EVALUATION OF SELECTED HERBICIDES FOR WEED CONTROL IN SORGHUM [*Sorghum bicolor* (L) Moench]

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DECLARATION AND RECOMMENDATION

Declaration

I hereby declare that this is my original work and has not been submitted in part or in whole for an award in any institution.

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Recommendation

This thesis has been submitted for examination with our approval as Egerton University supervisors.

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DEDICATION

To my caring late husband and my children for their moral, emotional and financial support.

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ABSTRACT

Sorghum (*Sorghum bicolor* L. Moench) is a drought tolerant crop with potential for industrial uses. Despite increase in demand for sorghum for industrial use, the local supply is low with weed management being one of the challenges. Seven herbicides treatments, Lumax (Mesotrine, Metolachlor, Terbuthylazine), Primagram (Atrazine, S-metolachlor), Dual gold (S-Metolachlor), Sencor (Metribuzin) 2,4-D (2,4-D amine salt), Maguguma (Atrazine, S-metolachlor) and Auxio (Bromoxnil, Tembotrine) were tested against two controls, no weeding and hand weeding, to evaluate their effects on density and biomass of weed and sorghum (*Sorghum bicolor* L. Moench) at Egerton University Njoro, Kenya. The herbicide treatments were laid out in a randomized complete block design (RCBD) with three replications. Seeds were planted at the onset of rainy season in each location in plots measuring 2.5 m by 4 m each consisting of six rows of sorghum. The study was done in two experiments; the first and second experiments tested the effect of selected herbicides and rate of application of promising herbicides, respectively on weeds and sorghum crop. Pre-emergence herbicides were applied immediately after sowing while post-emergence treatments were applied 30 days after sowing (DAS). Weed density and biomass was determined at 30 and 60 DAS. All the data were then subjected to analysis of variance (ANOVA) using SAS version 8.1 and treatment means were separated using Tukey's HSD test whenever the herbicide effects were significant ($P \leq 0.05$). Results showed significant (($P \leq 0.05$) differences among the herbicides evaluated. Amongst the seven treatments, Sencor (Metribuzin) and 2,4-D were the most effective herbicides in reducing the weed density by 96% and 90%, respectively compared to when no weeding. In the second experiment, a clear dose-dependent response of weed and sorghum biomass to Sencor and 2,4-D herbicides was observed. Increasing rate of application from 0.75 to 1.125 L/ha for Sencor resulted in ≥90 and >70% reductions in weed density and sorghum biomass, respectively but caused up to 92% increase in weed biomass at 30 DAS. With respect to 2,4-D, increasing rate of application from 1 to 3 L/ha resulted in >90% reduction in weed density and weed biomass and up to 70% increase in sorghum at 60 DAS. The highest sorghum biomass of 4117 kg/ha and 6505 kg/ha were recorded for Sencor at 1.875 L/ha and 2,4-D at 2.5 L/ha, respectively. From these findings, it is recommended that Sencor @1.875 L/ha and 2, 4-D @2.5 L/ha be validated for adoption by smallholder sorghum farmers to ensure effective weed management and contribute to increased sorghum production to meet the increasing industrial demand.

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LIST OF ABBREVIATIONS AND ACRONYMS

AEZ	Agro Ecological Zone
ANOVA	Analysis of variance
ASL	Above Sea Level
ASAL	Arid and Semi-Arid lands
BED	Biologically Effective Dose
CGIAR	Consultative Group on International Agricultural Research
DAS	Days After Sowing
EABL	East African Breweries Limited
FAO	Food and Agricultural Organisation
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GRDC	Grain Research and Development Corporation
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IWM	Integrated Weed Management
KAPAP	Kenya Agricultural Productivity and Agribusiness Project
MOA	Ministry Of Agriculture
MSD	Minimum Significant Difference
RUFORUM	Regional Universities Forum for Capacity Building in Agriculture
RVST	Rift Valley Institute of Science and Technology
SAS	Statistical Analysis Software
SSA	Sub- Saharan Africa
WCE	Weed Control Efficiency

CHAPTER ONE

INTRODUCTION

1.1 Background information

Sorghum (*Sorghum bicolor* L. Moench) is the fifth most important cereal crop after wheat (*Triticum aestivum*), rice (*Oryza sativa*), maize (*Zea mays)* and barley (*Hordeum vurgare*) (Brink *et al.*, 2006). As a C4 plant, sorghum is more adapted to hot and dry conditions than C3 crops which can be grown in double cropping system of long and short rain (Tacker *et al*., 2006). Sorghum is a dual-purpose crop grown for both grain and stems which are highly valued outputs. It is grown in traditionally small-scale farming system used for food. Sorghum can grow anywhere from sea level to 2,500 meters above sea level and requires a minimum rainfall of 250 mm per year and a minimum temperature of 10°C (Chemonics, 2010).

The area under sorghum production in Kenya has been increasing from 122,368 ha in 2005 to 173,172 hactares in 2009, but the national average yield per hectare has been decreasing from 1.2 MTs ha^{-1} to 0.5 MTs ha^{-1} over the same period. (GoK, 2009). Over the last one-decade sorghum production in Kenya ranged between 54,000 tons and 175,000 tons, varying significantly between years with production declining sharply in 2004 and 2008 (FAOSTAT, 2013). In 2004, decrease in production was mainly due to a reduction in yield, while in 2008 low production was strongly correlated with a reduction in both yield and total land planted to sorghum, resulting from post-election instability in 2007/2008 (Chemonics, 2010). Between 2008 and 2010, however, production tripled, increasing by almost 110,000 tons. Most of this growth was driven by expansion in the total area planted to sorghum, which was largely due to the promotion of sorghum as a drought-resistant crop in Kenya's Arid and Semi-Arid Lands (ASALs), emergence of EABL sorghum beer as well as attractive prices from increased consumption (MOA, 2011). Since 2008, total sorghum consumption in Kenya has increased once again, leveling off at more than 160,000 tons in 2010 to 2013 (FAOSTAT, 2013; MOA, 2010). According to FAOSTAT (2013), sorghum was recently cultivated on 42.1 million hectares that produced 67.61 million metric tons of grain, making it the 5th most cultivated crop in the global cereal area structure. The United States is the global leader in sorghum production, accounting for more than 22% of world production with export revenue that exceeds 1.5 billion US dollars.

Sorghum production is low due to constraints such as pest and diseases, weeds, inadequate quality and lack of capital to buy inputs. Among the biotic factors, weeds are among the major biotic factor responsible for low yields in sorghum causing yield losses in the range of 15 – 97% depending upon the type of weed flora and weed density (Thakur *et al,*.2016). Weeds are a problem in crop production (Gage & Schwartz, 2019; Nwosisi *et al*., 2019). They can reduce crop yields (Ball *et al*., 2019). They compete with crops for resources that include moisture; nutrients, space and light, and they can also harbour pests and diseases that infest crops (Tibugari *et al.,* 2020). In a study testing the competitive effects of weed and crop density on weed biomass and crop yield in wheat, Wilson *et al*., (1995) established that increasing weed density where crop populations were low resulted in high crop yield losses. Sorghum grows slowly during the first few weeks after emergence (Tibugari, *et al*., 2020). To prevent yield losses, weeds have to be controlled at critical periods during the crop growth cycle (Knezevic *et al*., 2002). It has been established through research that both light and heavy weed infestations during early growth can reduce grain sorghum yields, with high infestations causing yield losses of up to 20% (Barber *et al.,* 2015).

Due to acute shortage of labour during the early growth period of sorghum, most farmers opt for hand weeding or mechanical weeding operations, which is often delayed or left out unattended (Shad, 2015). In such situations, herbicides offer the most practical, effective and economical method of weed control and increase crop yield. However, the limited number of herbicides available to growers could be a challenge and rotational crop restrictions following a number of herbicides registered for use in grain sorghum (Fromme *et al*., 2012). Other problems include damage to the sorghum seedlings and unintended removal of crop seedlings (Moody & Cordova, 1985). Chemical control, on the contrary, is the most effective, economic and Weed control in sorghum by herbicides has received little attention in Kenya, while elsewhere in the world the herbicides have shown a promise in weed management. Miller and Libby (1999) concluded that crop yield responded positively when weeds were controlled by herbicides. Similarly, Ishaya *et al*. (2007) obtained higher yield in sorghum with herbicides as compared to cultural weed control. Hence, there is a need to change production techniques to suit large-scale production to meet the demand by reducing losses due to effects of weeds. Use of herbicides to control weeds is one of the ways of improving sorghum productivity (Ishaya *et al*., 2007). This study aimed at contributing to increased sorghum production for industrial uses in Kenya by evaluating the most effective herbicides in weed management in sorghum of practical way of weed management for sorghum.

1.2 Statement of the problem

Weeds are historically among the most damaging biotic factor in sorghum production; and continue to be a major problem in sorghum production and a threat to food security in sub-

Saharan Africa and Asia. Weeds are known to cause yield losses in the range of 10-100% depending on the weed pressure, weed species, weather conditions and level of weed management. A number of methods available for weed management include mechanical, cultural, biological and integrated weed. Manual weed cultivation as currently practiced in sorghum cannot cope with the peak. There is growing interest of turning sorghum into a cash crop and also offer alternative uses in malting and brewing. As a result, sorghum production techniques have to be improved to suit the demand of a large scale.

Herbicides use could provide a better alternative method of weed control in sorghum production. However, there are no known herbicides currently recommended for this purpose under Kenyan conditions. This current weed management technique has not been effectively implemented. Therefore, herbicides use needs to be evaluated for the control of weeds in sorghum.

1.3 Objectives

1.3.1 Broad objective

To contribute to increased sorghum production and improved food security in agriculture through appropriate use of herbicides for weed control in sorghum.

1.3.2 Specific objectives

To determine the:

i. Effect of selected herbicides on weed species distribution, density and biomass in sorghum

ii. Effect of selected herbicides on growth and yield of sorghum

iii. Effect of Sencor and 2, 4-D herbicide application rate on weed density and biomass in sorghum

iv. Effect of Sencor and 2,4-D herbicide application rate on growth and yield of sorghum

1.4 Hypotheses

i. The selected herbicides have no effect on weed species distribution, density and biomass in sorghum

ii. The selected herbicides have no effect on growth and yield of sorghum

iii. Sencor and 2,4-D herbicide application rate has no effect on weed control in sorghum

iv. Sencor and 2,4-D herbicide application rate has no effect on growth and yield of sorghum

1.5 Justification of the study

Sorghum is an important food security crop in Sub- Saharan Africa (SSA) especially in the marginal areas where other crops do not do well. In Kenya, 80% of land lies under arid and semi-arid regions, which is suitable for sorghum production based on its ability to tolerate drought. Production of sorghum faces a number of challenges including poor soils, pests, diseases and weeds. Most of the sorghum farmers in Kenya practice subsistence farming because they improved production techniques such as the use of herbicides to control weeds. Therefore, evaluation of herbicides on weeds in sorghum production will enable the commercialization of sorghum and provide information on the effects of herbicides on weeds and sorghum.

Herbicides contribute effectively and profitably to weed control by saving scarce and expensive labour necessary for weed control practices, conserving environment through reduced soil erosion, increasing crop production and reducing the cost of farming. Therefore, the adoption by farmers to use herbicides will increase sorghum production to meet industrial demand, improve livelihood through increase food and income. This will lead to economic development of a country through food security and revenue generation

CHAPTER TWO
LITERATURE REVIEW

2.1 Origin and geographical distribution of sorghum

Sorghum is thought to have originated in Ethiopia due existence of the greatest diversity in both cultivated and wild types of sorghum. From North Eastern tropical Africa, the crop was distributed all over Africa and along shipping and trade routes to the Middle East and India (Brink *et al*., 2006). In India, it is believed to have been carried to China along the silk route, through the slave trade and the coastal shipping to the South. It was subsequently introduced to Australia and South America. It is now widely cultivated in dry areas of Africa, Asia, Americas, Europe and Australia between latitude of 50˚N and 40˚S (Steduto *et al*., 2012).

2.2 Taxonomy of sorghum

Sweet sorghum (*Sorghum bicolor* L. Moench) belongs to genus sorghum in the family of Gramineae (Motlhaodi, 2016). In 1974, Moench established genus sorghum and brought all the sorghum together under the name *Sorghum bicolor* (Teshome *et al*., 1997). *Sorghum bicolor* is further broken down into three subspecies: *Sorghum bicolor bicolor*, *Sorghum bicolor drummondii* and *Sorghum bicolor verticilliflorum*. *S. bicolor bicolor* represented by agronomic types such as grain sorghum, sweet sorghum, Sudan grass and broomcorn (Dahlberg *et al*., 2011). Grain sorghum is mainly used as principal food and raw material for alcoholic beverages. Broom and sweet sorghum are used as raw materials for making broom and sweetener syrup respectively while grass sorghum is grown for green feed and forage use. The subspecies bicolour has been partitioned into five races namely; *bicolor*, *guinea*, *caudatum*, *kafir* and *dura* (Aruna *et al.,* 2018).

2.3 Botany of sorghum

Sorghum biology is classified as diploid with 20 chromosomes (Motlhaodi *et al*., 2014). Cultivated sorghum can be divided into three main categories based on end product utilization: grain sorghum for starch, sweet sorghum for sugar, forage and energy sorghum for biomass. Sweet sorghum is one of the many types of cultivated sorghum due to its high sugar content in the stem. Sweet sorghum is a very efficient source of bio-energy compared with sugar cane (*Saccharum officianarum* L.) and corn (*Zea mays* L.) as it uses C4 photosynthetic pathway to produce sucrose which can be directly fermented (Ali *et al*., 2008). Sweet sorghum is characterized by low grain yields, but high biomass production. It is tall and contains juicy stalks with 10-25% sugars (Wang *et al*., 2009). Though categorized, there are virtually no biological or taxonomic boundaries among these cultivated forms and they all belong to the same species: *Sorghum bicolor* (Ritter *et al*., 2007).

