

**INTEGRATED WEED MANAGEMENT USING INTERCROPPING AND  
WEEDING FREQUENCY FOR SORGHUM, DRY BEAN AND COWPEA**

**By**

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Philosophy (Crop Science)**

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## DECLARATION

I, **Conrad Baker**, declare that;

- The research reported in this thesis, except where otherwise indicated, is my original research.
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Signed \_\_\_\_\_

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Date: \_20 December 2021

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## **DEDICATION**

*This work is solely dedicated to Baker's family*

## GENERAL ABSTRACT

Weed management is a complex topic in agriculture. This is despite the fact that it may be one of the oldest crop management techniques to improve yield. Currently, agriculture predominantly uses chemical weed control because it produces results quickly, but it has many disadvantages regarding sustainable agriculture. Mechanical weed control also has a high risk regarding the need to mitigate sustainable agriculture challenges from the soil management perspective. Biological weed control is not reliable and could have counterproductive effects. This study aimed to expand the current knowledge about cultural weed control in the context of sustainable integrated weed management practices. Planting highly competitive crop species and manipulation of planting density are among the suggested approaches to cultural weed control. Sorghum (*Sorghum bicolor* (L.) Moench), dry beans (*Phaseolus vulgaris* L.), and cowpea (*Vigna unguiculata* (L.) Walp.) are traditional crops of southern Africa. Small-scale and subsistence farmers continue to rely on these crops as sources of food and fodder. The Agricultural Research Council of South Africa solicited an investigation into intercropping and frequency of weeding culturally in order to produce some indicators to advise small-scale farmers who have no capacity to use the predominant weed control strategies for commercial agriculture. The aim is also to promote sustainable agriculture practices that minimise or avoid use of herbicides. The study was designed to collect relevant data on the response of each one of the three crops to intercropping and cultural weeding frequency. The structure of the thesis is that it has a general review of literature on the topic and a focus on each crop response to the same field trial treatments over two growing seasons is presented in three different chapters. Finally, an integrated analysis of intercropping and weeding frequency interactions is presented in a separate chapter, before the general discussion of all the results are presented as a concluding chapter. Each chapter was written using a format for a separate complete manuscript. Crop growth traits associated with plant height, leaf number, chlorophyll content

index, land equivalent ratio (LER), biomass, yield, legume pod production and sweet sorghum Brix value were the major crop performance variables of focus over two growing seasons under sole-cropping, intercropping of all three crops and weeding frequencies. Overall, the study revealed that sweet sorghum benefitted from intercropping with legumes while weeds caused a significant pressure on crop agronomic performance, including land equivalent ratio (LER) and final yield compared with sole cropping. The effect of sweet sorghum on legumes during intercropping is minimised by the earlier legume growth and development to escape competition for light and possibly water and nutrients, respectively. It is generally recommended that reduction of weeding frequency may have less effect on sorghum yield in an intercropping system with dry beans or cowpeas. The principal component analysis (PCA) evaluation allowed the study to identify the predominant weed species based on the relative importance value (RIV%). Although this finding cannot be used to associate the weed species with the cultural weed management approach used in this study, it is a significant guideline for predicting weed occurrence, especially in the context of providing extension advice to small-scale farmers.

**Keywords:** beans; cowpeas; cultural weed management; intercropping; sorghum; yield; weeding frequency

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# CHAPTER 1

## GENERAL INTRODUCTION AND LITERATURE REVIEW

### 1.1 Abstract

The "food vs fuel" issue brought by the biofuel dispute, agrochemicals threat to humans, and the environment has compelled farmers to opt for sustainable alternative crop production systems. This review aims to explore sweet sorghum/ legume intercropping performance dynamics and the effect of intercropping as an eco-friendly approach towards weed management. Intercropping, a type of multiple cropping in which two or more crops, particularly legumes, are grown simultaneously on the same land. Sweet sorghum (*Sorghum bicolor* (L.) Moench) is advocated for as future dual food and fuel crop due to its tolerance to abiotic stresses such as limited moisture and its potentially high biomass production. This crop is underutilized in South Africa regardless of these advantageous features due to its limited weed management options. Weeds are a hurdle in crop production, contributing to a 15-97 % reduction of sorghum growth and yield under various climatic conditions. More research is needed to maximize sweet sorghum production as a multi-purpose crop to refine its performance to the intercropping system under different weed management, harmonizing the food vs fuel questions. However, a literature review directed attention towards weed management's neglected points through crop competition in sweet sorghum/legume intercropping systems. Furthermore, intercropping should integrate with other integrated weed management techniques to improve sorghum production in a sustainable manner environmental impact. However, sweet sorghum biomass yield can be attained as biofuel production can be restored in South Africa, stimulating employment opportunities in the agricultural sector.

Keywords: intercropping, legumes, sweet sorghum, weeds

## 1.2 Introduction

The extensive use of fossil fuels exacerbated the situation of increased greenhouse gas (GHG) emissions. Calls for resilient, sustainable cropping systems such as intercropping have been resounding in sustainable farming as an alternative option for improving crop production (Brooker et al., 2016) while reducing the undesirable environmental impact. In this context, renewable biomass sources for bioethanol production has sparked an interest. Consequently, plant biomass has been considered an alternative renewable source for biofuel production with low CO<sub>2</sub> emissions and production costs (Antonopoulou et al., 2008). However, a sustainable farming business should always use harvests for food or fodder before utilizing biomass for other markets (Schröder et al., 2018) to eliminate the 'food vs fuel' dispute brought by biofuel critics.

Thus, land use has to maximise biomass production for improved economic, environmental, and social outcomes (Schröder et al., 2018). This could be achieved by practising intercropping, simultaneously growing two or more different crops in the same area (Glaze-Corcoran et al., 2020; Stomph et al., 2020). Intercropping systems play a pivotal role in improving crop quality and yield by putting crops on the advanced level to utilize environmental resources efficiently (Brooker et al., 2015; Stomph et al., 2020) while enhancing resilience in water-limited, seasonal rainfall, pest, disease and weed challenged environments (Stomph et al., 2020). Numerous abiotic and biotic stresses are related to socioeconomic and crop management challenges (Ghersa, 2013). Weeds are major biotic hurdles to crop production in developing and developed countries (Chauhan, 2020). Weeds are the primary cause for yield loss in crop production and are seconded by fungi, bacteria, insects, rodents, nematodes, mites, and birds with lesser damage (Oerke, 2006), yet are the most underestimated pests.

Weeds compete with crops for growth factors, viz sunlight, water, nutrients, and space. Besides, they harbour insects and pathogens, which affect crop growth (Chauhan, 2020). Weed emergence time, density, and type are the critical factors influencing yield loss; however, once left

uncontrolled, 100% yield loss could be predicted (Chauhan, 2020). Weeding is done manually, mostly in developing countries with small farm sizes and urbanization and wage costs in the agricultural sector, making this practice less attractive (Chauhan, 2020). Sweet sorghum (*Sorghum bicolor* L. Moench), one of the most promising energy crops, has been promoted as a high potential crop for bioethanol production (Zhao et al., 2009) to reduce the reliance on petroleum fuel. The use of sweet sorghum as an energy crop is advantageous due to its capabilities to produce high yields in adverse conditions with relatively low inputs (Mathur et al., 2017). Also, sweet sorghum can yield around 30 t ha<sup>-1</sup> year<sup>-1</sup> (Mathur et al., 2017). Sweet sorghum as a multiple-use crop (fuel, feed, food, and fibre) can eliminate the 'food vs fuel' dispute brought by biofuel critics. Despite these potentials, there is a paucity of information regarding the intercropping of sweet sorghum/ legume species, mainly dry bean and cowpea, towards weed dynamics.

On the other hand, pulses are legumes consumed as dry grain (FAO, 1994); this excludes peanuts and soybeans since these are primarily harvested for oil. Pulses are nutritious grain legumes or pulse grains with low fat, fatty acid and protein-rich sources (Venter & Vorster, 2013). Dry bean (*Phaseolus vulgaris* L.) is a grain legume with good nutritional value for human consumption, a staple, and an economically vital crop in many countries worldwide, including South Africa. The dry bean is also susceptible to weed at the initial stages of vegetative development (Blackshaw, 1991). Therefore, understanding how dry bean responds to weed incidences is vital to inform weed management decisions, particularly in an intercropping system.

