of allelopathic crops changes over time. This can be explained by the fact that species of micro-organisms in soils are very diverse and decompose organic matter and potential allelopathic agents (Blum, 2003). As soil properties change, so do the activities of microbial species within the soil.

The two crops were very different from each other according to both the PCA and Cluster analysis results. Thereafter, the two maize varieties were quite different from each other. Among the sunflower varieties, these were the differences discerned: Record, Milika and Saona were very similar. Chongwe also had a close relationship to these three but was slightly more different from them. The two hybrids (PAN7371 and PAN7352) were then very different from the four OPV sunflowers. However, these two hybrids were then not very similar to each other too.

This outcome follows the expected trend that the two crops would be different. However, among the sunflowers, the trend is that the OPVs are more similar to each other than to the hybrids.

6.5 Crop yields

In this study, the percentage yield loss from the potential for the varieties of the two test crops (maize and sunflower) are shown in Figure 6.5.

Maize varieties performed below expected. Maize yields in this study were drastically reduced as compared to most sunflower yields grown in the same weedy environment, and the deduction is that this was the result of the effect of weeds. Maize had high number of weeds and higher weed biomass. The presence of high number of weeds had a negative effect on the growth of maize probably due to a disproportionate amount of growth resources appropriated by the weeds. Akobundu (1987) reported that weeds are more efficient in resource use and will therefore have a competitive edge over less efficient crops like maize. Paller (2002) showed that the potential yield losses due to weeds in maize have been estimated at 16 -80%. Meanwhile, maize is believed not to be allelopathic (Akinbo, O., <http://www.nepadbiosafety.net/abne/wp-content/.../Crop-biology-of-maize.pdf>; 27/11/2014) or if allelopathic, this tends to come out at maturity (Lehle and Putnam, 1982). Such latter activity would be of little or no use in suppressing weeds during the growth of the crop. This means that maize is most likely involved in resource competition with the weeds as opposed to interference competition.