2.4 Sorghum Diversity

Sorghum is a very genetically diverse crop both in cultivated and wild species (Iqbal *et al.,* 2010), with the *Sorghum bicolor* ssp. *bicolor* as the majority bearer of commercial varieties. Sorghum's five races are known as bicolor, guinea, caudatum, kafir and durra. The greatest variation within the sorghum genus is found in Ethiopia-Sudan (northeast Africa) where it is likely to have originated (Mundai *et al*., 2019)

Durra is the oldest and most drought-tolerant of the five races, originating in Ethiopia and later evolved in West Asia, where it remained widespread in semi-arid areas (Mundai *et al*., 2019). In Africa, durra is found in the region from the Horn of Africa/East Sahel to the West. Guinea sorghum is widely adapted in the wetter West Africa (western Nigeria to Senegal) and the caudatum race is associated with the Chari-Nile speaking Africans of the eastern savannah and largely extends from eastern Nigeria, Chad and western Sudan (Cullis, 2019). Kafir is mainly grown in areas stretching from Tanzania to South Africa. The high variation in sorghum is evident in the fact that over 18 subspecies were at one time recognized by scientists (Cullis, 2019).

Sorghum diversified according to local ecological conditions and the desired crop uses through selection and hybridization with wild sorghum (Cullis, 2019). Due to the sudden change in climate in the production regions, more adaptable varieties were developed others were imported from other areas, which brought about inter-variety crossbreeding at the local level (Mundia, 2018).

2.5 Ecology of Sorghum

Sorghum is primarily a plant of hot, semi-arid tropical environments that are too dry for maize. It is particularly adapted to drought due to a number of morphological and physiological characteristics which include: an extensive root system, waxy bloom on leaves that reduces water loss, and the ability to stop growth in periods of drought (Brink & Belay, 2006) and resume it when the stress is relieved. A rainfall of 500-800 mm evenly distributed over the cropping season is normally adequate for cultivars maturing in three to four months. Sorghum tolerates waterlogging and can be grown widely in temperate regions and altitudes up to 2300 m in the tropics. The optimum temperature is 25^0-31 ^{0}C but temperatures as low as 21^0C will not significantly affect growth and yield of sorghum.

Sorghum is a short day plant with a wide range of reactions to photoperiod (Brink & Belay, 2006). Some tropical cultivars fail to flower or to set seeds at high latitudes**.** Sorghum is well suited to grow on heavy vertisols commonly found in the tropics, where its tolerance to waterlogging is often required but is equally suited to light sandy soils. Since it is one of the major rain-fed crops for food and fodder in tropics and subtropics of the world which are already towards the higher side of the tolerant range of temperature, a small change in climate could therefore drastically reduce the production of the crop (Vander *et al*., 2013). The soil, climatic characteristics and the potential crop productivity in many of the Agro-Ecological Zones (AEZs) around the world offer much hope for enhancing future crop production (Sivakumar & Valentin, 1997).

2.6 Economic Importance of Sorghum

Sorghum (*Sorghum bicolor*) is a perennial crop with diverse uses with almost all parts of the crop utilizable in one way or another. However, the crop is mainly grown for its grains which are important for food security purposes. Sorghum is used for human consumption and as feed for animals. Nutritionally, most sorghum grains register 9% protein and low crude protein digestibility due to high percentage of prolamines and tannins (Devries & Toennissen, 2001). It has also been found to be a good source of insoluble fibres which may decrease transit time and prevent gastro-intestinal problems (Ledeer, 2004). In addition, the grains have beta-carotene, a pre-cursor of vitamin A which is important for human growth. In developing countries, the commercial processing of these locally grown grains into value-added food and beverage products is an important driver for economic development (Taylor *et al*., 2004). The use of sorghum not only provides farmers with a market for their products but also saves foreign exchange, which would otherwise be required to import cereals. It is often recommended as a safe food for coeliac patients, because it lacks the gluten the triticale tribe cereals wheat, rye and barley (Ciacci *et al*., 2007), being a member of the Panicoideae sub-family which also includes maize and most millets (Shewry, 2002). Sorghum therefore, provides a good basis for gluten-free breads and other baked products like cakes and cookies (biscuits) and snacks and pasta. In addition, the sorghum flour is traditionally used in making "ugali" (thick porridge or gruel). Sorghum grain is used as animal feed in the Americas, China and India. In India, the grain is used as animal/ poultry feed (Brink & Belay, 2006).

Sorghum grains are also malted and used for brewing beer in Kenya, Ghana, and Nigeria among other countries in the world. Significant research on the utilization of sorghum as malt in brewing industries has been done in South Africa since the mid-20th century and in

Nigeria during the 1970s (Palmer, 1992). In Nigeria, industries use about 200,000 tons of sorghum annually (Mohammed *et al.,* 2011). However, not all sorghum varieties are suitable for use in malting and brewing. Sorghum genotypes with high tannin levels are considered unsuitable since tannins bind to proteins making them less digestible yet they are the key source of energy for yeast during fermentation process (Ambula *et al.,* 2003). On the other hand, tannins, which are in high concentration in red-grained sorghum, contain compounds called antioxidants that protect cells against damage, a major cause for disease and aging. Sorghum syrup is concentrated and sterilized to make natural syrup. The syrup is used in confectionary industry as sweetener. The syrup can also be used instead of honey with breakfast foods. The juice can be concentrated to make jiggery as that of sugarcane.

The plant stem and foliage are used for green chop, hay, silage and pasture. In some areas, the stem is used for hut making. The plant remains after the sorghum head are harvested are used as fuel for cooking. The crop residues (Stover) are used as fodder for livestock because of its wide adaptation, rapid growth, high green and dry fodder, ratoon ability and drought tolerance. Forage sorghum is mostly utilized in North India and in West Africa. Forage sorghums are fed to animals as a green chop or hay (quickly dried sorghum for fodder). Moreover, bio-fuel is produced from sweet sorghum types. The stalks are used for ethanol production which is then blended with petrol to reduce fuel costs.

2.7 Sorghum Production

Sorghum is the fifth most important cereal crop after wheat, rice, maize and barley; and is the staple diet for more than 500 million people in more than 30 countries in the world. It is grown on 42 million ha in 98 countries of Africa, Asia, Oceania and Americas (Food and Agricultural Organisation (FAO), 2010) with Nigeria, India, USA, Mexico, Sudan, China and Argentina as the major producers in the world. In Sub-Saharan Africa, West Africa produces 60 % of the total grain, which represent 25 % of all sorghum grown in developing countries (FAO, 2010).

In India, the area under high yielding cultivars increased from 0.7 million ha in the early 1970s to 6.5 million ha in the late 1990s. While the area under sorghum production in Eastern and South Africa increased from the early 1970s to 2006, there was marginal (15 %) increase in yield from 800 kg ha^{-1} in the early 1970s to just over 920 kg per hectare in 2006. In Western and Central Africa, substantial improvement in production was achieved from 700 kg ha $^{-1}$ in the early 1970s to 1080 kg ha^{-1} in 2005 indicating increased production by 54 %. The area increased by almost two-folds, production increased nearly 2.5 times in early 1970s to 2006 (FAO, 2010).

In Latin America, the area increased marginally from 4 million ha in the early 1970s to 5 million ha in the early 1980s followed by a slight decrease till 2006, almost maintaining the level of the early 1970s (FAO, 2010). The production in 1980 was 15 tons up from 9 tons of early 1970s. This decreased steeply thereafter to 9 tons in the early 1990s. However, the production increased thereafter to 11 tons by 2006. The production increased from 200 kg per ha in the early 1970s to 3100 kg ha^{-1} in 2006.

Over a decade sorghum production in Kenya ranged between 54,000 tonnes and 175,000 tons, varying significantly between years with production declining sharply in 2004 and 2008 (Food and Agriculture Organization Corporate Statistical Database (FAOSTAT), 2013). In 2004, decrease in production was mainly due to a reduction in yield, while in 2008 low production was strongly correlated with a reduction in both yield and total land planted to sorghum, resulting from 2007/2008 post-election instability (Chemonics, 2010). Between 2008 and 2010, however, production tripled, increasing by almost 110,000 tons. Most of this growth was driven by expansion in the total area planted to sorghum, which was largely due to the promotion of sorghum as a drought-resistant crop in Kenya's ASALs, as well as attractive prices from increased consumption (MOA, 2011). Total sorghum consumption in Kenya increased from 128,250 tons in 2005 to 139,637 tons in 2007, but decreased to only 33,000 tons in 2008 due to post-election instability and an affiliated decline in sorghum production. Since 2008, total sorghum consumption in Kenya has increased once again, levelling off at more than 160,000 tons (2010 to 2013). Furthermore, EABL contracts created a significant increase in sorghum production (Ministry of Agriculture (MOA, 2010).

2.8 Challenges facing sorghum production

2.8.1 Pests and diseases

Sorghum midge (*Stenodiplosis sorghicola*), Africa sorghum headbugs (*Eurystylus oldi*) (Reddy *et al*., 2017), sorghum shootfly (*Atherigona soccata*), stem borers (*Buseola fusca, Chilo partellus* and *Sessamia calamistis*) (Brink & Belay, 2006) have serious economic impact on sorghum production. (Padmaja & Aruna , 2019) reported that 10-15% of the world sorghum crop is destroyed by sorghum midge, and in Western Kenya nearly 30% of sorghum grain valued at US$ 7 million is destroyed by the pest. Midge is one of the most damaging sorghum pest causing huge losses (Tao *et al*., 2003). Early planting integrated with use of insecticides are effective ways of controlling the pest. Shoot fly larvae attack shoots of seedlings and tillers causing ‘dead heart’. Stem borers cause damage in all crop stages. Damage by both shoot fly and stem borers can be reduced by early, non-staggered planting; and seed or soil treatments with appropriate insecticides (Brink & Belay, 2006). In Kenya, shoot fly, birds, ants, aphids and stem borers are major constraints in sorghum production in Eastern Kenya (Muui *et al*., 2013) while birds are the most serious pest of sorghum in Bomet district in Rift Valley province (Ochieng *et al*., 2011).

Common seed and seedling root diseases in sorghum are caused by soil and soil borne *Aspergillus, Fusarium, Pythium, Rhyzoctonia* and *Rhizopus spp*. They are controlled by treatment of the seeds with fungicides (Brink & Belay, 2006). Anthracnose (*Colletotrichum graminicola*) is common in hot and humid parts of Africa (Brink & Belay, 2006). Control measures include the use of resistant cultivars and crop rotation. Downy mildew (*Peronosclerospora sorghi*) may cause serious yield losses which can be avoided through use of resistant cultivars and seed treatment. Smuts (*Sporisorum spp*) are important panicle diseases. Loose and covered kernel smuts are controlled through seed treatment with fungicides while resistant cultivars and cultural practices such as crop rotation and removal of infected panicles effectively controls head smut and long smut. Grain mould is most severe in seasons when rain continues through the grain maturity stage and delay the harvest. Control measures include adjustment of the sowing dates to avoid maturation during wet weather and the use of resistant cultivars.

2.8.2 Drought

Drought is one of the most important abiotic stresses limiting sorghum (*Sorghum bicolor*) production around the world with great significance in the semi-arid tropics, where rainfall is generally low and its distribution erratic (Hadebe *et al*., 2017). Arid and semi-arid lands (ASALs) cover 80% of Kenyan land mass (MAFAP, 2013) posing a great challenge to crop production in these areas. An effective and sustainable way to alleviate problems of crop production associated with drought is the development of crops that withstand moisture stress (Ribaut & Poland, 2000). There are three types of drought in sorghum; Seedling, pre-flowering and post-flowering drought stress (ICRISAT, 1984; Rosenow & Clark, 1981). Post-flowering drought stress manifests in stalks lodging, charcoal rot (*Macrophomina phaseolina*) disease, reduced seed size, premature plant senescence and death (Rosenow, 1993). Drought affects livelihoods of half a billion people who live in the Semi-Arid Tropics (House, 1996). Soil water deficits were found to be the most important cause of yield loss in Eastern Africa with soil water deficits during crop establishment and during grain fill being major constraints in

Ethiopia, while mid-season water deficits were of relatively greater concern in Kenya and Uganda (Wortmann *et al*., 2006).

2.8.3 Soil Fertility Levels

Soil degradation and low fertility are among the most severe specific constraints for sorghum in Sub-Saharan Africa (Waddington *et al*., 2010). Several nutrient deficiencies or problems such as phosphorus deficiency, aluminum toxicity in acid soils, salinity toxicity and iron chlorosis on alkaline soils reduce yields in sorghum (Rooney, 2004). The degradation of land resources, particularly soils, pose a great threat to food production, food security and the conservation of natural resources (Omotayo & Chukwuka, 2009; Ye *et al*. 2010). In Zimbabwe, poor soil fertility is reported as major among the many production constraints (Makanda *et al*., 2009). Soil infertility, including nitrogen deficiency, soil physical degradation and poor fertilizer management are severe and widespread (Waddington, 2010). In Eastern horn of Africa, soil infertility is among the major challenges to sorghum production. In Ethiopia, declining soil fertility is a major constraint on crop production in the semi-arid highlands of Tigray (Corbeels *et al*., 2000). In Uganda, poor soil fertility was listed among the many constraints of low production of sorghum (Nabimba *et al*., 2005). In Kenya, low soil fertility and high cost of inorganic fertilizers are a major constraint to sorghum production in marginal environments (Ashiono *et al*., 2006).

2.8.4 Weeds

Weeds are a problem in sorghum production, causing yield reduction by competing with crops for soil moisture, nutrients, space and light resources while harbouring pests and diseases that infest crops (Brooke & McMaster, 2019; Faria *et al*., 2014). In a study on competitive effects of weed and crop density in wheat, Wilson *et al*. (1995) established that increasing weed density where crop populations were low resulted in high crop yield losses. Sorghum grows slowly during the first few weeks after emergence (Ferrell *et al*., 2018). To prevent yield losses, weeds have to be controlled at critical periods during the crop growth cycle (Knezevic *et al*., 2002). It has been established through research that heavy weed infestations during early growth can reduce grain sorghum yields, with high infestations causing yield losses of up to 20% (Barber *et al*., 2015).