Then again, cowpea (*Vigna unguiculata* (L.) Walp.) is a grain legume and source of protein that has been grown throughout the semiarid regions of Sub-Saharan Africa (Dube & Fanadzo, 2013). Cowpea has significant advantages through its use for human consumption, e.g., leaves and green pods harvested as vegetables and grains have significant protein and vitamin contents. Therefore, the remaining biomass for animal fodder makes it a dual-purpose crop that appears valuable to farmers. Cowpea is a grain legume like a dry bean that can fix atmospheric nitrogen, contributing

to soil fertility improvement, especially in smallholder farming systems with less fertilizer (Kyei-Boahen et al., 2017; Vanlauwe et al., 2019). Cowpeas can grow in moisture limited and harsh environmental conditions where several crops barely grow (Ddamulira et al., 2015). Several cowpea cultivars have a short growing cycle maturing within 60 to 80 days (Kyei-Boahen et al., 2017).

In general, the potential abilities of legumes to biological fix atmospheric N could aid in curbing the emissions of greenhouse gases such as carbon dioxide (CO<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O) than with applying mineral N fertilization hence pivotal in the soil carbon sequestration, thus reducing the overall fossil energy inputs (Stagnari et al., 2017). However, achieving sustainability is a significant obstacle with numerous challenges such as food security, land availability, and government policies (Deenanath et al., 2012). It is crucial to maximising crop biomass needed to supplement the bio-based economy while maintaining food security and sustaining natural resources and the environment (Cassman & Liska, 2007). Developing sustainable cropping systems for high biomass production is a significant hurdle, particularly for industrial utilization while sustaining other critical ecosystems functions (Fales et al., 2007), including nutrient retention (Schröder et al., 2018).

There are four types of intercropping patterns - row, mixed, strip, and relay intercropping (Brooker et al., 2015; Glaze-Corcoran et al., 2020). This study focuses on row intercropping – simultaneously growing two or more different crops, at least one crop planted in rows (Crusciol et al., 2012; Lithourgidis et al., 2011). However, information regarding sweet sorghum with legumes intercropping system for increasing food and bioethanol production is still scanty in South Africa. The study aims to assess sweet sorghum/legume intercropping yield and growth under different weeding frequencies. In this view, improved cropping systems to increase sweet sorghum bioethanol production would relieve the energy crisis and rural poverty (Muhammad et al., 2014; Zhao et al., 2009).

### **1.3 Aims and objectives**

This literature review discusses the current knowledge and status of sweet sorghum-legume base intercropping systems on yield, sustainable land-use efficiency, and weed management counter to sole cropping systems. The review assessed sweet sorghum, dry bean, and cowpea intercropping effects on below- and above-ground interaction and the impact of intercropping as sustainable agriculture on weed composition and dynamics. Besides, the benefits and challenges of sweet sorghum were evaluated as a high potential crop for bioethanol production and the adoption of intercropping in sustainable agriculture.

### **1.4 Advantages of the cereal-legume base intercropping**

Sweet sorghum is a C4 crop that can produce high biomass under adverse conditions (Yang et al., 2020), with low input requirements (Mathur et al., 2017). Compared with other C4 plants, sweet sorghum can produce more ethanol per hectare under moisture and nutrients limited cropping systems (Miller & Ottman, 2010). Its development as an energy crop is lagging compared to maize development (Rooney et al., 2007). Therefore, it is imperative to base studies on the whole crop performance, integrating below and above-ground responses to intercrops such as dry bean and cowpea prevailing in the dry land area.

Evaluations of climate-resilient sustainable cropping systems such as intercropping as an alternative option for advancing declining crop performance have been conducted elsewhere (Brooker et al., 2016). In this case, intercropping is reported to improve microbial interactions and benefit from the stimulated living rhizosphere by increasing crop biomass production, soil organic matter content, and nutrient availability (Duchene et al., 2017) as compared to sole cropping.

Mostly in agricultural systems, nitrogen (N), phosphorus (P), or water availability are limited resources (Brooker et al., 2015). Legume-based intercropping systems enhance soil fertility factors, i.e., soil organic and humus content, N and P availability (Jensen et al., 2012). Legumes

can improve soil health and minimize the reliance on fertilizer input by fixing atmospheric N via a symbiotic relationship within roots and rhizobia soil bacteria (Wagner, 2011). Also, the higher production of crop residues in intercrops can improve soil carbon levels in the long term, given that the crop residues are retained in the field (Stomph et al., 2020). Thus, intercropping has the potential to curb resource degradation (Feike et al., 2012).

Environmental resources are efficiently utilized in a well-designed intercropping pattern with increased biodiversity and minor pest incidences, resulting in improved crop productivity, quality, and nutrient status, minimizing farm inputs (Glaze-Corcoran et al., 2020). Moreover, some legumes can prevent N leaching by producing nitrification inhibitors (Smil, 2001), and not all of the roots in a root system may be active at any one time in terms of water or nutrient uptake (Robertson et al., 1993). However, reduced biomass in intercrop legume can lower total N<sub>2</sub>-fixed than sole legume (Bedoussac et al., 2015). Hence, designing the complementary and potential cereal/legume-based intercropping system, which reflects minimal environmental impact, is crucial.

### **1.5 Above and below-ground interactions for cereal-legume base intercropping**

Interaction occurs when one or more variables of a system affect other variables (Nair, 1993). The above and below-ground interaction of the different crop species is beneficial, particularly in cereal/legume intercropping systems (Stagnari et al., 2017). Different crops affect one another by altering the availability of numerous resources in the environment of the other (Cong et al., 2015). One root system may limit another's growth through competition for water and nutrients or allelopathic influences (Matthews et al., 2004). Below-ground competition between intercrops can be manipulated by managing crop spacing (Matthews et al., 2004). The intercrop species mixture, which improves root growth, is poorly documented (Stomph et al., 2020). However, cereals lacking strong rhizosphere acidification capacity when intercropped with legumes could benefit from nutrients solubilized by the legume root exudates within the rhizosphere (Li et al., 2016).

The challenge is the roots of the sweet sorghum, which exudates an allelopathic compound called sorgoleone. As produced by sorghum species, sorgoleone affects the growth of many plant species, but it is more aggressive on small-seeded species (Dayan et al., 2010). Below and above-ground interactions can influence plant communities' structure and composition (Zhang et al., 2013). Several studies have detailed the role of below-ground interactions in intercrops (Kiær et al., 2013). Cropping patterns and planting density is likely to influence intercrops' productivity through interaction (Hu et al., 2016; Huang et al., 2017). Root exudates can also have weed-suppressive effects on numerous plants (Glaze-Corcoran et al., 2020).

Therefore, understanding the below-ground or rhizosphere communications between the roots of intercrops involving sweet sorghum/legumes intercropping is vital since there are limited in resources, and the demand for food production is the main agenda in sustaining the ecosystem. However, early and continuing below-ground interactions may negatively affect above-ground interactions in a limited moisture environment (Glaze-Corcoran et al., 2020). Consequently, intercrop strategies in limited moisture conditions should maximise water use efficiency and productivity per water unit and reduce below-ground competition (Glaze-Corcoran et al., 2020).

Therefore, the integration of light interception dynamics in intercropping systems with the below-ground competition, water availability, and water use should be attentively monitored (Glaze-Corcoran et al., 2020). Below-ground competition is not supposed to be an issue if water and nutrients are sufficiently available (Schaller et al., 2003). In intercropping, proper crop selection is crucial due to high competition between the intercrops and may be fruitless when poorly selected (Maitra et al., 2020).

## **1.6 Weeds under intercropping systems**

Weeds are undesirable plants that interfere with cropping activities (Baker et al., 2018) and are the most underestimated pest in tropical agriculture (Akobundu, 1987). The manipulated environment

also benefit weeds and continually respond to the filtered pressures created by agronomic practices and the environment (Buhler, 2014). It is well documented that weeds compete with crops for limited resources such as soil nutrients, moisture, light, space, and host insects, hindering crop harvest and increasing the cost of such operations (Labrada and Parker, 1994), consequently decreasing crop yields yield and quality.