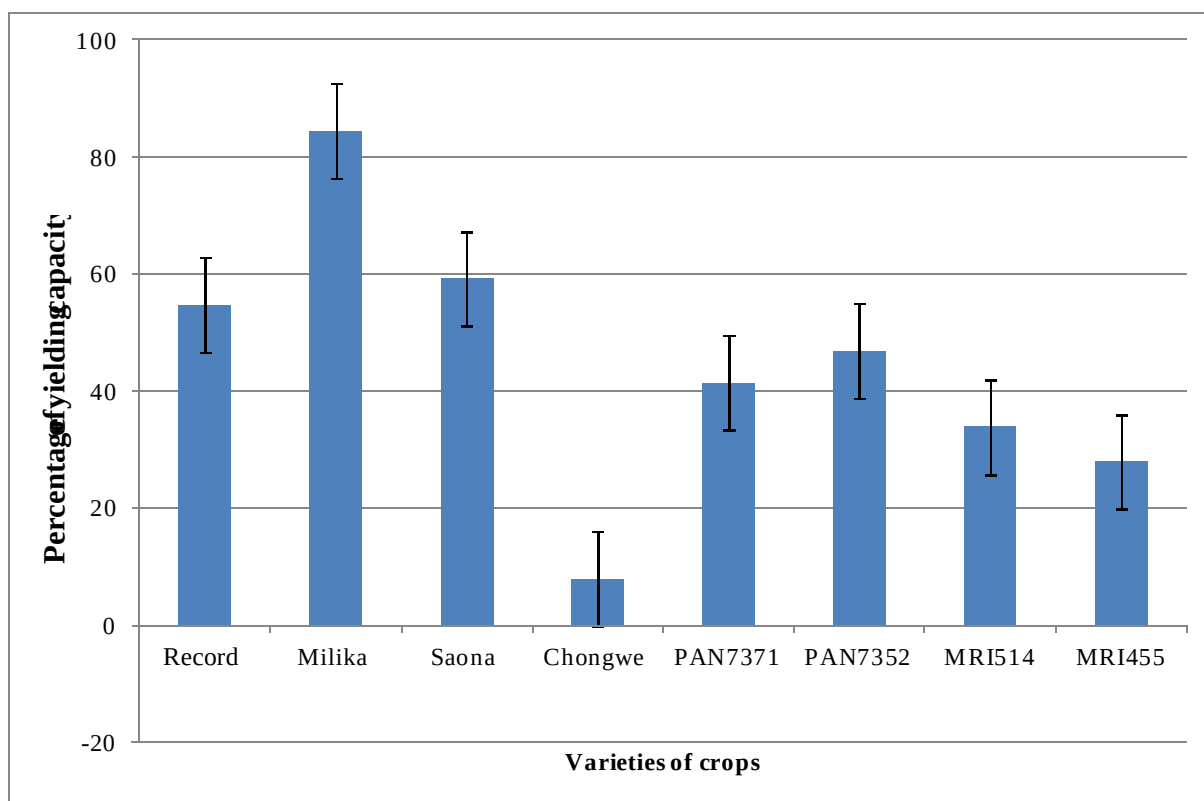


Figure 6.5: Percentage of the yielding capacity of each variety (actual yield as a fraction of the potential yield).

Sunflower, on the other hand had fewer weeds, probably because of its known allelopathic activities but also due to its growth habit. Leather (1987) reported that sunflowers are allelopathic in nature and negatively affect other plants growing in their vicinity. Kupidowski *et al.*, (2006) showed that sunflower can actively influence the growth of surrounding plants and even demonstrated selective phytotoxicity of their residues towards weeds. Bashir *et al.*, (2012) also indicated that the cultivated sunflower has been reported to be allelopathic to weeds. All these could explain why sunflower fields in the study had fewer weeds than their maize counterpart.

Varietal differences were observed among the sunflowers with Milika being the highest yielding variety (yielding above 80% of its potential yield) and Chongwe being the lowest, hardly yielding anything. Daugovish *et al.* (2003) showed that full competition from weeds can reduce the yield of sunflower by 58% while Varga *et al.* (2006), Milberg and Hallgren (2004), Martin *et al.* (2001) and Wall and Smith (2000) postulated that typical yield losses of sunflower due to weed competition were 40%. Milika also had the lowest weed suppressive capacity overall. This is probably linked to the cost associated with toxin production since toxin producers will normally grow more slowly than sensitive strains (Frank, 1994).

These differences can be explained in part as the varying competitiveness of the different varieties with weeds. Competition is an interaction between organisms or species in which the fitness of one is lowered by the presence of another due to limited supply of at least one resource used by both (Begon *et al.*, 2006). Competition comes in different forms; resource and interference competition. Resource competition involves direct acquisition of a resource with no interaction with competitors beyond depriving them of a resource while interference competition requires additional activities to those needed for resource competition (Amarasekare, 2002). Direct interference via allelopathy is one good example of interference competition (Weidenhamer *et al.*, 1989). In this study, it is believed that sunflower was involved in interference competition using allelopathy as an interference mechanism. This appears to have given sunflower a relative competitive edge over weeds as also observed by Anjum *et al.* (2005); Ciarka *et al.* (2004); Gawronska *et al.* (2004); Azania *et al.* (2003) and Batish *et al.* (2002).

These results seem to suggest different types of competition the two crops are involved in. While maize is apparently involved in resource competition with the weeds, sunflower appears to be involved in interference competition. Hence maize was being affected more by the presence of weeds since it had to literally “fight” for growth factors with the weeds while sunflower had an alternative mechanism – allelopathy, which gave it a competitive edge over the weeds. Sunflower, thus, was able to suppress the weeds and have lower infestation in the same environment. Allelopathy seems to be at play in this study where the crop known to possess this phenomenon (sunflower) is acting the way it is supposed to, having less weed infestation than its counterpart (maize) which does not get any benefits of allelopathic activity.