2.9 Major weeds species in sorghum production

Weeds commonly found in sorghum fields include *Amaranthus hybridus, Datura stramonium, Bidens pilosa, Physalis alkekengi, Pennisetum clandestinum, Chenopodium album, Raphanus raphanistrum , Digitaria scalarum, Gallinsoga parviflora, Commelina benghalensis, Tagetes erecta, Oxygonum sinuatum, Oxalis latifolia, Setaria sphacelata, Cyperus rotundus.*

The blackjack, *Biden pilosa* L., is a common weed throughout humid tropics and is the principal weed of *Sorghum bicolor* and other agricultural crops. The major allelochemical produced by *B. pilosa* responsible for inhibiting seedling growth in other crops including sorghum is XAD_{-4} (Khanh *et al*., 2009). The phenylheptatriyne produced by blackjack (*B. pilosa*) in the roots has its allelopathic activity enhanced by sunlight. Though blackjack has global distribution, Latin America and eastern Africa have the worst infestation of the weed (Mitich, 1994). This is attributed to fast reproduction by seeds that are favoured by warmer and wetter seasons. In Kenya, blackjack is regarded as principle weed of maize, tea, potatoes, bananas, sugarcane, coffee, cotton, vegetables and beans (Dube & Mujaju, 2013).

Blackjack has short life cycle ranging between 150 to 360 days depending on the onset of germination. It is a short-day plant requiring few days, about 10 to 14 short days to induce flowering. One plant is capable of producing over 3000 seeds, many of which readily germinate at maturity making up to a maximum of four generations per year in some areas (Mitich, 1994). These attributes indicate that uncontrolled growth of blackjack can be problematic in Kenyan agricultural sector causing huge loss in terms of crop yields. The spread of blackjack is fast allowing rapid colonization due their effective pollination mechanisms and their distinctive dispersal adaptations, which allow seed distribution by animals, water, humans and wind. The fertilizers used in improving crop growth and yields especially ammonium nitrate or sulphate are also known to increase number of heads, height, seeds per plant and branching of blackjack plant (Swanepoel *et al*., 2015).

Many other secondary metabolites with allelopathic activity have also been isolated from weeds particularly *Gallinsoga parviflora and Amaranthus hybridus* (Yadav *et al*., 2017). It reproduces only by seeds and is also common in eastern Africa and has widespread existence in Kenya where it is used by some communities as vegetable (Muthaura *et al*., 2010). Its seeds are relatively small making it easier for dispersal by wind where it germinates in the soil. Pigweed germination is stimulated by light and high temperature with greatest germination occurring in temperature between 20 and 35°C. This weed is problematic in that it gains fast spread since single plant can produce about 10000 seeds (Macrae *et al*., 2013). Furthermore, under unfavourable conditions for growth, the seeds can remain viable for several months to years where it germinates together with planted crops. Additionally, it possesses the C4 pathway of photosynthesis similar to sorghum thus sharing similar climatic conditions, which in turn enhances competition for soil nutrients.

The pigweed that emerge with crop and are not controlled can significantly reduce crop yield, *Amaranthus hybridus* is the principled weed reported to significantly reduce approximately 18% of yield of sorghum, maize and peas (Thobatsi, 2009). To enhance competitiveness in crop-weed competition, *Amaranthus hybridus* may overtop lower growing vegetables or respond to partial shading by taller plants by increasing stem growth and deploying foliage at greater heights to enhance light interception (Nandula *et al*., 2013). Higher level of shade due to higher crop population can greatly reduce the weed's growth, However it is not possible to achieve higher sorghum population relative to weed due to recommended population of 161,000–198,000 sorghum plantsha^{-1} to achieve maximum grain yield (Fernandez *et al*., 2012).

Fertilizer application that enhances nitrogen and phosphorous in soil is reported to stimulate increased seed production and growth of pigweed that intensifies weed competition against crop (Sweeney *et al*., 2008). Since fertilizer application is common method of crop management in sorghum production, use of herbicide targeting weed will prove useful. There is also evidence that pigweeds reduce crop yield through allelopathy (De Souza *et al*., 2011). The metabolism of plant cells can either be primary or secondary. Primary metabolism is essential for growth and survival of plant and is involved in processes like photosynthesis, transport and respiration. On the other hand, secondary metabolism is not universal or essential for all plants and result in production of phenols, alkaloids and terpenes (Rattan, 2010). The secondary metabolites of *Amaranthus hybridus* with allelopathic potential are responsible for protection against insect pest, diseases and interference of other plants which can affect their growth and development (Akula & Ravishankar, 2011). The allelochemicals produced by pigweed cause problem in agricultural production as it reduces germination of seeds, affect photosynthetic rate and consequently their growth and productivity. Allellochemicals extracted from *Amaranthus retroflexus* reduced yield of *Zea mays* by 15-20%. Interestingly, even though allelopathic potential of *Amaranthus hybridus* has negative effects on cultivated plants, (VanVolkenburg *et al*. 2020) reported potential use of such allelochemicals as potential herbicides to other weed plants.

2.10 Weed management in sorghum

Weed control during the first 6 to 8 weeks after planting is crucial, as weeds compete vigorously with the crop for nutrients and water during this period (Sundari & Kumar, 2002). Prevention strategies include farming practices that restrict spread of weed seeds and vegetative propagules at every step of production which include seed selection, field preparation, planting, fertilization, irrigation, transport, field sanitation and harvesting methods (Melander *et al* ., 2005). Cultural approaches play significant role to determine the competitiveness of a crop with weeds for above ground and below ground resources and hence influence weed management (Van & Chauhan, 2017)

Integrated weed management (IWM) is commonly described as a combination of mutually supportive technologies that control weeds. IWM combines appropriate weed control options including physical, chemical, biological and cultural weed control to achieve effective long term management(Chikowo *et al* .,2009). Alternately, it is a weed management program using a combination of preventive, cultural, mechanical and chemical practices. This can lead to reduced herbicide use (Knezevic, 2010).

2.10.1 Manual weeding

This method involves the use of labour for uprooting, plucking, and hoeing which has been used since ancient times (Abbas *et al*., 2018). It is the most efficient method used in areas where labour is cheaper and easily available. It can be adopted for weed control in all crops, sowing methods, and growth conditions. However, urgent need of labour during labour peak period cause economic losses to crops is a critical factor in the success of this method (Abbas *et al*., 2018). Rapid expansion of industries has caused a shift of small scale production into large scale level (Liu *et al*., 2018). These factors have caused lesser availability as well as high cost of labour for manual weeding. Sometimes, farmers may be forced to follow manual weeding due to lack of technical know–how and uncertain market conditions of herbicides regarding cost and availability (Abbas *et al*., 2018). Repeated hand weedings and involvement of intense labour make this method inconvenient, uneconomical, and unfeasible (Rao *et al*., 2007). Weed control on a large scale usually becomes impossible if manual control methods are adopted Akbar *et al*. (2011) compared the efficiency of manual weeding with other conventional weed control methods in direct-seeded rice cultivation and reported that manual weeding was more efficient than mechanical weeding and both were better than chemical control. Grain yield of direct-seeded rice was improved by 30% where manual weeding was done, 25% where mechanical weeding was done, and 7%–19% where recommended doses of different herbicides were applied. However, manual weeding is still practiced where labour is cheaper, easily available, and landholdings are small. Hand weeding is tedious and highly labour intensive but environment- friendly and economically viable option for the farmers. It has been estimated that 150 to 200ksh labour per person dayha^{-1} are required to keep rice crop free of weeds (Juraimi *et al*., 2013). Conventional tillage is effective for reducing populations of many biennial and perennial weeds that may arise from rhizomes or rootstock (Weber *et al*., 2017).

2.10.2 Mechanical weeding

Mechanical weeding involves the use of tillage implements like harrows, weeders, and cultivators driven by animals or engine power. These implements bury and uproot weeds grown between crop rows which are wide enough to facilitate movement of the implements without significant injury to crops. This method is applicable only in those crops sown in straight rows and having suitable row widths. Weeds grown within crop rows and closer to crop plants escape the control (Abbas *et al*., 2018). Weeds grown within crop rows incur much higher losses to crops than those grown between crop rows (Melander *et al*., 2012). Partially uprooted weeds may regain vigour through regeneration and root injury to crops may also occur (Hakansson, 2003). Mechanical cultivation requires repeated operations for effective weed control, reducing efficiency of weeding over chemical and manual control. Narrow cover area of wheel tracks is used for mechanical weeding which leads to more soil compaction than other tillage practices (Smith *et al*., 2011). Adverse environmental effects of using tillage for mechanical method include increased soil erosion, leaching of nutrients, global warming, and eutrophication (Ahlgren, 2004). Mechanical control utilizes high energy and contributes to global warming. It also increases decomposition and oxidation of organic matter in soil leading to depletion and loss of soil fertility. Apart from deteriorating soil structure, it also aggravates compaction of subsoil. Other disadvantages include destruction of natural habitats and wildlife (Abbas *et al*., 2018). Efforts in reducing tillage puts more pressure on use of other methods of weed control, especially with herbicides. Mechanical weeding is being used despite its disadvantages due to lack of safer techniques, awareness among farmers, and lack of environmental concerns on the part of farmers.

2.10.3 Chemical weed control

Herbicides are chemicals that inhibit or interrupt normal plant growth and development which can provide cost-effective weed control while minimizing labour. The potential for herbicide to kill certain plants without injuring others is called selectivity. Herbicides that kill or suppress the growth of most plant species are relatively non-selective (Das *et al*., 2014**)**. Chemical control of weeds is the application of herbicides. Chemicals for weed control were used at the start of 20th century which included copper salts and sulfuric acid (Hamill *et al*., 2004). During World War II, defoliating agents were used for vegetative destruction purposes. Later on these chemicals became herbicides. Discovery of selective herbicides lead to the application of herbicides in arable lands. Introduction of 2, 4-dichlorophenoxyacetic acid (2, 4-D) and 2-methyl-4-chlorophenoxyacetic acid (MCPA) in 1940s revolutionized weed control in cereals (Abbas *et al*., 2018). They were meant to control weeds more efficient than all other methods due to several advantages. These included less labour requirement, low cost of application, reduced soil erosion, and energy savings (Abbas *et al*., 2018). The global herbicides market was worth $ 32.64 billion in 2019. It is expected to grow at a compound annual growth rate (CAGR) of 13% and reach $51.47 billion by 2023. World population is growing and is expected to reach 10 billion by 2050 (Dublin, 2020) and more herbicides are expected to be consumed with increased demand for food. Herbicides include chemical substances that kill weeds by inhibiting photosynthesis, amino acids biosynthesis, lipid biosynthesis, respiration, auxin mimics and other mechanisms(Sherwani *et al* ., 2015). Chemical control of weeds has improved the yields of different crops from 10% to 50% (Ashiq & Aslam, 2014). They have reduced the need for tillage from 50% to 80% in different crops (Ashiq & Aslam, 2014). Application of herbicides has been necessitated in certain crops and sowing methods, such as in direct-seeded rice cultivation. The research on sustainable rice production is now focused at success of direct-seeded rice cultivation through the use of herbicides in weed management (Weerakoon *et al*., 2011). Weed infestations under direct-seeded rice cultivation may reduce the yield up to 85% leading to complete failure of the crop (Phuong *et al*., 2005). Narrow row spacing makes mechanical weeding not practical whereas manual weeding becomes impossible due to need of more frequent weeding and shortage of labour on large-scale production. Pre- and post-emergence techniques of herbicide applications have shown their effectiveness to suppress weeds grown in direct-seeded rice

The ever increasing reliance on herbicides has given rise to serious limitations. Zimdahl (2012) studied the shift in weed flora of US rice– maize–soybean cropping system. The original weed flora comprised of grasses (60%), sedges (25%), and broadleaved weeds (15%). Chemical control was administered for these weeds continuously up to 6 years. After this period, weed flora comprised of 80% grasses, 7% sedges, and 13% broadleaved weeds. He suggested that shift in weed flora occurs due to interspecific selection of weed species which was induced by herbicide application having similar mode of action and selectivity pattern. The chemical control of new flora becomes even more difficult with herbicides (Hakansson, 2003). 2, 4-D is widely used to control broadleaved weeds. The continuous application of such herbicides also leads to intraspecific selection of weeds and caused the development of herbicide-resistant biotypes of weeds (De Prado *et al*., 2004). More than 300 examples of herbicide resistance have been reported against 15 families of chemical herbicides. Heap (2013) reported 273 weed species resistant to different herbicides used for their control. It requires additional applications as well as high doses of compounds for control of these weeds which further increases the magnitude of resistance. To overcome this situation, several researchers have suggested that current herbicidal compounds should be continuously replaced with others having different modes of action (Kao-Kniffin *et al*., 2013). The discovery of new compounds is a concern in chemical weed control but it has been drastically reduced in recent years (Duke, 2012). It has widened the gap between increasing number of resistant weed species to be controlled and available herbicidal compounds effective against these weeds.