Selecting a sustainable weed control strategy based on agronomical, economic, and environmental considerations is challenging (Gholami et al., 2013). Farmers typically depend on various agrochemical and non-chemical approaches for weed control, especially herbicides (Hozayn et al., 2012). The high cost of herbicides, herbicide resistance, lack of expertise, lack of herbicide use training, and increasing environmental and human health concerns exacerbated how agrochemical weed management becomes an enormous hurdle. One of the sustainable weed management approaches to reduce the reliance on herbicide use is through intercropping. The high-density canopy cover or shade in an intercropping system may benefit eco-friendly weed control (Maitra et al., 2020). Generally, previous studies have reported that intercropping reduces weed emergencies. The dense canopy and shaded soil surface in intercropping systems affect soil moisture, resulting in lower soil evaporation (Nyawade et al., 2019). Hence the canopy cover in intercropping systems can filter the amount and quality of light reaching the soil surface needed by weed seeds for germination or seedling for growth. Reduced amount and quality of solar radiation reaching the soil surface negatively affect weed seed germination (Locke et al., 2002). However, future studies should focus on identifying significant aspects influencing weed suppression, for instance, crop combination, sowing, and harvest dates weeding operation or fertilizer level; these approaches will assist in the design of intercropping systems that could reduce the reliance on herbicides, fossil energy or intensive labour for weed control (Stomph et al., 2020). Additionally, the impact of weed suppression in the intercropping system is significantly higher than in the monoculture system, same to decreased rates of serious pest (Boudreau, 2013; Lopes et al., 2016) and disease (Boudreau, 2013; Brooker et al., 2016) incidences in intercrops.

## 1.7 Sweet sorghum as a biofuel crop

Sorghums can be classified as grain sorghum, sweet sorghum, forage sorghum, and energy sorghum based on morphological traits and utilization (Mathur et al., 2017). As a potential crop for bioethanol production, sweet sorghum has competitive advantages over other bioethanol crops, such as better acclimatization in less favourable climatic conditions, resistance to drought, salinity, waterlogging, and pest and disease (Nadir et al., 2009; Ray et al., 2019). Nevertheless, the essence of sweet sorghum is from the accumulation of sugars in the stalk, with lesser grain yield than grain sorghum (Codesido et al., 2013; Morey et al., 2018). Grain sorghum is cultivated for its grain and used as food or feed (Rooney, 2016), and forage sorghum is mainly used as a source of roughage for livestock (Bhat, 2019). Brix units are used to measure sugar concentration in stalks, representing the per cent soluble sugars; moreover, one degree Brix is equal to 1 g of sugar per 100 g of juice (Mathur et al., 2017).

Sweet sorghum can accumulate juice up to 78% of the total biomass, the Brix content depends on the variety, and it has been estimated to range from 14 to 23% (Almodares, 1996; Chavan et al., 2009; Vinutha et al., 2014; Ratnavathi, 2017). Besides, several factors influence Brix content viz environmental resources, internode position and harvesting stage (Qazi et al., 2012; Teixeira et al., 2017). For industrial ethanol production, the sweet sorghum harvesting stage is pivotal for determining sugar content in stalk juice (Prasad et al., 2019) since the total sugar content differs at stages of development or as the crop reaches maturity (Holou & Stevens, 2012; Teixeira et al., 2017). Sugar accumulation in the stem increases between milk and dough stages of most cultivars and declines toward senescence stages (Teixeira et al., 2017). Sweet sorghum is different from *Zea mays* which retain starch in the grains, whereas sweet sorghum retains carbohydrates in stalk juice as soluble sugar (Bihmidine et al., 2015).

Although sweet sorghum can be considered a potential feedstock, its yield varies with the soil type, temperature, geography, and fertility (Umakanth et al., 2019). The ambient temperatures play a

vital role in the deterioration of the harvested stalk sugar content, and the proportions of individual sugars change with negative consequences for further processing (Lingle et al., 2012; Eggleston et al., 2013). The yield accumulation per hectare of sweet sorghum grains and stalks are between 3-7 tonnes and 54-69 tonnes, respectively (Almodares & Hadi, 2009). However, dry biomass production of several potential bioenergy sorghum crops can reach between 18 to 32 t ha<sup>-1</sup> for sweet sorghum, 16 to 24 t ha<sup>-1</sup> for forage sorghum, and 32 t ha<sup>-1</sup> for photoperiod-sensitive sorghum (Rooney et al., 2007). Biofuels have been advocated because they help curb GHG emissions, but some studies reject this claim. However, there are suggestions that biofuels may increase GHG emissions (Gomiero, 2015). There are reports that biofuels and biomass are incapable of replacing fossil fuel; how could some authors reach a contradictory conclusion (Gomiero, 2015).

## 1.8 Conclusion

Sweet sorghum biomass yield can be improved by intercropping while curbing the "food vs fuel" debate. The sweet sorghum economic viability and eco-friendly production could boost rural livelihoods and smother future biofuel demands. However, agronomic challenges associated with sustainable weed control under intercropping systems need to be explored to encourage farmers' adopt sustainable cropping systems. Unlike monoculture systems, crop diversity through intercropping may cause economic costs for farmers, but in the short run, it can increase yields and profitability in the long run. Long-term research could be beneficial to understand better underlying mechanisms of the manipulated environment and the interactions within the diversified intercropping systems. Sweet sorghum, dry bean, and cowpea intercropping could potentially contribute to regional food security, constrained by weeds management challenges. Hence, agronomic sustainable weed control strategies such as intercropping seem to have greater importance. Improved yield could occur with component crops with different growth durations, mainly acquiring environmental resources at different times in the intercropping systems. Intercropping is less attractive as a weed control technique could be due to paucity of information, particularly the crop interaction and compatibility within a spatial arrangement of the given crop combination such as sweet sorghum, dry bean and cowpea intercropping. However, most intercropping research studies focus on intercrop production and yield. Research on compatible crop selection in intercropping systems focusing on competitive traits to suppress weeds is still scanty. Hence, related research-based are advocated particularly with crops such as sweet sorghum, dry bean and cowpea to endorse intercropping as a potential technology to control weed amongst resource-poor farmers.

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## CHAPTER 2

### SWEET SORGHUM PERFORMANCE IN A LEGUME INTERCROPPING SYSTEM AND WEEDING FREQUENCY COMBINATION

#### 2.1 Abstract

Sweet sorghum (*Sorghum bicolor* L. Moench) is highly susceptible to weed competition in the early growth stages; hence intercropping is expected to overcome the weed competition challenge. This study was conducted to determine the performance of sweet sorghum in legume intercropping systems under different weed management pressures at Ukulinga Research and Training farm of the University of KwaZulu-Natal in Pietermaritzburg, South Africa during 2017/18 and 2018/2019 growing season. Three cropping systems, sole crop, inter-row, intra-row intercropping, and three weed management levels (no weeding after crop emergency, weeding ceased after 50 days of crop emergency, and weeding throughout) were tested. Intercropping pattern had a significant ( $P < 0.05$ ) impact on crop growth, particularly the number of leaves per plant, while other treatments remained insignificant during the 2017/18 growing season. During the 2018/19 growing season, the intercropping pattern had a significant ( $P < 0.05$ ) effect on dry and fresh biomass and plant height at 60 days after emergence. An increase in weeding frequencies reduced brix ( $^{\circ}\text{Bx}$ ). Uncontrolled weed plots had the lowest sweet sorghum dry biomass accumulation, whereas the biomass increased as weeding frequencies increased but remained insignificant as weeding frequencies further increased from 50 to 100% weeding frequency in both seasons. Furthermore, hand hoe weeding applications after eight weeks negatively affect sweet sorghum biomass and contribute to crop injuries within the inter-cropping system.