6.6 Evidence of allelopathy in the two crops

In the current study, sunflower varieties interacted with weeds differently from the maize varieties as evidenced from the results and the discussions above. Weed diversity was similar in all the fields. However, weed density and biomass under sunflower were lower than those under maize while average seed/grain yield of the two crops showed that sunflower yielded 39% lower than the optimum yield for sunflower in this region but the maize varieties yielded 69% lower than the optimum (Appendix 4). Further, both the multivariate analysis results (PCA and Cluster Analysis) revealed that there were higher similarities among the sunflower varieties in comparison to them and the maize varieties.

CHAPTER SEVEN

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The study established that indeed there was weed suppression by some of the local sunflower varieties used in the study and it was deduced that this could be attributed to the possibility that sunflower was involved in interference competition with weeds, allelopathy being the reason for the interference.

Weed intensity (both density and biomass) was higher in maize than in sunflower. This intensity was affected by locations (which had different soil types), the seasons which differed quite appreciably with each other (one was drought and the other was a normal year), and the time of sampling.

On average, sunflower yielded better in the presence of weeds (with the group leader Milika yielding above 80% of the potential) than the maize which collectively yielded only about 30% of the potential.

No varietal differences were observed for maize on weed suppressiveness but these were observed in sunflower. However, Milika the highest yielding sunflower also appeared to have the least weed suppressive capacity pointing to the issue of cost incurred by the plant associated with toxin production. Hence, the production of allelochemicals by the sunflower varieties appeared to be costly in terms of its productivity for the economic yield of seeds.

7.2 Recommendations

Sunflower can be encouraged as an alternative crop for small holder farming since it will grow with reduced weed pressure and lessen weeding requirement.

Breeders should consider the cost of toxin production so that they can come up with sunflower varieties that have both high allelopathic activities and will be high yielding.

This is a broad area of study and many facets of it are still begging for research which should be encouraged by various researchers.

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APPENDICES

Appendix 1:

A. Meteorological data for the research sites

No.	Parameter	Year 1 (2009)	Year 2 (2010)
1.	Annual average temperature (T°C)	19.1	19.0
2.	Annual average maximum temperature (TM°C)	27.8	28.4
3.	Annual average minimum temperature (Tm°C)	11.1	10.9
4.	Total annual precipitation (PP mm)	-	-
5.	Annual average wind speed (V kmh ⁻¹)	9.6	10.1
6.	Number of days with rain (RA)	89	84
7.	Number of days with snow (SN)	0	0
8.	Number of days with storm (TS)	54	52
9.	Number of foggy days (FG)	27	31
10.	Number of days with tornado (TN)	1	1
11.	Number of days with hail (GR)	0	1
12.	Highest temperature recorded (°C)	35.8 (10 th Oct)	37.4 (13 th Oct)
13.	Lowest temperature recorded (°C)	4 (1 st July)	4 (21 st June)
14.	Maximum wind speed (kmh ⁻¹)	79.5 (26 th Dec)	79.5 (13 th June)
15.	Annual average wind speed (kmh ⁻¹)	9.6	10.1
16.	Annual visibility (km)	14.4	13.8

B. Monthly long term rainfall figures (mm)

No.	Month	Field Station	Liempe Farm
1.	January	220	227
2.	February	183	183
3.	March	85	87
4.	April	28	31
5.	May	3	3
6.	June	0	0
7.	July	0	0
8.	August	0	0
9.	September	1	1
10.	October	18	17
11.	November	90	87
12.	December	207	205
TOTAL		834	841

Appendix 2: Field layout



Not drawn to scale.

Appendix 3: Results tables

Appendix 3.1: Weed diversity in the study areas (combined for both seasons and locations) listed in alphabetical order