Herbicides also cause losses of crops and crop products through toxicity caused by drift and residual effects. Similarly, they also reported the presence of residues of pendimethalin, metolachlor, and pretilachlor in edible portions of several food crops. A major portion of herbicides applied under field conditions contacts non-target species and soil (Crone *et al*., 2009). Some herbicides like triazines and sulfonyl urea may persist in soil long enough to affect the growth of subsequent sensitive crops (Zimdahl, 2007). A phenomenon has been reported in US corn–soybean rotations. Atrazine or imazaquin herbicides applied to soybean persisted in soil and reduced germination and growth of corn grown later on as subsequent crop Pimentel (2005) demonstrated increased susceptibility of some crops to insects and diseases following application of 2, 4-D for weed control. Herbicides applied under inappropriate soil, and weather conditions may cause yield reductions of crops from 2% to 50% (Pimentel *et al*., 1993). Herbicides may be transported to nearby non target crops through drift reducing growth and yield of sensitive crops up to several miles downwind (Hakansson, 2003). Herbicide drift is also responsible for damages to wildlife and mammals causing death, growth reduction, poisoning, and loss of fertility (Pimentel, 2005). The abundance and distribution of wild plants in a native region are regulated by populations of their natural enemies. Herbicides may also kill beneficial natural enemies (predators and parasites) of crop pests, which may induce more severe pest attacks as well as emergence of new pests (Hoddle, 2004). This may require additional and more expensive control treatments to sustain existing crop yields. Herbicides in soil although not reducing populations of soil microflora and microfauna, may induce intraspecific and interspecific selection (Hakansson, 2003). Microorganisms and invertebrates present in soil are crucial to the functioning of ecosystems, mediating the processes of recycling of plant nutrients, decomposition of organic wastes, biological nitrogen fixation, formation of soils, and regulation of plant nutrients. Herbicides can be toxic to these organisms leading to disturbances in biologically driven processes of soil microorganisms and other invertebrates. Apart from these, herbicides have also been identified as the sole chemical threat to 33 endangered species of which 27 are angiosperms (Smith *et al*., 2000). Dinitropheonls (DNOC and Dinoseb) disturb respiration processes of many organisms (Hakansson, 2003). Herbicides, especially water soluble compounds, may be transported to waterbodies through leaching and runoff. Pimentel (2005) suggested that degradation of these compounds in ground water is extremely slow due to presence of very few microorganisms.

Herbicide-tolerant plants often have the ability to metabolize or break down the chemical to non-active compounds before it can build up to toxic levels at the site of action. An altered site of action refers to genetically different plant biotypes that have a structurally altered site of action that prevents herbicide binding and activity (Lombardo *et al*., 2016). Contact herbicides affect the part of the plant that come in contact, such compounds are generally ineffective for long-term perennial weed control. Pre-plant incorporated herbicides are mixed into the soil prior to planting. Incorporation of some herbicides is necessary to prevent surface-loss from volatility or photo decomposition (Dallas *et al*., 2013**)**. Pre-emergence herbicides are applied to the soil surface after the crop is planted but before crop seedlings and weeds appear above the ground. Post-emergence herbicides are applied after the crop and weeds have emerged. Most post-emergence herbicides have foliar activity only, while a few do provide foliar and soil activity (Mark *et al.*, 2014). Fewer herbicides are available for broadleaf weed control in sorghum than in corn or soybean. Products such as bromoxynil plus atrazine, dicamba plus atrazine, and 2, 4-D + atrazine all contain about 227.3 L atrazine along with the other herbicide. They should be applied when sorghum is in the three- to six-leaf stage and weed sizes conform to label guidelines.

2.11 Role of herbicides in weed management in sorghum

Sorghum is often infested by grass and broadleaved weeds (Vencill & Banks, 1994). Knezevic *et al*. (1997) known to account for 33 per cent loss of potential production and 30-45 per cent loss of plant nutrients from the soil. Chemical weed control is the most effective method to suppress weeds in order to get healthy and vigorous crop stand. Miller and Libbey (1999) reported that crop yield generally responded positively to improved weed control.

Similarly, Rab *et al.* (2016) reported that herbicide application increased biological yield and decreased weed biomass significantly.

The major problems associated with use of herbicides in sorghum include unavailability of herbicides registered both for pre- and post-emergence applications, restrictions on the use of terbuthylazine , low efficacy of pre-emergence herbicides with inadequate rainfall conditions and unavailability of selective post-emergence grass herbicides (Delchev & Georgiev 2017). Previous study by Solaimalai *et al.* (2000) indicated that application of herbicide increased the yield of sorghum and its intercrops over unweeded check and hand weeding.

Chemical weed control is a better supplement to conventional method and forms an integral part of the modern crop production. It is quick, more effective, time and labour saving method than others (Abbas *et al*., 2018). Success of chemical weed control methods depends upon several factors such as weed emergence pattern, application timing and stage of crop (Tanveer *et al*., 2019).

2.12 Pre-emergence weed control

Currently, the available herbicide active ingredients labelled for pre-emergence use in forage sorghum is atrazine and metolachlor (or s-metolachlor), and they are sold either alone or in combination with each other. Atrazine will control many annual broadleaf weeds and metolachlor is a good option for many annual grasses (Co *et al*., 2019). Lumax (s-metolachlor + mesotrione + atrazine) site of action: Seedling Shoot and Root Inhibitors (15) + Hydroxy phenyl pyruvate dioxygenase (HPPD) synthesis inhibitors (27) + Photosystem II, Seedling Growth Inhibitors. The seedling growth inhibitors work during germination and emergence and include three groups: 1) the seedling shoot inhibitors (carbamothioates), 2) the seedling shoot and root inhibitors (acetamides), and 3) the microtubule assembly inhibitors (dinitroanilines). S-metolachlor belongs to acetamides and it gives the best total weed control due to a high efficacy against the broadleaved species of weeds **(**Gikas *et al*., 2018). Mesotrione is a selective herbicide that controls many broadleaf and some grass weeds in corn. It disrupts carotenoid biosynthesis by inhibiting the hydroxyphenylpyruvate dioxygenase (HPPD) enzyme, which results in plastoquinone (PQ) synthesis inhibition (Oliveira *et al*., 2018). PQ is involved in the phosphorylation process and is a cofactor for phytoene desaturase, a necessary enzyme for carotenoid synthesis.

Metribuzin [4-amino-6-(1, 1-dimethylthio-3-(methylthio) 1, 2, 4-triazin-5(4H)-one] is a Photosystem II (PSII) inhibitor herbicide that interrupts the electron transfer proteins by inhibiting plastoquinone binding (Choe *et al*., 2014). The herbicides act as inhibitors of the oxidase enzyme to block the production of chlorophyll and chloroacetamide herbicides in crops. Rotational crops such as corn and cotton and use of an additional mode of action is a sound strategy to reduce the risk of resistance to these and other herbicide (Choe *et al*., 2014)

Metribuzin is soil-applied herbicide which gives good to excellent control of small-seeded annual broadleaves and fair to good control of certain large-seeded broadleaves and others like kochia, lambs' quarters, Russian thistle, and wild buckwheat (Moechnig *et al*., 2013). S-Metolachlor is a chloroacetamide herbicide that can be applied early pre-transplant incorporated, pre-transplant, or post-transplant to control annual grass and broadleaved weeds. S-Metolachlor is absorbed by germinating grasses mainly through the shoot just above the seed but broadleaved weeds are through the root and the shoot. Susceptible grass species in s-metolachlor-treated soils fail to emerge or show malformed and twisted seedlings with leaves rolled in the whorl (Vencill, 2002). Acetamide, chloroacetamide, oxyacetamide, and tetrazolinone herbicides are examples of herbicides that are currently thought to inhibit very long chain fatty acid synthesis (Schmalfuβ *et al*., 2000). These compounds typically affect susceptible weeds before emergence. Susceptible broadleaved species will have chlorotic and necrotic leaves and often have growth reduction (Vencill, 2002). S-Metolachlor can effectively control troublesome weeds such as *Setaria faberii* Herrm. (Giant foxtail), *Setaria viridis* (L.) Beauv. (Green foxtail), *Setaria glauca* (L.) Beauv. (Yellow foxtail), *Digitaria sanguinalis* (L.) Scop. (Large crabgrass), *Digitaria ischaemum* (Schreb) Muhl. (Smooth crabgrass), *Echinochloa crusgalli* (L.) Beauv. (barnyardgrass), *Panicum dichotomiflorum* Michx. (*fall panicum), Panicum capillare* L. (witchgrass), *Cyperus esculentus* (yellow nutsedge), *Amaranthus retroflexus* L. (redroot pigweed), *Solanum americanum* (American black nightshade) and *Solanum ptycanthum* (eastern black nightshade) (Vencill, 2002).

Pre-emergent herbicides can offer an alternate mode of action to many post-emergent options since they can reduce selection pressure on subsequent post-emergent herbicide applications; remove much of the early season weed competitive pressure on a crop and can protect yield better than post-emergence. They can save costs, especially in the fallow where multiple operations may be required. They also can reduce the time pressure on spraying operations, especially in situations when double knocking is a requirement; have a major role to play in patch eradication where a weed blow-out can be GPS logged and a pre-emergent herbicide can be applied to manage the patch (Edwards *et al* ., 2018). Pre-emergent herbicides can play a key role in weed management. Pre-emergent herbicides reduce weed competition early in the crop when the crop is most susceptible to weed competition. This helps to maximize grain yield (Iqbal *et al*., 2020).

2.13 Post-emergence weed control

Growth regulator herbicides consist of the synthetic auxin and auxin transport inhibitor compounds. Most growth regulator herbicides are readily absorbed through both roots and foliage and are translocated in both the xylem and phloem. They are used to control broad leafed weeds. 2, 4-Dichlorophenoxyacetic acid (2, 4-D) is a common systemic herbicide used in the control of broadleaf weeds (Grossmann, 2007) and is a synthetic auxin first produced in the 1940's. It is one of many so-called phenoxy herbicides. These herbicides are both structural and functional analogues of the natural auxin indole-3-acetic acid (IAA). 2, 4-D causes uncontrolled and unsustainable growth causing stem curl-over, leaf withering, and eventual plant death. Do not treat sorghum in boot, tassel, or soft dough stage (Grossmann, 2007).

Mesotrione is a member of the tri-ketone family of herbicides derived as a natural phytotoxic from *Callistemon citrinus* which inhibits a critical enzyme, B-hydroxyl-phenyl pyruvate dioxygenase (HPPD), in carotenoid biosynthesis. This compound acts by competitive inhibition of the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD), a component of the biochemical pathway that converts tyrosine to plastoquinone and α-tocopherol (Mitchell, 2001). It is a new herbicide being developed for the selective pre- and post-emergence control of a wide range of broad-leaved and grass weeds in crops. It is a member of the benzoylcyclohexane-1,3-dione family of herbicides. Mesotrione act by inhibiting 4-hydroxyphenylpyruvate-dioxygenase in plants (Felix *et al*., 2007).

Bromoxynil is a photosystem II inhibitor which disrupts photosynthesis. It is used to control many broad annual broadleaf weeds including *Ipomoea spp*, *Sesbania exaltata* (Raf.) *Coryl*, *Chenopodium album* L., *Ambrosia artemisiifolia L., Sida spinosa* L., and *Anoda cristata L*. It does not effectively control grass species and only controls *Amaranthus spp*. with properly timed applications. Bromoxynil is used as a post emergence herbicide (Fromme *et al*., 2012).

Tembotrione was first launched as a maize herbicide in 2007 by Bayer Crop Science (Van *et al*., 2009). Tembotrione inhibits the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD) efficiently in numerous weed species. The compound is sold in various mixtures and formulations under the trade names Auxo, Capreno, Laudis or Soberan. HPPD is an enzyme of the biosynthetic pathway that converts tyrosine to plastoquinone and tocopherol. Plastoquinone is a cofactor for the phytoene desaturase, a component of the carotenoid biosynthetic pathway. The depletion of plastoquinone levels by inhibition of HPPD results in depletion of carotenoids and an absence of chloroplast development in emerging foliar tissue which then appears bleached and stunted (Pileggi *et al* ., 2012).

Atrazine is a photosystem II inhibitor (Choe *et al*., 2014). Atrazine is a herbicide used to control annual broad leaf and grass weeds in agriculture and landscape maintenance of residential and commercial settings (Warnemuende, 2006). This herbicide affects electron transport in photo system II disrupting the photosynthetic process of targeted weeds (Qian *et al*., 2014). 2-chloro-4-ethylamino-6-isopropyl-amino-1-s-triazine is the chemical name for atrazine (Solomon *et al*., 1996).

CHAPTER THREE
EFFECT OF SELECTED HERBICIDES ON WEED DISTRIBUTION, DENSITY AND BIOMASS IN SORGHUM

Abstract

Weeds are a major biotic stress that has to be addressed to achieve adequate grain supply to meet increasing industrial demand for sorghum. A study was conducted to determine the effect of herbicides on weed management in sorghum. A field experiment was conducted at Egerton University Njoro, Kenya during the short rains (August 2014) and long rains (March 2015). The experiment was carried out in randomized complete block design (RCBD) and replicated three times. Four pre-emergence herbicides namely Lumax (Mesotrine, Metolachlor, Terbuthylazine), Primagram (Atrazine, S-metolachlor), Dual gold (*S*-Metolachlor) and Sencor (Metribuzin) were used. In addition, three post-emergence herbicides namely 2,4-D (2,4-D amine salt), Maguguma (Atrazine, S-metolachlor) and Auxio (Bromoxnil, Tembotrine) were used. Positive and negative controls comprised of hand weeding and no weeding respectively. Pre-emergence treatments were applied immediately after sowing while post-emergence treatments were applied 30 DAS. Weed density and biomass were determined at 30 and 60 DAS. The data were subjected to analysis of variance using SAS version 8.1. Means were separated according to Tukeys significant difference (MSD) whenever the herbicide effects were significant ($P \leq 0.05$). Results showed significant ($P \leq 0.05$) differences in the effect of the treatments evaluated. Amongst the four pre-emergence herbicides, Sencor (Metribuzin) was more effective herbicide in reducing the weed density by 96% and 79% compared to no weeding and hand weeding, respectively. For post-emergence herbicide applications, 60 DAS, weed densities were reduced by 90, 43 and 26% when 2, 4-D, Maguguma and Auxio were used, respectively. Adoption of Sencor and 2, 4-D at recommended rates will ensure effective weed management and contribute to increased sorghum production to meet the increasing industrial demand.