**Keywords:** biomass; Brix; intercropping; weeding frequency; weed management

## 2.2 Introduction

Sweet sorghum (*Sorghum bicolor* L. Moench) is one of the most underutilized crops in South Africa (Mabhaudhi et al., 2017), yet its biomass can be valuable for producing energy (Tang et al., 2018). Concerns about rising fuel prices and energy demands are some of the few reasons why biofuels have been advocated for with the potential to reduce the environmental impact brought by the emissions of greenhouse gases (Gomiero, 2015). Sweet sorghum (SS) is a multipurpose crop that has of late attracted considerable interest as a potential energy crop. Moreover, its drought and heat tolerance traits (Hadebe et al., 2017) make it one of the most suitable plant material for biofuel production, particularly in limited moisture conditions (Prasad et al., 2019). Sweet sorghum is relatively a small-seeded grass with retarded growth from the first few weeks after emergence (Damasceno et al., 2014), which affects its competitive ability with weeds (Bassam, 2010). The limited number of suitable herbicides for the crop exacerbates sorghum weed control management challenges (Damasceno et al., 2014), but for small-scale farming hand weeding is the option which happens to be a significantly labour-consuming activity.

Sustainable intensification of the agricultural systems in the developing world requires a balanced approach to "Green Revolution", which includes inter- and intra-row cropping (Martin-Guay et al., 2018). Intercropping is the practice of growing two or more crops in the same piece of land simultaneously (Jensen et al., 2020). It has been promoted as a potential technology to prevent further environmental degradation (Feike et al., 2012), such as soil erosion. This can minimise environmental pollution and greenhouse gas emissions accelerated due to agrochemicals' overuse and the associated reduction of soil fertility and microbial biodiversity (Peoples et al., 2019). Intercropping can reduce the risk of weeds, pests and minimize the application of agrochemicals while stimulating biodiversity and increasing yield and yield stability (Jensen et al., 2020). Additionally, the impact of weed suppression in the intercropping system is characterised by a significant decrease in the occurrence of serious pests (Boudreau, 2013; Lopes et al., 2016) and

disease (Lopes et al., 2016) compared with monoculture. Intercrops affect disease dynamics through the change of micro-climate, hence modifying temperature and moisture, leading to change in host morphology and physiology and direct pathogen inhibition (Boudreau, 2013). Weed suppression is one of the advantages of intercropping, but it is criticised for complicating physical and chemical weed control strategies (Korres, 2018).

Previous research showed that regardless of weed species, grain sorghum yields doubled in weeded plots during the first two weeks after planting compared to non-weeded plots (Burnside & Wicks, 1967). However, weed growth beyond two weeks after grain sorghum emergence negatively affected grain sorghum yield (Smith et al., 1990). Generally, weeds compete with crops for nutrient resources within the inter-row spaces (Xu et al., 2020). Some weeds are a food resource for insects and sources of plant diseases (Capinera, 2005), affecting crop yield and quality. A recent study showed that sorghum forage quality was affected by intercropping and weed control treatments such that the crude protein and total ash were affected by sorghum intercropped with 33% and 66% hairy vetch under no weeding plots (Rad et al., 2020).

Increased crop diversity in the intercropping systems could reduce the synthetic nitrogen (N) global requirement and concomitantly favours sustainable cropping systems (Jensen et al., 2020) through biological N fixation by legumes. Sweet sorghum has been shown to require less fertilizer and it is easily cultivated on marginal lands (Yadav et al., 2019). Moreover, it can grow up to 3 m in plant height and yield between 45–112 t ha<sup>-1</sup> of fresh biomass (Shukla et al., 2017). Its sizeable fibrous root system helps to absorb water more effectively, and leaf blades are covered with a waxy coating that reduces water loss, which partly contribute to drought-resistance (Bassam, 2010).

Legumes are frequently preferred in many published intercropping systems (Hauggaard-Nielsen & Jensen, 2005). The use of selected leguminous crops such as dry bean (DB) (*Phaseolus vulgaris* L.) and cowpea (CP) (*Vigna unguiculata* L. Walp.) for intercropping can also help suppress weeds

(Bilalis et al., 2010). Legume species have low N absorption during early growth, yet the low N absorption factors are unknown (Dayoub et al., 2017). The low soil N uptake could contribute to their susceptibility to weed competition (Corre-Hellou et al., 2011) and this could possibly make them suitable for intercropped systems with non-legumes (Naudin et al., 2010). However, previous studies reported that N limitation reduces canopy photosynthesis by reducing leaf area development and leaf photosynthesis rate (Li et al., 2009). Therefore, early canopy cover plays a crucial role in establishing competitive advantages towards weeds (Fayaud et al., 2014).

The information regarding legume's potential to reduce fossil energy inputs and greenhouse gas emissions from agricultural systems relying on mineral N fertilization and the carbon sequestration in soils remains scanty (Stagnari et al., 2017). A better understanding of competition in intercropping systems is pivotal to determine compatible intercropping pattern arrangements to avoid inter and intraspecies competition, thus alleviating the degraded agricultural ecosystem and cereals and weeds competition on limited resources.

There is also a paucity of information on intercropping patterns and weeding frequency effects on sweet sorghum (SS) production. There has been a prolonged interest in maximizing the marginal land in Southern African countries to produce plant biomass for biofuels (Fundira & Henley, 2017). It becomes vital to execute research-based on appropriate cropping systems that would produce higher yields and enhance soil productivity. One possible obstacle that may affect yield is weed pressure, and one feasible and sustainable approach in improving crop productivity and reducing weed pressure is through intercropping.

Nevertheless, for intercropping to be efficient, crop selection and spatial arrangement are essential. Currently, not much has been done on SS hence this study. The study main objective was to evaluate sweet sorghum (SS) performance in a dry bean (DB) or cowpea (CP) intercropping system compared to sole cropping under different weeding management levels, with a particular focus on crop development biomass production.

## 2.3 Materials and methods

### 2.3.1 Experimental site, design, and trial management

A field experiment was conducted at Ukulinga Research and Training farm of the University of KwaZulu-Natal in Pietermaritzburg, South Africa (29°39'56.6"S 30°24'26.2"E) during 2017/18 and 2018/2019 growing season. Generally, from mid-October to late April is considered a growing season for summer crops in South Africa. The site has an annual rainfall of 644–838 mm, an average temperature of 18.4°C, and an altitude of 791 m (Chimonyo et al., 2016). A disk plough and rotovator implements were used for land preparation.

A Randomised Complete Block Design (RCBD) with a split-plot treatment structure was used for three crops viz, dry bean (*Phaseolus vulgaris* L.) cultivar Ukulinga, cowpea (*Vigna unguiculata* L. Walp.) var. Agrinawa, and sweet sorghum (*Sorghum bicolor* L. Moench) var. Supasweet II. Twenty-seven treatment combinations composed of three subplots intercropping patterns (sole crops, inter-row, and intra-row spacing), and three main plots weeding frequencies (No weeding after emergency= 0%, weeding ceased after 50 days of emergency = 50%, and weeding throughout = 100%) and replicated three times, resulting in a total of 81 plots.

The plot dimensions were 4.2 m × 3 m resulting in a gross plot area of 12.6 m<sup>2</sup>, whereas 1 m between plots and 2 m between replicates were maintained. All treatment combinations were planted using 0.60 m inter-row and 0.30 m intra-row spacing (55 555.6 plants ha<sup>-1</sup>) to achieve uniformity for both sole crops and intercrops. The field trials were sown on 13 December 2017 and harvested on 11 April 2018 for the 2017/18 growing season and again sown on 14 December 2018 and harvested on 03 April 2019 for the 2018/19 growing season. Planting dates were based on sorghum production guidelines (Chimonyo et al., 2016). The land was under fallow for two years before planting. Therefore, fertilizer (NPK) was applied based on soil analysis at planting, and limestone ammonium nitrate (LAN) was applied as top-dressing, and all crops were planted simultaneously. Weed control was performed manually by hand-hoeing and no herbicides were

used. During crop growing season, five manual (hand hoe) weeding frequencies were executed every 10 days up to 50 days of weed control after crop emergence (50 DWACE), eight hand hoe-weeding frequencies were applied for the weed-free treatment and no weeding was done for the control.

### *2.3.2 Data, collection: growth parameters, yield, and yield components*

The data collected were the dry and fresh biomass, the number of leaves per plant, plant height and sweet sorghum sugar content Brix (°Bx). Whole plants were harvested from 1.44 m<sup>2</sup> then the fresh weight of sweet sorghum stalks, including leaves, were measured to determine biomass production. Moreover, the oven-drying was kept at 50 °C for dry biomass determination. Based on the average of four randomly selected plants per plot, a meter ruler was used to measure plant height, and a handheld refractometer was used to measure °Bx at the third internode from the above-ground.