Weed species

Acanthospermum hispidum
Achhranthes aspera
Ageratum conyzoides
Amaranthus hybridus
Amaranthus spinosus
Amaranthus thumbergii
Bidens pilosa
Bidens schimperi
Boerhavia diffusa
Celosia trigyna
Cleome gynandra
Cleome hirta
Commenlina benghalensis
Corchorus olitorius
Cynodon dactylon
Cyperus esculentus
Cyperus rotundus
Datura stramonium
Digitaria milanijiana
Digitaria ternata
Eleusine indica
Eragrostic aspera
Euphorbia heterophylla
Euphorbia hirta
Galinsoga parviflora
Hibiscus meeusei
Leucas martiniensis
Nicandra physalodes
Ocimum canum
Oxalis latifolia
Oxalis obiquifolia
Panicum maximum
Portulaca olearaceae
Rottboellia conchinchinensis
Sesamum calycinum
Sonchus oleraceae
Targetes minuta
Trichodesma zeylanicum

3.2 ANOVA Tables for Weed Density

3.2.1 Sunflower only

Source	df	SS	MS	Fcalc	Fcrit	Significance
Rep	3	25538	8513	1.42	2.65	ns
Variety	5	56780	11356	1.90	2.26	ns
Season	1	9591	9591	1.60	3.89	ns
Time	2	61909	30955	5.17	3.04	ns
Loc	1	183618	183618	8.23	10.13	ns
Rep*Loc	3	66938	22313			
Variety*Season	5	37863	7573	1.01	2.9	*
Rep*Variety*Season	15	112556	7504			
Variety*Loc	5	31031	6206	1.04	2.26	ns
Variety*Time	10	82916	8292	1.39	1.88	ns
Season*Loc	1	131841	131841	22.03	3.89	*
Season*Time	2	71063	35531	5.94	3.04	*
Loc*Time	2	22210	11105	1.86	3.04	ns
Variety*Season*Loc	5	57396	11479	1.92	2.26	ns
Variety*Season*Time	10	58585	5858	0.98	1.88	ns
Variety*Loc*Time	10	62599	6260	1.05	1.88	ns
Season*Loc*Time	2	120029	60015	10.03	3.04	*
Pooled error	205	1226672	5983.766			
TOTAL	287	2419135				

3.2.2 Maize only

Source	df	SS	MS	Fcalc	Fcrit	Significance
Rep	3	3113	1038	0.62	2.73	ns
Variety	1	253	253	0.15	3.98	ns
Season	1	2817	2817	1.69	3.98	ns
Loc	1	54150	54150	32.57	3.98	*
Time	2	32586	16293	9.80	3.13	*
Variety*Season	1	28	28	0.02	3.98	ns
Variety*Loc	1	20	20	0.01	3.98	ns
Variety*Time	2	8441	4221	2.54	3.13	ns
Season*Loc	1	17604	17604	10.59	3.98	*
Season*Time	2	14890	7445	4.48	3.13	*
Loc*Time	2	778	389	0.23	3.13	ns
Variety*Season*Loc	1	1411	1411	0.85	3.98	ns
Variety*Season*Time	2	5029	2515	1.51	3.13	ns
Variety*Loc*Time	2	6915	3457	2.08	3.13	ns
Season*Loc*Time	2	53290	26645	16.02	3.13	*
Pooled error	71	118056	1662.761			
TOTAL	95	319381				

3.2.3 Combined crops

Source of Variation	df	SS	MS	F-value	C F	Sign.
Replication	3	22547	7515.667	1.518624	2.635106	ns
Variety	7	57847	8263.857	1.669804	2.040575	ns
Season	1	3396	3396	0.6862	3.873066	ns
Location	1	237606	237606	10.77741	10.12796	*
Location*Replication	3	66140	22046.67			
Time	2	92477	46238.5	9.343004	3.026257	*
Variety*Season	7	46903	6700.429	1.353896	2.040575	ns
Variety*Location	7	31213	4459	0.900991	2.040575	ns
Variety*Time	14	93375	6669.643	1.347676	1.725305	ns
Season*Location	1	145004	145004	29.29967	3.873066	*
Season*Time	2	83981	41990.5	8.484649	3.026257	*
Location*Time	2	18522	9261	1.871288	3.026257	ns
Variety*Season*Location	7	63248	9035.429	1.825709	2.040575	ns
Variety*Season*Time	14	65586	4684.714	0.946599	1.725305	ns
Variety*Location*Time	14	73980	5284.286	1.067749	1.725305	ns
Season*Location*Time	2	172605	86302.5	17.43838	3.026257	*
Pooled Residual Error	296	1464903	4948.997			
TOTAL	383					