3.1 Introduction

Crop yield loss due to weed interference is one of the major threats to optimum crop production and global food security. Among various sorghum yield limiting factors, weed infestation remains a big challenge (Tuinstra *et al*., 2009). Weeds remain one of the biggest threats to Kenyan agricultural sector as it competes for space and sunlight with crop apart from utilizing moisture and nutrients. Low productivity in agriculture is related to poor weed control;

under water-stress condition, weeds can reduce crop yield more than 50% through moisture competition (Rajcan & Swanton, 2001). Weed control is one of the approaches that can be used to improve crop performance by reducing weed-crop competition. A number of methods available to control weeds depend on: type of crop scale of the problem, resources available, time constraints (Shad, 2015). Critical period for weed control depends on the density, competitiveness and emergence periodicity of the weed population (Zystro *et al*., 2012). Different weed control methods are available however, chemical control method has been reported by various authors across the world as the most effective and economical method to suppress weeds resulting in healthy crops (Khaliq, 2011; Khaliq *et al*., 2012).

It has been suggested that good crop establishment can be achieved by keeping farm weed free for the initial period of 3-4 weeks after planting (Chauhan *et al*., 2012). The post-emergence is only used for existing weeds especially perennial and annual broadleaf weeds though some work on grassy weeds (Pannacci & Covarelli, 2009). Walsh *et al*. (2013) reported that herbicides applied early soon after sprouting is more effective in killing young weeds compared to mature weeds. This is economical to farmers since fully established weeds may need multiple herbicide application to kill them.

A successful weed control through application of pre-emergence herbicide is important for farmers to realize increased yields. However, if for some reason a pre-emergence herbicide treatment was not applied, the famers should still consider applying 2, 4-D as post-emergence herbicides. Application of either pre-emergence or post-emergence soon before grassy and broadleaf weeds produce seed helps in minimizing weed density. Weeds have been categorized as broadleaf (dicots) or grasses (monocots); possess different hormones which are the main target for controlling weed. Therefore, the aim of this study was to determine effective herbicides for weed management in sorghum.

3.2 Materials and Methods

3.2.1 Experimental site

This experiment was carried out at Egerton University (0°23′ S, 35°35′ E, and 2267 metres above sea level (masl). The annual mean precipitation is 1000 mm and the mean temperature of 15.9 °C. The soils are mollic andosols soils and situated in the agro-ecological zone low highland 3 (LH3) (Jaetzold *et al*., 2006) .This environment represents major sorghum growing regions with a rich weed seed bank and an area where no herbicide application has been done before.

3.2.2 Experimental Design and Procedures

Field trials was conducted during the short rains on July- Nov, 2014 and long rains March- June 2015 to evaluate the efficacy of selected pre- and post-emergence herbicides on weeds, growth and stalk yield of EUSS25 line of sorghum. A land size of 45 m x 12 m was disc ploughed and harrowed to a fine tilth before planting for better crop emergence and seedling development. The treatments were laid out in a Randomized Complete Block Design (RCBD) with three replicates per treatment. The experimental plot measured 4.0m x 2.5m. A path of 1.5 m separated the replicates.

Sorghum was sown in each of the experimental plots at a spacing of 60 cm x drill at a depth of about 2.5-4 cm and a seed rate of 8 kg per ha^{-1} which was carried out just before the onset of the rains. During sowing, NPK (20:20:0) fertilizer was applied at rate of 50 kg P_2O_5 kg and 50kg N ha^{-1}. After crop emergence sorghum was thinned to intra row spacing of 15 cm. Given the spacing, each experimental unit had six rows of sorghum. Top dressing was done later using Calcium Ammonium Nitrate (26% N) at the rate of 40 kg Nha^{-1} were split into two applications of 20 kg Nha^{-1} at planting and top dressed with 20 kg Nha^{-1} three weeks after seedling emergence. Except for the herbicide treatments, all other crop husbandry practices were uniform across experimental plots.

3.2.3 Herbicide Treatments

Nine treatments were evaluated for weed density; weed biomass and sorghum response to herbicide application. Four herbicides, namely Primagram, Lumax, Sencor and Dual Gold, were applied during planting as pre-emergence whereas the remaining three; 2, 4-D, Maguguma and Axio were applied as post emergence herbicides at 30 DAS (Table 3.1). One hand weeded and unweeded plots were included as positive and negative controls, respectively. Herbicide application was done using sprayer with flat fan nozzles on each experimental plots. Pre-emergence herbicide application was done once at planting.

Table 3.1 : Treatments, trade name, active ingredients and recommended rates

Herbicide treatment (trade name)	Active compound (s)	Rate of application ($l\ ha^{-1}$)
Primagram	S-Metolachlor 280 g/l, Atrazine 370 g l^{-1}	5.6
2 ,4-D	2,4-D amine salt 560 g/l	3
Sencor	Metribuzin 480 g l^{-1}	1.5
Dual gold	S-metolachlor 960 g l^{-1}	2
Maguguma	S-metolachlor 290 g l^{-1}, Atrazine 370gl^{-1}	2
Lumax	Mesotrione 37.55 g l^{-1} Terbuthylazine 125 g l^{-1} Metolachlor 375 g l^{-1}	4
Auxio	Bromoxynil 262 g/l Tembotrine 50gl^{-1}	1.5

3.2.4 Data collection

Data were recorded on weed density, weed species distribution and biomass for both the weeds and sorghum. Crop emergence and stand count was determined by counting the number of plants in 12m^2 after thinning the crop. It was done by removing excess seedling to achieve a spacing of 15 cm between the plants and 60 cm between the rows to achieve optimum plant population.

$$\text{Optimum plant population} = \frac{\text{Area}}{\text{Spacing}}$$

Where, Area is the experimental plots (12 m^2) and spacing (0. 60 x 0.15 m = 0.09 m^2)

Weed counts and species distribution were done 30 days after application of pre-emergence herbicides which coincides with the three - leaf stage of crop. The second weed count was done at 60 days after sowing when the post - emergence herbicides have shown effects. Counting and identification of weed species was done from 1 m^2 quadrat thrown randomly in each plot.

Weed biomass was taken at 30 DAS and 60 DAS by harvesting all the above ground growth of weeds within the 1 m^2 quadrat thrown randomly in each experimental plot. The weeds were gathered together and put in a paper bag and later oven-dried at a temperature of 60°C to a constant weight. The oven-dried weight in grams was then converted to $kgha^{-1}$ for each plot. In addition to weed biomass, sorghum biomass sampling was done at same time as in weeds, from 0.6 m length on each of the two border rows. The sorghum shoots harvested at the crown level and samples placed in paper bags and dried in an oven at 60 ^{0}C to constant weight. Weed control efficiency (WCE) is the percentage of weed reduction due to a weed control treatment and is a measure of effectiveness of control method (Das, 2008).

$$WCE= \frac{DMC-DMT}{DMC} x\ 100$$

Where DMC is the weed dry matter in no weeding treatment and DMT is dry matter in a treatment.

Data on crop yield was not collected due to total crop loss arising from bird damage.

3.3 Data analysis

Data collected were subjected to analysis of variance (ANOVA) using Statistical Analysis Software (SAS) version 8.1 (Littel *et al*., 2002). Treatment means were separated using Tukey's HSD test at at P≤0.05.

3.4 Results and discussion

3.4.1 Weed Flora

Major weed flora observed in the experimental plots comprised of *Datura stramonium, Bidens pilosa, Pennisetum clandestinum, Digitaria scalarum, Gallinsoga parviflora, Commelina benghalensis, Tagetes minuta, Anagallis arvensis, Oxygonum sinuatum, Oxalis latifolia, Setaria sphacelata and Cyperus rotundas.* Broadleaf weeds namely *Bidens pilosa, Gallinsoga parviflora and Amaranthus hybridus* were among the predominant weed species as shown in (Table 3.2). Broad-leafed weeds recorded 82% and narrow leafed were 18% of the total weed density. *Amaranthus hybridus* recorded the highest weed density of 18% of the total weed density in No weeding as per Table 3.2. This study shows that *Amaranthus hybridus* exhibit higher competitive ability than other weeds*;* this is attributed to the fact that pigweed can grow rapidly at high temperatures and high light intensity to tolerate drought, and compete aggressively with the crop for light, moisture, and nutrients (Shrestha & Swanton, 2007). This weed is able to avoid shading by rapid stem elongation. The higher weed density could be due to its ability to produce many seeds where a mature plant can produce seeds at the range of 100 000 to 600 000 under favorable conditions, making a total plant population of 0.4–2 billion per acre (Massinga *et al.*, 2001). The data regarding to *Amaranthus hybridus* revealed that weed density at 30 days after sowing (DAS) was significantly affected by all weed control treatments (Table 3.2) compared to No weeding. The maximum reduction of pigweed was recorded where 2, 4-D, Sencor and Hand weeding were applied. *Bidens pilosa* is one of the broad-leafed weeds that recorded high weed density as per Table 3.2 .The results on Table 3.2 indicate that *Bidens pilosa* density was affected by all herbicide treatment with Sencor recording the lowest as compared to No weeding. It is fast growing and very invasive that result into a number of ecological problems for example is allopathic effects. *Bidens pilosa* contains allelopathic substances which affect seed germination, plant growth and chlorophyll synthesis by plant leaves (Khanh *et al.,* 2009). Its allelopathic effects are also useful in promoting its capacity in interspecific competition and its invasiveness (Arthur *et al*., 2012).

Narrow leafed weeds had two troublesome species; the *Digitaria scalarum* and *Cyperus rotundus*. Kikuyu grass (*Pennisetum clandestinum*) was found in some experimental plots. Results in Table 3.2 shows that Primagram and Sencor were effective in reducing most of the narrow leafed weeds. In plots treated with 2, 4-D, all broad leafed weeds were effectively controlled (Table 3.2). 2, 4-D is effective in controlling broad leafed weeds as compared to other treatments. These results conformed to that of Solaimalai *et al*. (2004) which shows synthetic auxin herbicides as being effective in broad leaf weeds in cereals. The results in Table 3.2 show that Sencor had the lowest number of weed species. This finding conformed to that of Tuti and Das (2011) who reported that Metribuzin can effectively control broad leaf weeds and some grasses.

Table 3.2: Weed species found in the experimental plot

Weed species	No weeding	Primagram	2,4-D	Sencor	dual Gold	Maguguma	Hand weeding	Lumax	Auxio
Amaranthus hybridus	36	6	0	0	8	2	0	9	30
Datura stramonium	3	1	0	0	2	2	2	0	0
Bidens pilosa	31	4	3	0	9	6	2	4	23
Physalis alkekengi	3	1	0	1	5	0	3	6	15
Pennisetum clandestinum	10	0	5	0	3	7	6	3	2
Chenopodium album	8	0	0	1	4	1	1	9	1
Raphanus raphanistrum	12	5	0	0	1	1	4	1	4
Digitaria scalarum	6	0	3	1	7	6	3	8	3
Gallinsoga parviflora	26	6	0	1	6	2	1	4	4
Commelina benghalensis	3	2	0	0	8	8	0	3	9
Tagetes erecta	2	2	0	1	0	5	1	0	14
Oxygonum sinuatum	7	2	0	1	5	3	1	4	4
Oxalis latifolia	5	2	2	1	3	7	0	1	9
Setaria sphacelata	12	0	3	1	9	1	0	3	7
Cyperus rotundus	3	2	4	3	1	5	2	4	1
Total	171	42	28	8	22	77	56	29	61
Broad leaf	140	40	0	3	15	57	37	18	43
Narrow leaf	31	2	28	5	7	20	19	11	18

3.4.2 Weed density

The pre-emergence herbicides significantly reduced the weed density in sorghum compared to the un-weeded check (Table 3.3). However, amongst the four pre-emergence herbicides, Sencor (Metribuzin) was the most effective herbicide in reducing the weed density by 96% compared to no weeding at 30 DAS (Table 3.3).

Table 3.3: Effect of selected herbicides on weed density in sorghum

	Weed density (number m^{-2})	
Treatments	**At 30 DAS**	**At 60 DAS**
No weeding	2542.7^{a*}	2705.7^{a}
Hand-weeding	2303.2^{a}	251.4^{cde}
Auxio	1948.2^{a}	1122.7^{b}
2,4-D amine salt	1712.1^{ab}	83.2^{de}
Maguguma	2192.8^{a}	871.3^{bc}
Primagram	378.2^{c}	713.4^{bcd}
Sencor	48.8^{e}	59.1^{e}
Dual Gold	832.3^{bc}	591.1^{bcde}
Lumax	460.4^{c}	934.2^{b}
Tukeys $MSD_{0.05}$	890.4	389.54

*Means with same letter in the column do not differ significantly (*P*≤0.05) using Tukey's HSD test; DAS – Days after sowing

The positive effect of hand weeding was seen at 60 DAS, where weed density was reduced by 91% compared to No weeding control. Based on the data above most smallholder farmers prefer this method of weed control because it is the most efficient method used in areas where labor is cheaper and easily available. It is practical method of weed control in all crops, sowing methods, and growth conditions. However, urgent need of labour during labour peak period cause economic losses to crops is a critical factor in the success of this method (Shad, 2015). Repeated hand weeding and involvement of intense labor make this method inconvenient, uneconomical, and unfeasible (Rao *et al*., 2007). Weed control on a large scale usually becomes impossible if manual control methods are adopted (Akbar *et al*., 2011). However, the use of Sencor recorded lower weed density compared to hand weeding. This finding conformed to those of Jabran *et al.* (2012) who recorded higher weed suppression and more yield from the plots treated with herbicides than those that were hand weeded. Some of the perennial weeds are persistent and difficult to control than annuals using tillage due to their underground rhizomes, stolons and tubers. In their underground parts, these weeds store food material and can regenerate several new plants even after being uprooted (Colquhoun, 2001). This makes hand weeding less effective option. The efficacy of Sencor (Metribuzin) and Lumax (S-metolachlor + Atrazine+ Mesotrione) were however comparable in 30 DAS. On the other hand, Primagram (S-Metolachlor+Atrazine) and Dual gold (S-metolachlor) reduced the weed density by about 67% compared to no weeding plots. At 60 DAS the efficacy of these pre-emergence herbicides could still be noted with Sencor (Metribuzin) being the most effective in reducing the weed density of both broad and narrow leaf weeds. These results are in agreement with that of Nanher *et al.* (2015) who reported reduced weed densities when metribuzin was used weed control in potatoes and wheat production, respectively. Sencor is absorbed through the plant shoots while they are still underground and kill or injure the shoots before they emerge from the soil. This occurs due to inhibition of the enzyme activity and the disruption of protein synthesis and other subsequent bio-chemical reactions which in turn inhibit the weed growth and few weed species survive the herbicide action.