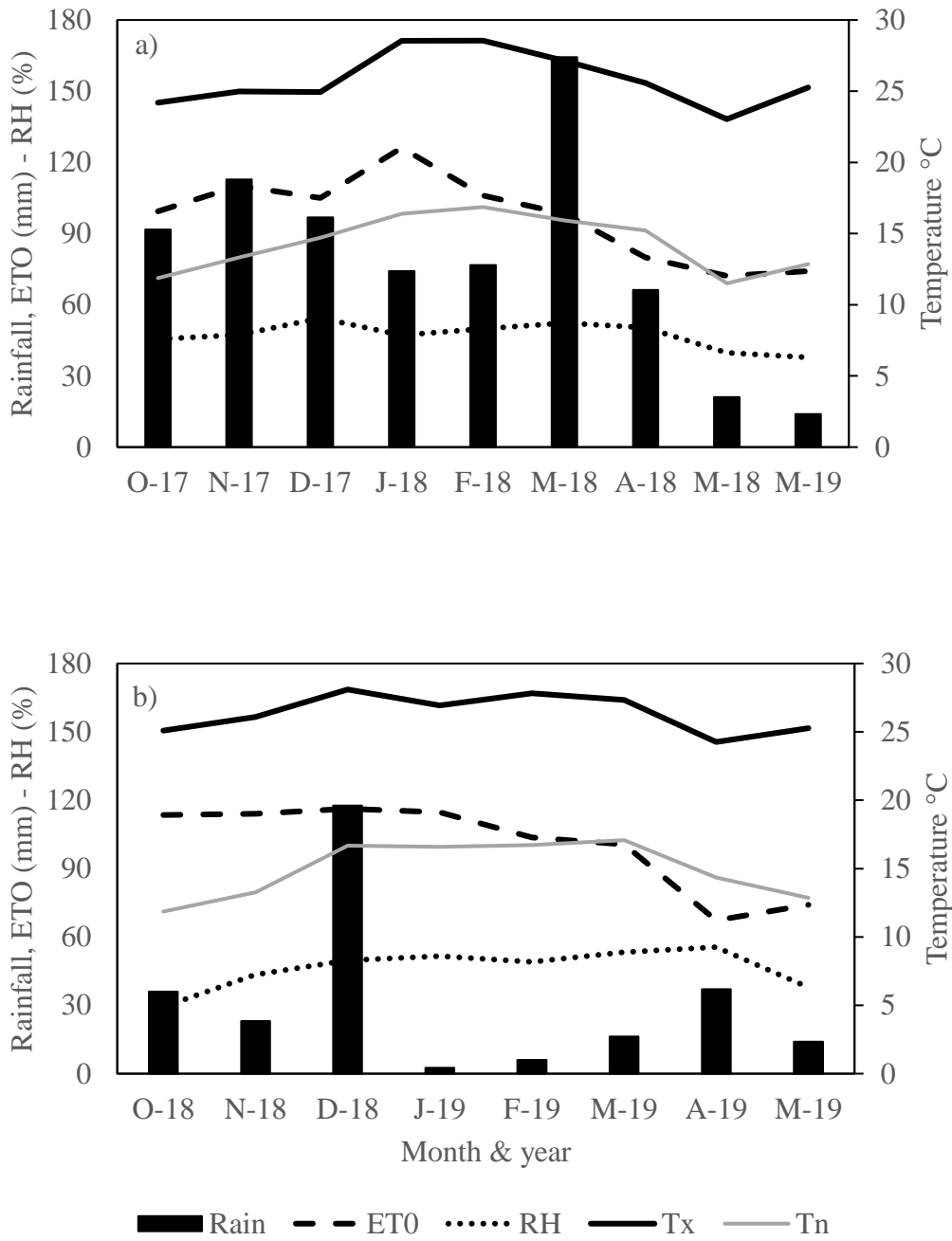
Land equivalent ratio (LER) was determined using the formula as shown below;

$$\text{LER} = \sum (Y_{pi}/Y_{mi}),$$

$Y_p$  denotes the crop yield in intercropping, and  $Y_m$  denotes the crop yield in the sole cropping (Willey, 1979). Legume species were changed in accordance with the data.

### *2.3.3 Climatic data*

The total monthly rainfall was 703 mm in the 2017/18 growing season, whereas the 2018/19 growing season received 252.73 mm at Ukulinga Research Farm. The average minimum and maximum monthly temperatures were 14.47 °C–25.87 °C during the 2017/18 growing season and 14.92 °C–26.36 °C during the 2018/19 growing season (Fig. 2.1).



### 3.3.3

**Fig 2.1.** Average monthly rainfall, relative evaporation (ETO), relative humidity (RH), maximum (Tx), and minimum (Tn) temperature °C from October to May during the (a) 2017/18 and (b) 2018/19 growing season.

### 2.3.4 Soil sampling and analysis

Soil samples were collected by hand auger up to a depth of 20 cm in a zig-zag pattern randomly. Soil fertility results were used as a guideline for fertilisation as explained above (section 2.3.1). Soils at Ukulinga Research Farm are slightly acidic (Table 2.1). The experimental soil is classified as Chromic luvisol, with clay content at less than 29%, field capacity of 46 %, permanent wilting point of 23 % and water saturation at 46 % (Chimonyo et al., 2016).

**Table 2.1.** Soil chemical properties at 0-30 cm depth of the experimental site.

Growing season	pH (H <sub>2</sub> O)	P	K	Ca mg/kg	Mg	Na	Org C %	Total N	CEC. cmol (+)/kg	Bulk density (g·cm <sup>-3</sup> )
2017/18	6.0	27.7	-	-	-	-	1.8	0.2	-	1.1
2018/19	5.9	52.9	406.8	1801.7	614.8	51.6		0.1	21.7	1.1

### 2.3.4 Statistical analysis

Analysis of variance (ANOVA) was used to compare the effects of intercropping pattern and weeding frequency on sweet sorghum dry and fresh biomass, the number of leaves per plant, plant height and °Bx using GEN STAT<sup>®</sup> statistical software version 18. At the level of significant effects ( $P \leq 0.05$ ), a standard error of the difference (SED) and least significant difference (LSD) were used to separate the means. The principal component analysis was used to evaluate the intercropping pattern and weeding frequency association with SS dry and fresh biomass, the number of leaves per plant, plant height, and °Bx.

## 2.4 Results

### 2.4.1 Intercropping patterns and weeding frequency effects on sweet sorghum agronomic traits

Analysis of variance showed that in both years intercropping pattern had a varied impact effect on crop growth and Brix quality traits (Table 2.2). At 80 DAE intercropping pattern × weeding

frequency interaction was significant ( $P \leq 0.05$ ) on plant height, while others remained nonsignificant (Table 2.2). On the other hand, the intercropping pattern had a significant ( $P \leq 0.05$ ) effect on dry and fresh biomass, plant height 60 DAE during the 2018/19 growing season (Table 2.3). Weeding frequency had a significant ( $P \leq 0.05$ ) effect on °Bx, dry and fresh biomass, plant height 80 DAE, number of leaves 60 and 80 DAE (Table 3). Moreover, intercropping pattern  $\times$  weeding frequency interaction was significant ( $P \leq 0.05$ ) on fresh biomass and the number of leaves per plant 60 DAE, while other treatments remained nonsignificant (Table 2.3).

**Table 2.2.** Analysis of variance of °Bx, dry and fresh biomass, height, number of leaves during the 2017/18 growing season.

Source of variation	df	°Bx	Dry biomass	Fresh biomass	Height		Number of leaves	
					60 DAE	80 DAE	60 DAE	80 DAE
					ms	ms	ms	ms
Intercropping pattern	4	1.88 ns	2.39 ns	26.56 ns	1637 ns	14415*	0.55 ns	4.80**
Weeding frequency	2	8.39*	102.84**	2067.7**	4851.9**	31957**	10.02**	15.47**
Intercropping pattern × weeding frequency	8	1.97 ns	2.80 ns	72.2 ns	3210.4 ns	23802*	0.08 ns	0.72 ns
Residual	28	1.82	2.76	47.45	5829	36199	0.35	0.73
CV		29.6	18.6	18.9	10.4	17.9	1.9	3.0

ns: not significant; \*and \*\*significant at 0.05 and 0.001 probability levels, respectively. DAE = Days After Emergence; °Bx= brix; ms= mean square; df= degree of freedom; CV= coefficient of variation.