3.3 ANOVA Tables for Weed Biomass

3.3.1 Sunflower only

Source	df	SS	MS	F calc	F crit	Significance
Replication	3	769.8	256.6	1.78	2.66	ns
Variety	5	1030.2	206	0.79	2.9	ns
Variety*Replication	15	3922.2	261.2			
Season	1	545.8	545.8	3.79	3.89	ns
Location	1	19.3	19.3	0.03	10.13	ns
Location*Replication	3	1931.9	644			
Time	2	9467.7	4733.8	13.74	5.14	*
Time*Replication	6	2007.6	344.6			
Variety*Season	5	4599.1	919.8	3.65	2.9	*
Variety*Season*Replication	15	3777	251.8			
Variety*Location	5	3251.6	650.3	4.52	2.26	*
Variety*Time	10	4903.4	490.3	3.41	1.88	*
Season*Location	1	5044.7	5044.7	35.04	3.89	*
Location*Time	2	6627.9	3313.9	23.02	3.05	*
Season*Time	2	2977.9	1489	4.92	5.14	ns
Season*Time*Replication	6	1814.6	302.4			
Variety*Season*Location	5	1561.7	312.3	2.17	2.26	ns
Variety*Season*Time	10	3800.2	380	2.64	1.88	*
Variety*Location*Time	10	3198.7	319.9	2.22	1.88	*
Season*Location*Time	2	1800.8	900.4	6.25	3.05	*
Pooled error	178	25627.2	143.973			
TOTAL	287	88679.3				

3.3.2 Maize only

Source	df	SS	MS	F calc	F crit	Significance
Rep	3	120.7	40.2	0.40	2.73	ns
Variety	1	193.7	193.7	1.92	3.98	ns
Season	1	89.5	89.5	0.89	3.98	ns
Loc	1	40.1	40.1	0.40	3.98	ns
Time	2	4054.8	2027.4	20.08	3.13	*
Variety*Season	1	71.6	71.6	0.71	3.98	ns
Variety*Loc	1	566.6	566.6	5.61	3.98	*
Variety*Time	2	971	485.5	4.81	3.13	*
Season*Loc	1	12.1	12.1	0.12	3.98	ns
Season*Time	2	617.6	308.8	3.06	3.13	ns
Loc*Time	2	2471.7	1235.8	12.24	3.13	*
Variety*Season*Loc	1	150.4	150.4	1.49	3.98	ns
Variety*Season*Time	2	208.5	104.2	1.03	3.13	ns
Variety*Loc*Time	2	452.9	226.5	2.24	3.13	ns
Season*Loc*Time	2	877.1	438.5	4.34	3.13	*
Pooled Error	71	7168.8	100.969			
TOTAL	95	18067.1				

3.3.3 Combined

Source of Variation	df	SS	MS	F-value	Crit-F	Significance
Replication	3	640.2	213.4	1.6	2.64	ns
Variety	7	1298.6	185.51	0.91	2.49	ns
Variety*Replication	21	4295.5	204.55			
Season	1	623.3	623.3	1.58	10.13	ns
Season*Replication	3	1183.6	394.53			
Location	1	48.7	48.7	0.09	10.13	ns
Location*Replication	3	1538.4	512.8			
Time	2	12838.2	6419.1	48.1	3.03	*
Variety* Season	7	4682.9	668.99	2.99	2.49	*
Variety* Season* Rep	21	4701.4	223.88			
Season x Time	2	3300.7	1650.4	4.14	5.14	ns
Season* Time*Rep	6	2393.4	398.9			
Variety*Location	7	3829	547	4.1	2.05	*
Variety*Time	14	6558.6	468.47	3.51	1.73	*
Season*Location	1	4000.3	4000.3	30	3.88	*
Location*Time	2	8649.3	4324.7	32.4	3.03	*
Variety*Season*Location	7	2768.6	395.51	2.96	2.05	*
Variety*Season*Time	14	4303.5	307.39	2.3	1.73	*
Variety*Location*Time	14	4101.8	292.99	2.19	1.73	*
Season* Location*Time	2	2354.3	1177.2	8.82	3.03	*
Pooled Residual Error	245	32711.2	133.52			
TOTAL	383	106822				