However, Primagram (S-Metolachlor+Atrazine) reduces from 74 to 58% and Lumax (S-metolachlor+ Atrazine+ Mesotrione) from 69 to 49 % did not have a longer residue effect in this study as shown by increased weed density at 60 days after sowing. Dual gold is somehow persistent as shown by its ability to kill weeds even at 60 DAS.

The pre-emergence herbicides kill weeds before they sprout however they don't prevent germination of weed seeds. In the early development stages, sorghum plants are relatively small, fragile and have slow growth (Silva *et al*., 2014). Competition with weed at this stage is quite low, and if no control measures are taken in the first few weeks after the emergence , stalk and grain yield can be reduced by around 35-70% (Rodrigues *et al*., 2010).The germinated seeds once in contact with pre-emergent herbicides cannot emerge (Mitchell *et al*., 2001). This explains why the plots treated with pre-emergence herbicides had significant reduction in weed density compared to the No weeding. Therefore pre-emergence treatment is the best option for controlling weeds in sorghum.

The difference in weed densities among the treatments could be attributed to properties of individual herbicides such as solubility, volatilisation, photo degradation, breakdown, persistence and weed tolerance. One major challenge with pre-emergence herbicides is that they need to be applied in a moist soil for it to be effective. This is because pre-emergence herbicides are taken up by roots of germinating weeds (Kaapro & Hall, 2012) or through coleoptile or meristem of germinating seedling. The uptake by root will occur when herbicide is available in soil moisture. Metribuzin has high solubility (1165 mg/L) followed by S-metolachlor (480 mg/L) while atrazine has lowest solubility (30 mg/L) all at 20°C (GRDC, 2015). The atrazine can therefore fail to provide good weed control under dry conditions.

Efficacy of applied herbicides declines due to photo degradation in presence of sunlight resulting in loss of weed control mechanism. Adequate rainfall immediately after application of pre-emergence is known to reduce unacceptable loss. Metribuzin (Khoury *et al*., 2006), mesotrione (Carles *et al*., 2017), atrazine and S-metolachlor (Shaner & Henry, 2007) undergo some level of photo degradation. Comparing persistence of three herbicides under no tillage, Bedmar *et al*. (2017.p.3065) found S-metoachlor had significantly greater persistence (82-141 days) than atrazine and acetochlor. Atrazine had lowest persistence range of 13 to 29 days. The persistence varies depending on component of herbicide, soil type, application rate and speed of breakdown. According to GDRC (2015), S-metolachlor (Dual Gold), and metribuzin (Sencor) are non-persistent having DT_{50} value ranging between 11-31 days compared to atrazine (Gesaprim) having moderate persistence (DT_{50}=60). Since sencor has low persistence, it was able to clear majority of weeds within 30 days after planting to create long lasting effect of low weed density.

Generally, use of post-emergence herbicide reduced weed density significantly than no weeding control (Table 3.3). 2, 4-D was effective post-emergent treatment recording lowest weed density compared to No weeding; Auxio and Maguguma however was comparable to hand weeding. Thirty days after the application of post emergence treatment, weed densities were reduced by 97, 91, 68 and 59% when 2, 4-D, Hand weeding, Maguguma and Auxio were used, respectively. Although both Auxio and Muguguma were less effective than hand weeding, they reduced weed density significantly by about 58.5 % compared to no weeding. However, No weeding treatment resulted in increase in weed density by 6% at duration of 30 days, this low increase in rate is due to fact that the crop and some weeds are more aggressive than others forming the canopy that suppresses their growth. For the post-emergence herbicide treatment, 2, 4-D was most effective in reducing weed density compared to other herbicides. Hand weeding was comparable to 2, 4-D indicating that it can be carried out in case of sorghum production where herbicides have not been applied. 2, 4-D is a synthetic auxin and systemic herbicides used for controlling broadleaf weeds. It causes unregulated cell, uncontrolled growth leading to damage to chloroplasts, membranes and vascular tissues which finally causes the death of the whole plant (Zahoor *et al.,* 2017). 2,4-Dichlorophenoxyacetic acid (2, 4-D) is the most common phenoxy herbicide that is effective against wide variety of broadleaf plants and is used primarily in forestry, lawn and agriculture (Kennepohl *et al.,* 2010). Broadleaf weeds were predominant in experiment explaining why 2, 4–D was effective in reducing weed density by 97%. 2, 4-D was applied in sugarcane where *Amaranthus hybridus* were successfully eliminated boosting yields (Smith *et al*., 2008). However, the half-life of 2, 4-D in soil is relatively short, due to several microbes that readily degrade it especially bacterium *Alcaligenes eutrophus* (Dekker & Duke, 1996).

Maguguma (S-metolachlor and Atrazine) and Auxio (Bromoxynil and Tembotrine) were also effective in reducing weed density compared to no-weeding. Both herbicides have two combinations of active ingredients hence giving better results. Chauvel *et al*. (2012,pp. 320-326) argued that one active ingredient is usually strong against few weeds, but weak against many other thus necessitating combining different active ingredients to achieve a broader spectrum. Though 2, 4-D and atrazine may cause leaf burn; these effects are usually outgrown within two weeks and are recommended for application before sorghum plant height exceeds 38cm (Smith & Scott, 2010). Atrazine, active component of Maguguma is usually effective when weeds are small especially for control of *Amaranthus hybridus* (Norsworthy *et al*., 2008). Bromoxynil and S-metolachlor in combination with other herbicides have shown significant efficacy (95%) in control of broadleaf weeds in grain sorghum fields (Hennigh, *et al.,* 2010).

In this study, 2, 4-D and Sencor have proven effective in reducing weed density and thus were used in second experiment to determine appropriate rate of application to achieve optimum weed control and yield of sorghum.

3.4.3 Weed biomass

Weed biomass was remarkably influenced by weed control treatments at all stages of observation (Table 3.4). Results showed that the use of Sencor (Metribuzin) had a significant effect on weed biomass at 30 and 60 DAS after application. The herbicide reduced weed biomass by 85% and 92% compared to no weeding at 30 and 60 DAS, respectively .This treatment reduced the weed pressure improving the competitive ability of the crop to important resources for growth thus leads to increase in sorghum biomass. In No weeding treatment, weeds grow undisturbed, therefore they were able to maximise the available resources to accumulate dry matter leading higher biomass. Relative to hand weeding, Sencor reduced weed biomass by 68% at 60 DAS. Primagram, Lumax and Dual gold were inferior as hand weeding at 30 and 60 DAS, respectively. Sencor use as pre-emergent herbicides can control weeds at early stages making the crop to be more competitive by forming a canopy thus suppressing the growth of weeds. This work conformed to that of Chauhan, 2012 that states that a single or double herbicide application would control weeds at the early stage of the crop and reduces the need for future weed management.

Table 3.4: Effect of selected herbicides on weed biomass in sorghum

	Weed biomass (kg/ha)		**Weed Control**
Treatment	**30 DAS**	**60 DAS**	**Efficiency(WEC)**
No Weeding	1542.7[a^]	1888.7[a]	0
Hand Weeding	809.0[ab]	323.7[d]	82.9
Primagram	1303.2[ab]	716.4[c]	62.1
Sencor	121.2[c]	82.09[d]	95.7
Lumax	525.5[bc]	735.9[bc]	61.1
Dual Gold	917.2[ab]	945.8[bc]	49.9
2,4-D	1004.7[ab]	245.4[d]	87.0
Maguguma	937.1[ab]	858.8[bc]	54.5
Auxio	1026.5[ab]	1001.8[b]	47.0
Tukeys $MSD_{0.05}$	540.6	267.5	91.6

*Means with same letter in the column do not differ significantly ($P \leq 0.05$) MSD, Das – Days after sowing.

Result in Table 3.4 reflects the ability of Sencor in reducing weed biomass. Sencor (Metribuzin) is a selective triazinone herbicide acting as an inhibitor of photosynthesis, specifically the inhibition of the photosynthetic electron transfers in light reaction stage (Singh *et al.,* 2015). Metribuzin is also used as both pre- and post-emergence herbicide in crops such as potatoes, sugarcane and tomatoes. It is absorbed through roots and leaves and transported by xylem where it is concentrated in roots, stems and leaves (Tuti & Das, 2011). In this study Metribuzin was tested as a pre-emergence herbicide. Sencor (Metribuzin) in suppressing and preventing survival, growth and competitive ability of weeds (Azadbakht *et al.,* 2017)

Amongst post emergence treatments 2, 4-D (2, 4-D amine salts) proved more effective in reducing weed growth as indicated by reduced dry weight, compared to other treatments (Table

3.4). Hand weeding and use of 2, 4-D was equally effective in reducing weed biomass. However, considering the initial weed biomass at the time of application of the treatment, 2, 4-D reduced the weed biomass by 60.7% while hand weeding reduced the biomass by 42.8%. 2, 4-D is among the first herbicide compounds that are selectively effective against dicot but not monocot plant species (Andrew *et al*., 2010). The 2, 4-D amine salt differs from corresponding esters in that ester formulations tend to volatilize more than amines. Secondly, though esters have wider weed control, they tend to cause crop injury since they are readily soluble rendering easy absorption (Knezevic *et al*., 2013). Herbicide effect was manifested by twisted, thickened and elongated leaves and stems which eventually killed the plant (Grossman, 2009). Highest dry weight of weeds was observed under no weeding treatment.

Use of herbicides in crop management has been suggested as a technological alternative to hand weeding for increased crop yields. In a study where predominant weed species were Bermuda grass (*Cynodon dactylon*), horse purslane (*Trianthema portulacastrum*), Jungle rice (*Echinochlova colona*), Purple nutsedge (*Cyprus rotundus*), crow foot grass (*Dactyloctenum aegyptium*), field bind weed (*Convolvulus arvensis*) and goose grass (*Eleusine indica*), a significant weed density was observed when S-metolachlor and atrazine were applied for weed management in maize (Mahmood *et al*., 2015). The present study showed that 2, 4-D and Sencor presented above 85% weed biomass suppression hence can be adopted as alternative for efficient weed management approach in sorghum.

Several studies reported advantage of herbicide use in increasing maize grain yield (Abuzar *et al*., 2011; Borghi *et al*., 2013). Since herbicide application for weed management reduces competition for the resources. Similarly, comparing pre-emergence herbicides application effect on sorghum yield Geier *et al*. (2017) found that Acetochlor, S-metolachlor and Atrazine were best in weed control though a significant sorghum crop injury was reported. There are limited post-mergence herbicides for controlling grass weeds in sorghum hence need for combination of various herbicides to kill narrow leaf and broadleaf weeds. Weed density and biomass was reduced when bromoxynil, atrazine and 2-4 D were combined with nicosulfuron and rimsulfuron for weed management in sorghum (Tuinstra, 2010). Previous studies are in consensus with current study whereby herbicide application resulted in decreased weed biomass significantly.

Weed control efficiency (WCE) denotes the magnitude of weed reduction due to weed control treatment. It was worked out by the formula suggested by Mani *et al* 1973.
Sencor, 2, 4-D and Hand weeding recorded high WCE of 95.7%, 87% and 82.9% respectively. Auxio and Dual gold recorded low WCE (Nayak *et al.,* 2014). Result shows that hand weeding

were one of the best methods of controlling weeds especially in small scale holding. It is the most common method among the farmers because of its cost effectiveness in small holding set up and less skilled labor required (Rueda-Ayala *et al*., 2010).

3.4.4 Crop stand count

Generally, crop stand is affected by different herbicide treatment at 30 and 60 DAS due to (Table 4.3). Sorghum stand was decreased by 51% in the pre-emergence dual gold treatments. In contrast, there was no decrease in sorghum stand count when Sencor and 2, 4-D were applied (Table 4.3). The use of Lumax and Axio decreases sorghum stand count by 29% and 17% respectively.

The results revealed that, sorghum stand count was significantly influenced by the herbicides treatment. Lowest sorghum stand count was recorded with the use of dual gold. This study shows that Dual gold was non selective. Lumax and Axio show some degree of non-selectivity. Several factors can influence the selectivity, such as the crop stage development, the plant genetic material and the soil and weather conditions at the application (Norworthy *et al.,* 2012).

Table 3.5: Effect of selected herbicide on sorghum stand count

	Sorghum stand count (plants/12 m^2)	
Treatment	**30 DAS**	**60 DAS**
No weeding	136.66^{a}	135.47^{a}
Hand weeding	135.43^{a}	135.84^{a}
Auxio	110.00^{bc}	100.33^{bc}
2,4-D	133.33^{a}	133.23^{a}
Maguguma	120.67^{ab}	114.52^{ab}
Primagram	126.67^{ab}	126.54^{ba}
Sencor	135.33^{a}	136.43^{a}
Dual gold	65.33^{d}	64.71^{d}
Lumax	94.06^{c}	94.78^{c}
Tukeys		
MSD $_{0.05}$	20.99	20.622

Means with same letter in the column do not differ significantly ($P \leq 0.05$) MSD, DAS – Days after sowing

When Atrazine is applied in the pre-emergence stage; it is absorbed by the soil and reaches the leaves. It acts by inhibiting the transport of electrons in the photosynthetic electron transport (Takano *et al*., 2008). This process leads to photo-inhibition and photo-oxidation of the photosystem II (Ramel *et al*., 2009), increasing the production of oxygen reactive species, which leads to oxidative stress and damage to the cell membranes (Hugie *et al*., 2008). The lowest growth of shoots in relation to the root zone in plants cultivated in the presence of S-metolachlor is because the herbicide, which inhibits the meristems division, is absorbed mainly by the hypocotyl, affecting the apical meristem of the shoots with higher intensity than on the roots. On the other hand, for the plants that underwent the diclosulam treatment, their roots had lower growth by this inhibitory action on the acetolactate synthase (Johnson *et al*., 2012).