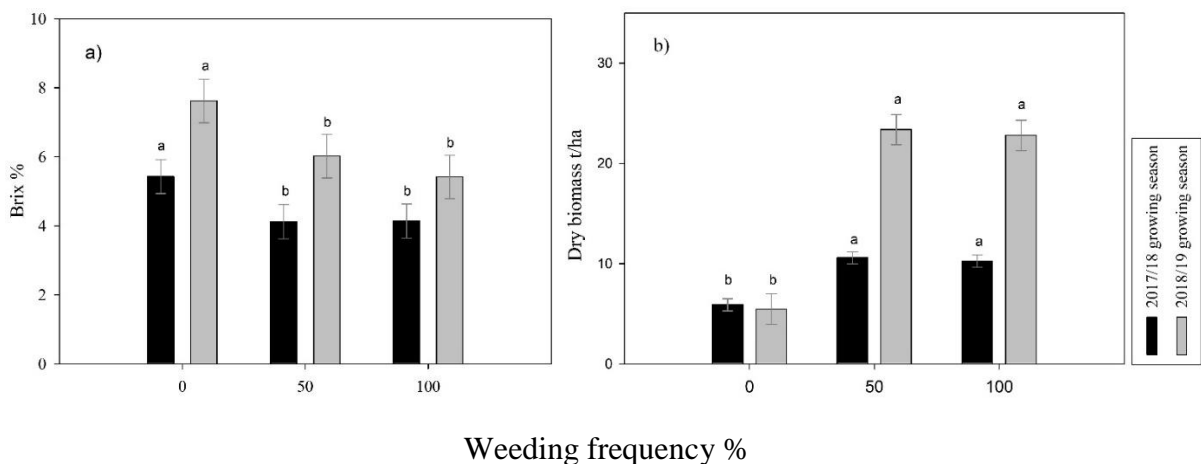
**Table 2.3.** Analysis of variance of °Bx, dry and fresh biomass, height, number of leaves during the 2018/19 growing season.

Source of variation	df	°Bx	Dry biomass	Fresh biomass	Height		Number of leaves	
					60 DAE	80 DAE	60 DAE	80 DAE
					ms	ms	ms	ms
Intercropping pattern	4	23.29 ns	74.05**	120.26 *	2943.4*	205 ns	1.56 ns	1.41 ns
Weeding frequency	2	38.8**	1554.91 ***	7168.41 ***	1788.4 ns	8569*	5.38***	5.15**
Intercropping pattern × weeding frequency	8	18.13 ns	37.05 ns	109.18**	639.1 ns	342 ns	1.49*	0.63 ns
Residual	28	84.1	17.26	30.74	746.3	1789	0.62	0.72
CV		27.3	24.1	13.0	25.6	22.1	10.2	8.9

ns: not significant; \*, \*\*, \*\*\* significant at 0.05, 0.01, and 0.001 probability levels, respectively. DAE = Days After Emergence; DAE = Days After Emergence; °Bx = brix; ms = mean square; df = degree of freedom; CV = coefficient of variation.

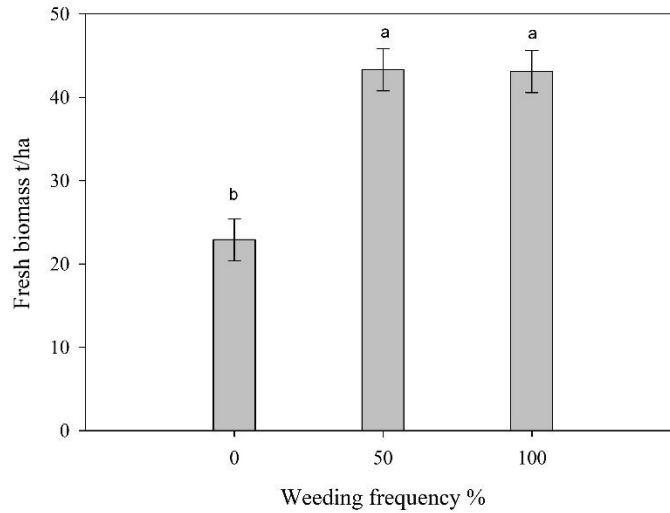
#### 2.4.2 Weeding frequency, intercropping pattern and their interaction on Brix and biomass

A comparison of the means of °Bx during the 2017/18 and 2018/19 growing seasons indicated that °Bx was higher in response to 0% weeding and declined as weeding frequency increased and there were no significant differences between 50 and 100% weeding frequency (Fig. 2.2a). Intercropping pattern had a significant effect on dry biomass for both growing seasons (Fig. 2.2b). Dry biomass was significantly lower at 0% weeding frequency but increased as weeding frequency increased (Fig. 2.2b). Furthermore, the 0% weeding frequency differed significantly compared to 50 and 100% weeding frequency, but there were no significant differences between 50 and 100% weeding frequency for biomass accumulation in both the 2017/18 and 2018/19 growing seasons (Fig. 2.2b). During the second year (2018/19 growing season), there was a twofold increase in dry biomass accumulation compared to the 2017/18 growing season at 50 and 100% weeding frequency, respectively (Fig. 2.2b).



**Fig 2.2.** Mean comparing of weeding frequency effect on SS (a) °Bx and (b) dry biomass accumulation during the 2017/18 and 2018/19 growing season. The error bars indicate SED.

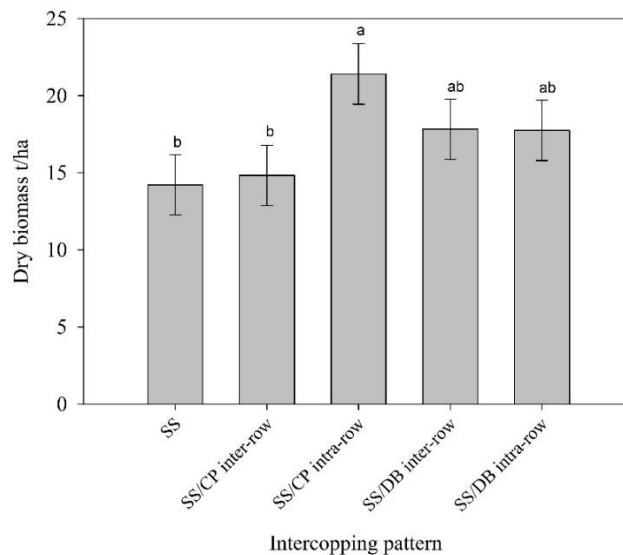
During the 2017/18 growing season, weeding frequency had a significant ( $P < 0.05$ ) effect on SS fresh biomass (Fig. 2.3). The fresh biomass increased as weeding frequency increased; however, it remained insignificant at 50 and 100% weeding frequency (Fig. 2.3).



**Fig 2.3.** Mean comparison of weeding frequency effect on SS fresh biomass accumulation during the 2017/18 growing season. The error bars indicate SED.

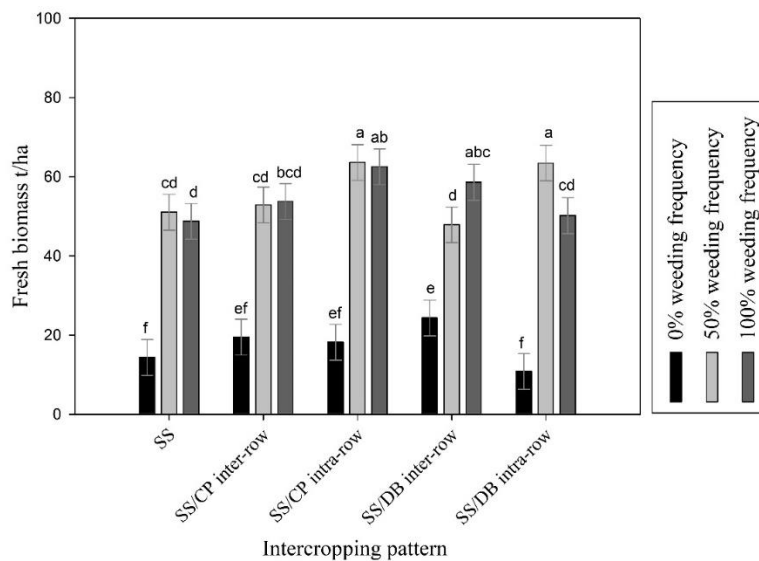
#### 2.4.3 Dry and fresh biomass yield accumulation as affected by intercropping pattern

The intercropping pattern significantly ( $P < 0.05$ ) influenced the dry biomass in the 2018/19 growing season. The sole SS and SS  $\times$  CP inter-row intercropping (SS/CP inter-row) had the lowest dry biomass accumulation, whereas the SS/CP intra-row intercropping had the highest dry biomass accumulation (Fig. 2.4).