3.4 ANOVA Tables for Crop Yield

3.4.1 Sunflower only

Source	df	MS	Fcalc	Fcrit	Significance
Replication	3	2002545	75.70	2.65	*
Variety	5	258	0.00	2.9	ns
Variety*Replication	15	390312			
Season	1	5293347	12.67	10.13	*
Season*Replication	3	417857			
Location	1	1452439	54.90	3.89	*
Variety*Season	5	451849	1.02	2.9	ns
Variety*Season*Replication	15	441399			
Variety*Location	5	619140	1.20	2.9	ns
Variety*Location*Replication	15	514931			
Season*Location	1	4885219	20.80	10.13	*
Season*Location*Replication	3	234891			
Variety*Season*Location	5	108032	4.08	2.26	*
Pooled Error	210	26454			
TOTAL	287				

3.4.2 Maize only

Source	df	MS	Fcalc	Fcrit	Significance
Replication	3	15662144	2825.572	2.74	*
Variety	1	2925266	7.249999	10.13	ns
Variety*Replication	3	403485			
Season	1	24809666	1.904577	10.13	ns
Season*Replication	3	13026336			
Location	1	1298501	1.272438	10.13	ns
Location*Replication	3	1020483			
Variety*Season	1	2974911	4.870914	10.13	ns
Variety*Season*Replication	3	610750			
Variety*Location	1	1592007	3.136045	10.13	ns
Variety*Location*Replication	3	507648			
Season*Location	1	18036245	11.21799	10.13	*
Season*Location*Replication	3	1607797			
Variety*Season*Location	1	3080717	555.7851	3.98	*
Error	67	5543			
TOTAL	95				

3.4.3 Combined

Source	df	MS	Fcalc	Fcrit	Significance
Replication	3	8630170	255.6406	2.64	*
Variety	7	18154773	11.15789	2.49	*
Variety*Replication	21	1627080			
Season	1	247981	0.05017	10.13	ns
Season*Replication	3	4942774			
Location	1	224629	1.154721	10.13	ns
Location*Replication	3	194531			
Variety*Season	7	5012741	3.099981	2.49	*
Variety*Season*Replication	21	1617023			
Variety*Location	7	1030574	1.828997	2.49	ns
Variety*Location*Replication	21	563464			
Season*Location	1	16302136	24.5097	10.13	*
Season*Location*Replication	3	665130			
Variety*Season*Location	7	1462886	43.33321	2.04	*
Error	277	33759			
TOTAL	383				

Appendix 4.0: Vital statistics of the two crops, sunflower and maize

Parameter	Variable					
	Weed density (no. m ⁻²)		Weed biomass (gm ⁻²)		Crop yield (kg ha ⁻¹)	
	Sunflower	Maize	Sunflower	Maize	Sunflower	Maize
Mean	66.06	69.42	17.88	18.90	737.7 (61%)	1857.0 (31%)
SE mean	5.41	5.92	1.04	1.41	32.1	130.0
Std dev	91.81	57.98	17.68	13.79	544.9	1272
Variance	8429.04	3361.93	308.99	190.18	296864.2	1616891
CV	138.99	83.53	98.30	72.96	73.86	68.47
Minimum	1.00	1.00	0.28	0.46	0.00	622
Q1	20.00	28.25	5.42	6.61	328.3	865
Median	47.00	52.00	12.93	17.33	699.8	1457
Q3	86.00	98.75	25.81	26.63	1032.6	2331
Maximum	1277.00	311.00	126.00	58.34	3095.9	5535
IQR	66.00	70.50	20.36	20.02	704.2	1466
Skewness	8.52	1.57	2.36	0.70	1.17	1.41