The data in Table 3.2 shows no growth of *Raphanus raphanistrum* where Sencor and 2,4-D were applied; this could also be due to optimum population of sorghum as in Table 3.5 that can exert allelophatic effect on the weed inhibiting germination and development of *Raphanus raphanistrum* (Glab *et al.,* 2017).

Plate 3.1: Effect of Lumax on stand count of sorghum

3.4.5 Sorghum biomass

The results showed that different herbicide treatments had significant ($P \leq 0.05$) effects on sorghum biomass (Table 3.6). Significantly lower dry matter was recorded in weedy check compared to all other treatments. The dry matter accumulation in sorghum crop increased with the advancement of crop that maximum was observed at 90 DAS (Table 3.6). The dry matter accumulation differed significantly among different weed control treatments over crop growing season with no weeding recording the lowest dry matter accumulation of sorghum in all stages of crop development.

These findings are in agreement with the work done by Bolaji and Etejere (2015) who reported highest dry matter accumulation on the use of metribuzin (Sencor) with 45%, 69% and 75% increase in dry matter accumulation in 30, 60 and 90 DAS respectively as compared with No weeding treatment. On the other hand, 2, 4-D herbicides recorded the 66% and 71% increase in dry matter accumulation in 60 and 90 DAS respectively as compared to No weeding. Increase in dry weight of crop plant is directly related to growth and development of crop. Proper growth of crop required sufficient availability of moisture, nutrient, sunlight and carbon dioxide (Singh *et al*., 2011). If weeds were not controlled by herbicides, they compete for resources that would ultimately hamper plant growth and dry matter accumulation. Therefore, reduction in weed density and weed biomass provides more utilization of space, water, light and nutrients by the crop, and thus results in improved crop biomass through better photosynthesis and overall growth and metabolic activities of the crop (Ghosh *et al*., 2016). Similarly, Muoni *et al*. (2013) concluded that herbicide application is the best weed control method for obtaining higher crop yield. This study found Sencor (Metribuzin) to be the most effective pre-emergence herbicide in improving crop biomass while 2, 4-D was effective post-emergence herbicide for reducing weed pressure resulting in increased crop biomass.

Table 3.6: Effects of selected herbicides on sorghum biomass

Treatments	Sorghum biomass (kg/ha)		
	30 DAS	60 DAS	90 DAS
No weeding	1113.5^{c}	2984.3^{e}	3763.0^{fe}
Hand weeding	1407.2^{bc}	11564.5^{cd}	18274.4^{c}
Auxio	1232.2^{bc}	3244.5^{de}	8298.6^{d}
Maguguma	1229.5^{bc}	7110.6^{c}	15597.0^{c}
Primagram	1837.2^{b}	10704.9^{b}	13769.4c
2,4-D	1312.6^{bc}	14603.3^{a}	22656.5^{b}
Sencor	2973.5^{a}	16520.9^{a}	25911.7^{a}
Dual gold	1566.3^{bc}	3888.0^{cde}	9723.0^{d}
Lumax	1386.7^{cd}	5965.0^{cde}	15934.8^{c}
Tukeys $MSD_{0.05}$	663.5	3379.6	3041.0

*Means with same letter in the column do not differ significantly ($P \leq 0.05$) MSD, DAS – Days after sowing

The use of Sencor and 2, 4-D could replace hand weeding which is more labour intensive than chemical weed management. Hand weeding recorded slightly lower sorghum biomass compared to Sencor and 2, 4-D; this is because partially uprooted weeds may regain vigour through regeneration and root injury to crops may also occur which affect the growth and development of the crop (Hakansson, 2003). Hand weeding requires repeated operations for effective weed control, reducing efficiency of weeding over other conventional methods Herbicide use also helps to achieve timely intervention within the critical period of weed management and thus ensures minimal crop yield loss attributed to weeds.

3.4.6 Correlation among weed density, weed biomass and sorghum biomass

Simple correlation (Table 3.7) revealed that weed density and weed biomass significantly and positively correlated. This implies that the higher the weed density the higher the weed biomass. On the other hand, the weed biomass and the sorghum biomass had a negative correlation an indication that where weeds biomass increases, the sorghum biomass decreases and vice versa. The study showed negative relationship between weed biomass and sorghum biomass indicating that the eradication of weeds reduces crop damage due to harmful effects of weeds hence enhancing yield performance. Similar results were reported by Liu *et al*. (2009) where the reduction in crop yield had direct correlation with weed competition. The results revealed that controlling weeds in sorghum production is necessary to increased yield quality and quantity.

Table 3.7: A simple correlation for weed density, weed biomass and sorghum biomass

	Weed den 30 DAS	Weed biomass 30 DAS	Sorghum biomass 30 DAS	Weed den 60 DAS	Weed biomass 60 DAS	Sorghum biomass 60 DAS	Sorghum biomass 90 DAS
Weed den 30 DAS	1	0.718^{***}	-0.462^{***}	0.444^{*}	0.409^{*}	-0.469^{*}	-0.332^{**}
Weed biomass 30 DAS		1	-0.739^{***}	0.587^{**}	0.667^{***}	-0.669^{***}	-0.657^{***}
Sorghum biomass 30DAS			1	-0.425^{*}	-0.529^{**}	0.657^{***}	0.550^{**}
Weed den 60 DAS				1	0.917^{***}	-0.604^{***}	-0.802^{***}
Weed biomass 60 DAS					1	-0.742^{***}	-0.921^{***}
Sorghum biomass 60DAS						1	0.825^{***}
Sorghum biomass 90DAS							1

* And ** significance at $P \leq 0.05$ and *** significance at $P \leq 0.01$

Weed density and weed biomass recorded a negative correlation to sorghum biomass this is due to the fact that weeds usually absorb larger amount of mineral nutrients faster than crop plants and transpire faster than the crop causing crop moisture stress. Nutrient removal by weeds leads to huge loss of nutrients in each crop season (Rana & Rana, 2015). Absorption of nutrients by weeds at expense of the crop slows down dry matter accumulation of the crop leading to low sorghum biomass. The actual evapotranspiration from the weedy crop fields is much more than the evapotranspiration from a weed free crop field (Rana & Rana, 2015). The higher weed density and biomass result in severe the competition for water, carbon dioxide and light interception leading to low sorghum biomass. Water, carbon dioxide and light are important raw materials for photosynthesis contributing directly to dry matter accumulation.

The results demonstrate the importance of early herbicide application in controlling the weeds. The herbicide degradation rate or metabolism could be faster in big plants, thus herbicide rates may need to be increased to achieve the same level of control.

CHAPTER FOUR

EFFCET OF RATE OF APPLICATION OF SENCOR AND 2, 4-D HERBICIDES ON WEED DENSITY, WEED BIOMASS AND SORGHUM

Abstract

A field study was conducted at Egerton university Njoro campus Kenya during the short rains in March 2015 to determine the effect of rate of application of Sencor and 2, 4-D herbicides on weed density, weed biomass and dry weight of sorghum. The experiment was conducted in a randomized complete block design replicated three times. Ten treatments comprised of both Sencor (Metribuzin 480gl^{-1}) at 0.75, 1.125, 1.5, 1.875, 2.25 litres ha^{-1} and 2, 4-D (2, 4-D amine salt 560g/l) at 1, 1.5, 2, 2.5 and 3 litres ha^{-1} application rates. Weeds density, weed biomass and crop biomass were assessed in response to the treatment at 30 and 60 days after the application. All the data was and subjected to analysis of variance using SAS version 8.1. Means were separated according to Tukey's MSD (Minimum Significant Difference) test whenever the herbicide effects were significant ($P \leq 0.05$). Analysis of variance (ANOVA) revealed significant ($p \leq 0.05$) differences in the effect of the treatments evaluated. At 30 DAS, the lowest weed density of 12.67 weeds m^{-2}, 12.00 weeds m^{-2} and 8.3 weeds m^{-2} were observed with 1.5, 1.875, 2.25 litres of Metribuzin, respectively. The highest weed density was observed on Metribuzin at 0.75, 1.125 litres and 2, 4-D at 1, 1.5 in the 60 DAS. Higher rates of herbicides application recorded a decline in biomass of sorghum in both Metribuzin at 1.875, 2.25 and 2, 4-D at 2.5, 3 litres with 37.4%, 63.5% and 40%, 69.3% compared to 1.5 litres of Metribuzin and 2 litres of 2, 4-D the rate that recorded the highest sorghum biomass. Adoption of Sencor and 2, 4-D in 1.5 and 2 litres respectively will ensure effective weed management and contribute to increased sorghum production to meet the increasing industrial demand.

4.1 Introduction

Sorghum is the second most important staple crop after maize and useful for food security of households. Due to its resistance to drought, diseases and the notorious Striga weed, sorghum regularly out yields maize. However, there have been decline in its production. The largest groups of producers in Kenya are small-scale subsistence farmers (Food security department (FSD), 2004). Being poor in resources, unreliable rainfall, most of sorghum farmers have only minimum access to production inputs and improved credit facilities for their purchase (FSD, 2004). The factors like low profitability of sorghum, biotic factors and less demand as a food grain has affected its importance. Farmers still continue to grow sorghum though to a certain minimum level, which can be referred to as household food/fodder security level (Muui *et al.*, 2013). Weeds are among the major production constraints in sorghum. Due to its initial slow development weed interference is most significant during the first 30 days after emergence (Silva *et al.*, 2014). The lack of herbicides selective to sorghum has hampered the weeds control, mainly the grasses species (Reis *et al.*, 2019).

The level of weed suppression is mainly determined by the competitiveness of the crop, environmental conditions and herbicides dose. The parameters to consider when evaluating herbicide doses are: weed flora and growth stage, crop competitiveness, climatic conditions, application technique, formulation/adjuvant and combination with other pesticides (Kudsk, 2008). Possibly increased doses of the herbicide have caused greater absorption of herbicides by crops, which may have exceeded the plant inherent capacity to metabolize the herbicide. Higher doses may reduce herbicide selectivity, leading to injury of both the crop and the weed (Pessoa *et al.*, 2017). The persistence and phytotoxicity increases with increasing rate of application of the herbicide (Peres-Oliveira *et al.*, 2017). Previous study in Nigeria comparing rates of Primextra, Dual gold (atrazine and metolachlor) showed that the use of different doses of herbicide up to the recommended dose, positively influenced growth and yield of maize while an overdose affected the parameters adversely (Chinyere *et al.*, 2017). A study was conducted to determine the effect of rates of application of Sencor and 2, 4-D herbicides on weed density, weed biomass and dry weight of sorghum.

4.2 Materials and methods

The most effective type of pre - and post - emergence herbicides from Experiment 1 in section 3.2.1 were used to evaluate the effect of herbicide rate on weeds, growth and yield of sorghum. Except for the herbicide treatments all other crop husbandry practices were uniform across experimental plots. The treatments were arranged in a 2x5 factorial randomized complete block design (RCBD) with three replicates. Different rates of pre- emergence and post - emergence herbicide applied to plots measuring 3 m by 4 m with six rows of sorghum. Factor 1 was the type of herbicide i.e. Sencor and 2, 4-D and factor 2 was the herbicide rate as follows: Sencor (Metribuzin $480 gl^{-1}$) at 0.75, 1.125, 1.5, 1.875, 2.25 litres ha^{-1} and 2, 4-D (2, 4-D amine salt 560g/l) at 1, 1.5, 2, 2.5 and 3 litres ha^{-1} application rates. The treatment was applied using sprayer with flat fan nozzles. Ten treatments applied at the same stages of growth as in experiment 1.

The weed control efficiency (WCE) was calculated using the formula by Mani *et al.* (1973). WCE is the percentage of weed reduction due to a weed control treatment and a measure of effectiveness of control method (Das, 2008). WCE is a derived parameter that compares different treatments of weed control on basis of dry weight across them. Data collection and analysis was done as per chapter three.

4.3 Results and Discussions

4.3.1 Rate of application of Sencor and 2, 4-D herbicide on weed density

Rates of herbicide application significantly ($P \leq 0.01$) influenced weed density. Compared to unweeded control, weed density was significantly reduced under different herbicide application rates (Table 4.1). At 30 DAS, Sencor @ 1.5l, 1.875l, and 2.25l equally recorded the lowest weed density of 12.67N/m^2,12.00N/m^2 and 8.3N/m^2. The highest weed density was observed on Sencor @ 0.75l, 1.125l and 2, 4-D@ 1l 2, 4-D, 1.5l 2, 4-D at 60 DAS. The data showing higher number of weeds in at low herbicide application rate could be a result of weeds Weed develop resistance to herbicides were observed in low application rates of Metribuzin and 2, 4-D. The results show that herbicide resistances increase in some weeds with low rates of application than the recommended rates. This study conformed to what was recorded by Manalil *et al*. (2011) that the evolution of herbicides resistance was faster at low herbicide rates than at higher rates.