**Fig 2.4.** Mean comparison of intercropping pattern effect on SS dry biomass accumulation during the 2018/19 growing season. The error bars indicate SED.

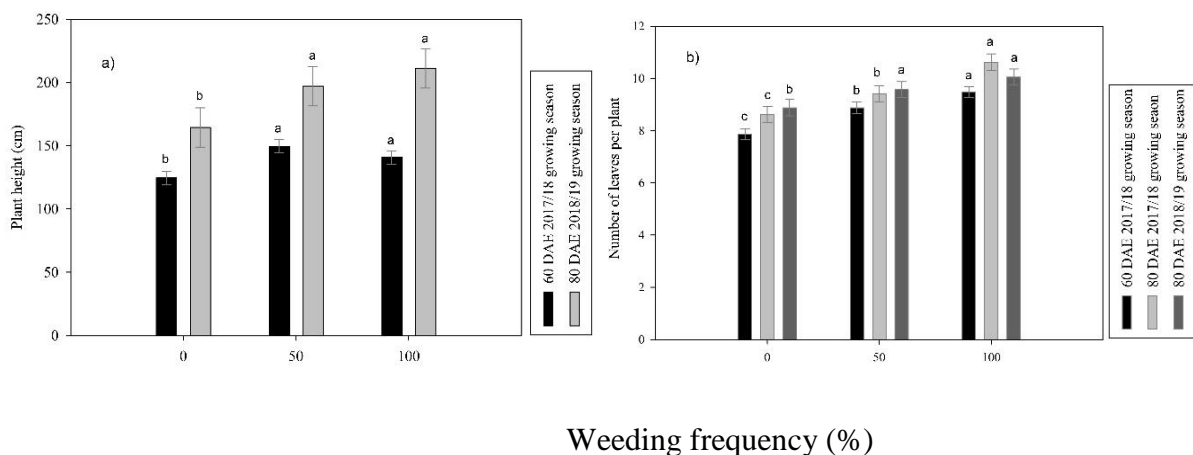
During the 2018/19 growing season, intercropping pattern  $\times$  weeding frequency interaction had a significant ( $P < 0.05$ ) effect on SS fresh biomass (Fig. 2.5). The SS fresh biomass remained lower at intercropping pattern  $\times$  0% weeding frequency throughout; however, the biomass increased as weeding frequency increased (Fig. 2.5). The lowest fresh biomass was observed in SS/DB intra-row intercropping  $\times$  0% weeding frequency, while the most considerable fresh biomass accumulation was observed in SS/CP intra-row intercropping  $\times$  50 and 100% weeding frequency (Fig. 2.5). The intercropping pattern  $\times$  weeding frequency interaction results showed that SS fresh biomass accumulation significantly increased as weeding frequency increased in a SS/DB inter-row intercropping  $\times$  weeding frequency. However, under SS/DB intra-row intercropping  $\times$  weeding frequency, the biomass significantly decreased from 50 to 100% weeding frequency (Fig. 2.5). Furthermore, the other treatment interaction remained insignificant between 50 and 100% weeding frequency (Fig. 2.5).



**Fig 2.5.** Mean comparison of intercropping pattern  $\times$  weeding frequency interaction effect on SS fresh biomass accumulation during the 2018/19 growing season. The error bars indicate SED.

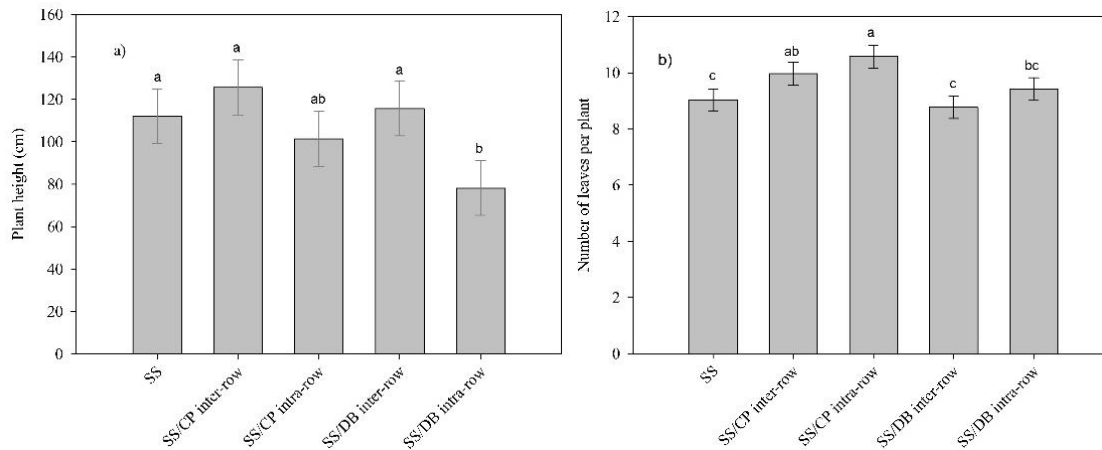
#### 2.4.4 Impact of intercropping pattern, weeding frequency and their interaction on SS height and number of leaves per plant

Weeding frequency had a significant effect on SS plant height; the lowest plant height was recorded at 0% weeding frequency and increased as weeding frequency increased to 50%; however, it declined at 100% weeding frequency in the 60 DAE 2017/18 growing season (Fig. 2.6a). The lowest plant height was observed at 0% weeding frequency and increased as weeding frequency increased from 50 to 100% in 60 and 80 DAE 2018/19 growing season (Fig. 2.6a). Weeding frequency significantly affected the SS number of leaves per plant; 50 and 100% weeding frequency had the highest number of leaves per plant in the 60, 80 DAE 2017/18 growing season, and 80 DAE 2018/19 growing season (Fig. 2.6b).



**Fig 2.6.** Mean comparison of weeding frequency effect on SS (a) height and (b) the number of leaves per plant 60 and 80 DAE during the 2017/18 and 2018/19 growing seasons. The error bars indicate SED.

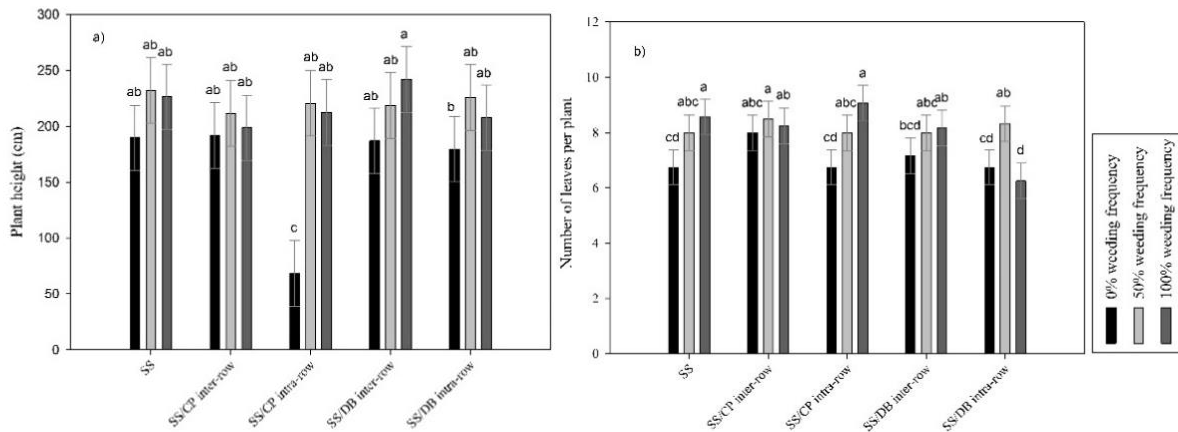
The SS/CP inter-row intercropping system had the highest plant height, while SS sole cropping and SS/CP inter-row intercropping had the lowest (Fig. 2.7a). Intercropping pattern influenced SS number of leaves per plant, and SS/CP intra-row intercropping had a significantly higher SS number of leaves, whereas sole SS had lower SS number of leaves per plant during the 80 DAE 2017/18 growing season (Fig. 2.7b).