Table 4.1: Effect of Sencor and 2, 4-D herbicide application rate on weed density in sorghum

Herbicide	Rate of herbicide Ha^{-1} in l	Weed density (Number/m²)	
		At 30 DAS	**At 60 DAS**
Sencor (Metribuzin)	0.75	229.67^{c}	254.67^{a}
	1.125	100.67^{d}	113.33^{b}
	1.5	12.67^{e}	12.00^{c}
	1.875	12.00^{e}	11.67^{c}
	2.25	8.33^{e}	12.33^{c}
2,4-D (2,4-D amine salts)	1	440.67^{a}	228.00^{a}
	1.5	365.00^{ab}	100.33^{b}
	2	346.33^{b}	16.67^{c}
	2.5	434.00^{a}	12.67^{c}
	3	409.33^{ab}	10.00^{c}
Tukeys $MSD_{0.05}$		83.96	67.17

*Means with same letter in the column do not differ significantly ($P \leq 0.05$), Das – Days after sowing

4.3.2 Effect of rate of application of Sencor and 2, 4-D herbicide on weed biomass and sorghum biomass

The results showed the amount of herbicide applied significantly influenced the weed biomass and sorghum biomass. At 60DAS, lower rates of herbicides application of Sencor @ 0.75l, 1.125l and 2, 4-D 1l,1.5l recorded higher weed biomass of 230.73gm^{-2}, 167.05 gm^{-2} and 313 gm^{-2} ,115.78 gm^{-2} respectively (Table 4.2). More weeds tend to survive at low rates of herbicide application. The herbicide rate of 1.5l of Sencor and 2l of 2, 4-D recorded the highest sorghum biomass and low weed biomass (Table 4.2). Higher rates of herbicides application at Sencor @ 1.875l , 2.5l and 2,4-D @2.5l and 3l recorded a decline in biomass of sorghum with 37.4%, 63.5% and 40% ,69.3% compared to 1.5l of Sencor and 2l of 2, 4-D the rate that recorded the highest sorghum biomass (Table 4.2). Herbicide rates are registered on the basis of the biologically effective dose (BED). The BED is the herbicide dose which provides a 90% reduction in weed dry matter (Knezevic *et al.* 1998). The BED depends on other factors such as weed density, weed growth stage, application dose and growing conditions.

Table 4.2: Effect of Sencor and 2, 4-D herbicide application rates on weed and sorghum biomass

Herbicides application rate (ha^{-1})		Weed biomass (gm^{-2})		Sorghum biomass ($kgha^{-1}$)	
		At 30 DAS	At 60 DAS	At 30 DAS	At 60 DAS
Sencor (Metribuzin)	0.75	994.38^{b}	2230.73^{b}	1252.39^{c}	2445.77^{e}
	1.125	852.50^{b}	1467.5^{c}	1731.47^{b}	3134.84^{e}
	1.5	128.18^{c}	525.18^{ef}	2953.54^{a}	10197.37^{a}
	1.875	107.02^{c}	80.90^{ef}	1321.98^{c}	4117.09^{b}
	2.25	76.02^{c}	16.83^{f}	818.68^{cd}	1689.97^{bc}
2,4-D (2,4-D amine salts)	1	2246.81^{a}	1313.73^{a}	1820.71^{c}	2484.02^{e}
	1.5	1858.89^{a}	582.78^{d}	1921.75^{c}	57.14^{de}
	2	1763.20^{a}	61.11^{e}	2320.29^{c}	10052.86^{a}
	2.5	2210.42^{a}	59.43^{cd}	2020.14^{cd}	6504.67^{cd}
	3	2084.11^{a}	14.50^{e}	1915.57^{d}	4321.02^{e}
Tukeys MSD $_{0.05}$		347.9	444.6	64.68	2773.17

*Means with same letter in the column do not differ significantly ($P \leq 0.05$), DAS – Days after sowing,

This study shows that weeds contribute to low crop yield and is responsible for increasing gap between potential and actual yield per hectare. Due to increasing cost of labour for hand weeding, the use of herbicide is encouraged for controlling weeds. The effect of different concentration of post-mergence herbicides 2,4-D has been reported to affect growth and yield of sorghum (Besançon *et al*., 2016). Their study pointed out the risk of crop injury and reduction of grain sorghum yield with increased application of 2, 4-D (330 g acid equivalent ha^{-1}). This study showed that application of Sencor and 2, 4-D at recommended rates of 1.5L of Sencor and 2L of 2, 4-D, respectively had a positive effect on growth and yield of sorghum, measured in terms of biomass. Additionally, such recommended dose resulted in significant reduction in weed biomass. Increased rates of the herbicide have caused greater absorption of herbicides by crops, which may have exceeded the crop capacity to metabolize the herbicide. These higher doses cause crop injury (Pessoa *et al*., 2017). The persistence and phytotoxicity increased with increasing rate of application of the herbicide (Peres-Oliveira *et al*., 2017).

This study showed that application of herbicides below the BED-biologically effective dose led to increased weed density and weed biomass and thus decrease sorghum biomass. Regarding pre-emergence herbicides Sencor, application at recommended rate of 1.5l reduced weed biomass by 87.1% compared to plots treated with half of the standard rate at 30 DAS. Similar results were observed for post-emergence herbicide 2, 4-D in 60 DAS where weed biomass was about 77% lower in plots with recommended herbicide dose compared to 50% of standard rate. These trends are consistent with findings of other studies in maize and other crops (Haughton *et al*., 1999). Additionally, application of Sencor and 2, 4-D at recommended rates had best positive effect on the crop revealed by maximum sorghum biomass.

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

5.1.1 Conclusions

This study show weeds respond differently to herbicide treatments. The application of Sencor and 2, 4-D for weed control in sorghum resulted in significant reduction in weed density and weed biomass and increase in sorghum biomass. The combined analysis show Sencor and 2, 4-D at recommended rates resulted in improvement in growth of cultivated sorghum evident by maximum increase in sorghum biomass and reduction in weed density and weed biomass. Optimum herbicide application rate for effective weed control in sorghum is 1.5l ha^{-1} Sencor per hectare and 3l ha^{-1} 2, 4-D per hectare.

5.2 Recommendations

i) Since evaluated Sencor and 2, 4-D exhibit high weed control efficiency over control treatment at different stages of growth, it is therefore recommended that 2, 4-D and Sencor be used in control of weeds in sorghum production.

ii) Special attention should also be paid on testing the efficacy of Sencor and 2, 4-D across different environments.

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APPENDICES

Appendix 1. Research permit certificate

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Ref No: 792175

Date of Issue: 29/April/2021

RESEARCH LICENSE

This is to Certify that Ms.. Emily Chepkoech of Egerton University, has been licensed to conduct research in Nakuru on the topic: EFFECTS OF SELECTED HERBICIDES ON WEED MANAGEMENT IN SORGHUM for the period ending : 29/April/2022.

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Applicant Identification Number

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Appendix 2. An abstract page of published paper

Metribuzin and 2,4-D as potential herbicides for weed management in sorghum [*Sorghum bicolor* (L) Moench]

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Grain sorghum demand for industrial and domestic uses has triggered increased production of sorghum. Field experiment was conducted at Egerton University Njoro, Kenya to determine the most effective herbicide(s) for weed management in sorghum. The experiment was carried out in a randomized complete block design (RCBD) with nine treatments replicated three times. The treatments consisted of four pre-emergence herbicides namely Lumax® (Mesotrine, Metolachlor, Terbuthylazine), Primagram® (Atrazine, S-metolachlor), Dual gold® (S-Metolachlor) and Sencor® (Metribuzin). In addition, three post-emergence herbicides namely 2,4-D (2,4-D amine salt), Maguguma® (Atrazine, S-metolachlor) and Auxio® (Bromoxnil, Tembotrine) were included. Positive and negative controls comprised of hand weeding and no weeding, respectively. Pre-emergence treatments were applied immediately after sowing while post-emergence treatments were applied 30 days after sowing. Weed density and biomass were determined at 30 and 60 days after sowing. Means were separated according to least significant difference (LSD) whenever the herbicide effects were significant ($P \leq 0.05$). Analysis of variance revealed significant ($P \leq 0.05$) differences in the effect of the treatments evaluated. When used as pre-emergence herbicide, Sencor (Metribuzin) was more effective in reducing weed density by 96 and 79% relative to un-weeded and hand weeding treatments, respectively. The post-emergence 2,4-D herbicide reduced weeds by 90, 43 and 26%. Sencor and 2, 4-D were more effective in managing weeds in sorghum and currently, could be the best option for farmers in Kenya and elsewhere.

Key words: Sorghum, herbicides, Sencor, weeds

uAppendix 3. Analysed data output

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The GLM Procedure

Tukey's Studentized Range (HSD) Test for Weed30

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05

Error Degrees of Freedom	16
Error Mean Square	93974.7
Critical Value of Studentized Range	5.03101
Minimum Significant Difference	890.43

Means with the same letter are not significantly different.

Tukey Grouping		Mean	N	TRT
	A	2542.7	3	1
	A			
	A	2303.2	3	7
	A			
	A	2192.8	3	6
	A			
	A	1948.2	3	9
	A			
B	A	1712.1	3	3
B				
B	C	832.3	3	5
	C			
	C	460.3	3	8
	C			
	C	378.8	3	2
	C			
	C	115.5	3	4

The GLM Procedure

Tukey's Studentized Range (HSD) Test for Wdbiom30

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	34640.89
Critical Value of Studentized Range	5.03101
Minimum Significant Difference	540.62

Means with the same letter are not significantly different.

Tukey Grouping		Mean	N	TRT
	A	1230.3	3	1
	A			
B	A	1026.5	3	9
B	A			
B	A	937.1	3	6
B	A			
B	A	917.4	3	5
B	A			
B	A	809.0	3	7
B	A			
B	A	804.8	3	3
B				
B	C	525.5	3	8
B	C			
B	C	524.2	3	2
	C			
	C	121.2	3	4

The GLM Procedure

Tukey's Studentized Range (HSD) Test for Sorgbio30

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	52173.97
Critical Value of Studentized Range	5.03101
Minimum Significant Difference	663.47

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	TRT
A	2973.5	3	4
B	1837.2	3	2
B			
C B	1566.3	3	5
C B			
C B	1407.2	3	7
C B			
C B	1386.7	3	8
C B			
C B	1312.6	3	3
C B			
C B	1232.2	3	9
C B			
C B	1229.5	3	6
C			
C	1113.5	3	1

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The GLM Procedure

Tukey's Studentized Range (HSD) Test for Weed60

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	50649.04
Critical Value of Studentized Range	5.03101
Minimum Significant Difference	653.7

Means with the same letter are not significantly different.

```
Tukey Grouping        Mean     N    TRT

        A           2705.7     3    1

        B           1122.7     3    9
        B
        B            934.2     3    8
        B
C       B            871.3     3    6
C       B
C       B    D       713.4     3    2
C       B    D
C   E   B    D       591.1     3    5
C   E        D
C   E        D       251.4     3    7
    E        D
    E        D        83.2     3    3
    E
    E                 59.5     3    4
```

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The GLM Procedure

Tukey's Studentized Range (HSD) Test for Wdbiom60

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	8478.149
Critical Value of Studentized Range	5.03101
Minimum Significant Difference	267.45

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	TRT
A	1888.72	3	1
B	1001.81	3	9
B			
C B	945.79	3	5
C B			
C B	858.86	3	6
C B			
C B	735.93	3	8
C			
C	716.41	3	2
D	323.68	3	7
D			
D	245.40	3	3
D			
D	82.09	3	4

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The GLM Procedure

Tukey's Studentized Range (HSD) Test for Sorgbio60

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	1353728
Critical Value of Studentized Range	5.03101

Minimum Significant Difference 3379.6

Means with the same letter are not significantly different.

```
Tukey Grouping        Mean      N    TRT

       A           16520.9      3    4
       A
       A           14603.3      3    3

       B           10704.9      3    2

       C            7110.6      3    6
       C
   D   C            6564.5      3    7
   D   C
   D   C   E        5965.1      3    8
   D   C   E
   D   C   E        3888.0      3    5
   D       E
   D       E        3244.5      3    9
           E
           E        2984.3      3
```

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The GLM Procedure

Tukey's Studentized Range (HSD) Test for Sorgbio90

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	1096470
Critical Value of Studentized Range	5.03101
Minimum Significant Difference	3041.5

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	TRT
A	25911.7	3	4
B	22656.5	3	3

B			
B	20940.4	3	7
C	15934.8	3	8
C			
C	15597.0	3	6
C			
C	13760.5	3	2
D	9723.0	3	5
D			
D	8298.6	3	9
E	3763.0	3	1

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The CORR Procedure

7 Variables: Weed30 Wdbiom30 Sorgbio30 Weed60 Wdbiom60 Sorgbio60 Sorgbio90

Simple Statistics

Variable	N	Mean	Std Dev	Sum	Minimum	Maximum
Weed30	27	1387	939.02853	37457	45.86000	2701
Wdbiom30	27	766.21000	350.48433	20688	98.85000	1257
Sorgbio30	27	1562	586.14363	42176	1002	3212
Weed60	27	814.71519	794.38007	21997	50.96000	2813
Wdbiom60	27	755.41000	522.15744	20396	41.94000	1960
Sorgbio60	27	7954	4862	214758	2229	16909
Sorgbio90	27	15176	6972	409756	3624	27180

Pearson Correlation Coefficients, N = 27
Prob > |r| under H0: Rho=0

	Weed30	Wdbiom30	Sorgbio30	Weed60	Wdbiom60	Sorgbio60	Sorgbio90
Weed30	1.00000	0.71755	-0.64152	0.44414	0.40983	-0.46873	-0.33205
		<.0001	0.0003	0.0203	0.0338	0.0137	0.0906
Wdbiom30	0.71755	1.00000	-0.73922	0.58722	0.66694	-0.66903	-0.65734
	<.0001		<.0001	0.0013	0.0001	0.0001	0.0002
Sorgbio30	-0.64152	-0.73922	1.00000	-0.42485	-0.52914	0.65681	0.55019
	0.0003	<.0001		0.0272	0.0045	0.0002	0.0029
Weed60	0.44414	0.58722	-0.42485	1.00000	0.91650	-0.60385	-0.80177
	0.0203	0.0013	0.0272		<.0001	0.0009	<.0001
Wdbiom60	0.40983	0.66694	-0.52914	0.91650	1.00000	-0.74151	-0.92082
	0.0338	0.0001	0.0045	<.0001		<.0001	<.0001
Sorgbio60	-0.46873	-0.66903	0.65681	-0.60385	-0.74151	1.00000	0.82532
	0.0137	0.0001	0.0002	0.0009	<.0001		<.0001
Sorgbio90	-0.33205	-0.65734	0.55019	-0.80177	-0.92082	0.82532	1.00000
	0.0906	0.0002	0.0029	<.0001	<.0001	<.0001	