### Intercropping pattern

**Fig 2.7.** Mean comparison of intercropping pattern effect on SS (a) 60 DAE height and (b) 80 DAE number of leaves per plant during the 2018/19 and 2017/18 growing season, respectively. The error bars indicate SED.

The SS/CP intra-row intercropping  $\times$  0% weeding frequency interaction had a significantly lower plant height while SS/DB intra-row intercropping  $\times$  100% weeding frequency interaction had the highest plant height, but differences among other treatments were nonsignificant in the 2017/18 growing season (Fig. 2.8a). Intercropping pattern affected SS height, and SS/CP inter-row intercropping had significantly higher SS height, whereas SS/DB intra-row intercropping recorded the lowest SS height for 60 DAE in 2018/19 growing season (Fig. 2.8a). The SS/CP intra-row intercropping  $\times$  100% weeding frequency interaction had the highest number of leaves per plant, whereas SS/DB intra-row intercropping  $\times$  100% weeding frequency interaction had the lowest number of leaves per plant 60 DAE in 2018/19 growing season (Fig. 2.8b).



Intercropping pattern

**Fig 2.8.** Mean comparison of intercropping pattern × weeding frequency interaction effect on (a) height and (b) 60 DAE number of leaves per plant during the 2017/18 and 2018/19 growing season. The error bars indicate SED.

#### 2.4.5 Land equivalent ratio (LER) of SS/ DB or CP intercropping in weed interference

Land equivalent ratio values were influenced by intercropping pattern and weeding frequency (Table 2.4). During the 2017/18 growing season, the LER value ranged between 0.91 and 2.69, whereas, in the 2018/19 growing season LER value ranged between 1.16 and 2.65 (Table 2.4). The 2017/18 growing season showed that SS/CP intra-row combined with 50% weeding frequency resulted in greater LER (2.69) than other treatments, while in the 2018/19 growing season, SS/DB intra-row with 0% weeding frequency resulted in higher LER (2.65) than other treatments (Table 2.4).

**Table 2.4.** Sweet sorghum, DB, and CP LER for 2017/18 and 2018/19 growing season.

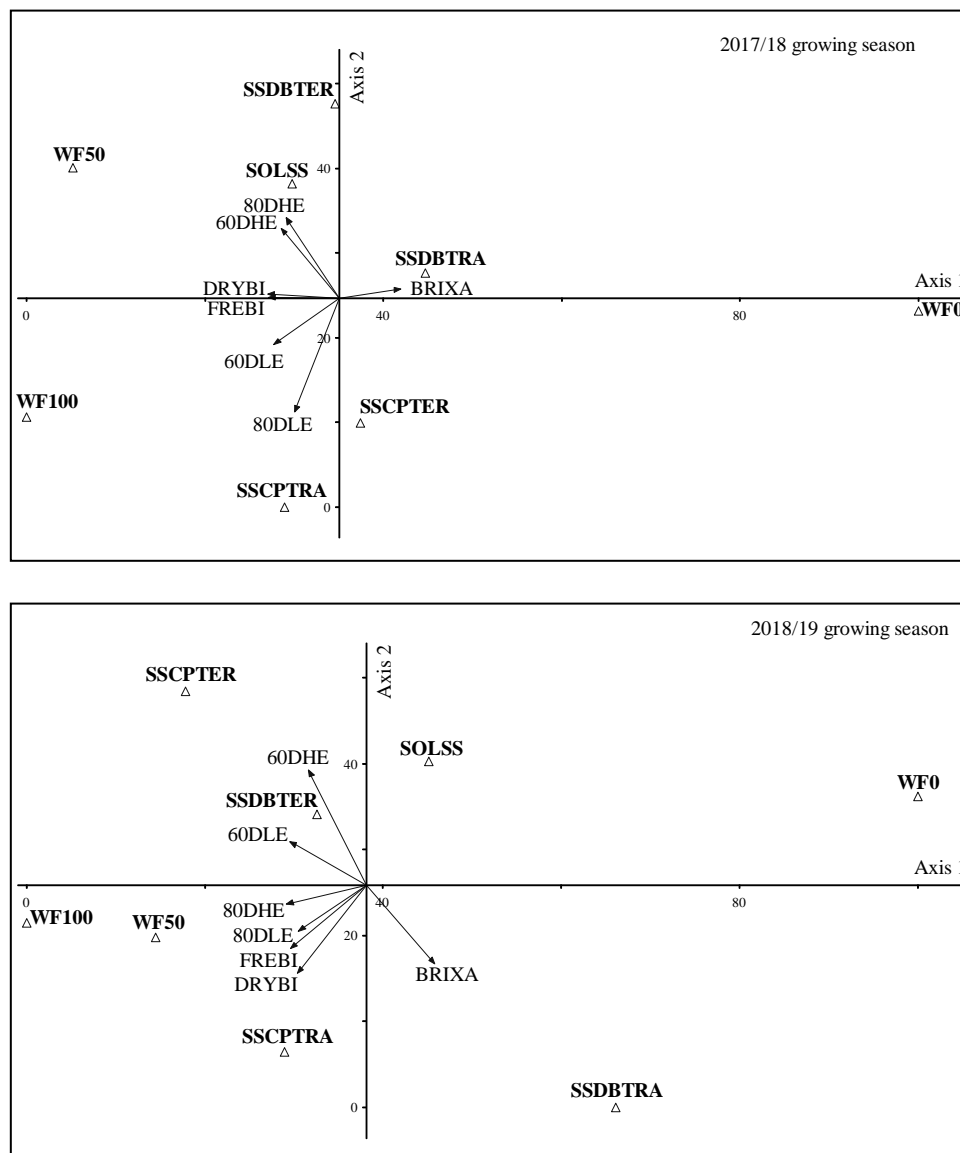
Growing season	Intercropping pattern	Weeding frequency %			Total plot
		0	50	100	
2017/18	SS/CP inter-row	0.97a	1.91c	1.51b	1.61
	SS/CP intra-row	1.48b	2.69d	2.29c	2.26
	SS/DB inter-row	0.91a	2.03c	1.70c	1.66
	SS/DB intra-row	1.12a	2.78d	2.1c	2.19
2018/19	SS/CP inter-row	1.16a	1.60b	1.28a	1.36
	SS/CP intra-row	1.65b	2.45d	1.85c	2.47
	SS/DB inter-row	1.27b	1.65b	1.82c	1.96
	SS/DB intra-row	2.65d	1.84c	1.60b	1.75

Values sharing the same letters are not significantly different ( $P \leq 0.05$ ).

#### **2.4.6 Principal component analysis (PCA) of SS/ DB or CP intercropping in weed interference**

To better understand the °Bx, dry biomass, fresh biomass, plant height, and the number of SS leaves in response to intercropping pattern and weeding frequency, the PCA was used to analyze their correlation over growing seasons (Fig. 2.9). The first axis showed a significant ( $P < 0.001$ ) relationship during the 2017/18 and 2018/19 growing season with eigenvalues higher than one, the first and second axes 67.94% and 18.69% for the 2017/18 growing season while the 2018/19 growing season accounted for 72.98% and 18.71% of the total variation, respectively (Fig 2.9). The PCA ordination showed a positive and strong correlation between SS/DB intra-row and Bx during the 2017/18 and 2018/19 growing season (Fig. 2.9). During the 2017/18 growing season, dry biomass, fresh biomass at 60 and 80 DAE plant height were associated with sole SS, 50% weeding frequency, and SS/DB inter-row intercropping (Fig. 2.9). Likewise, the 60 and 80 DAE number of leaves correlated with 100% weeding frequency and sweet SS/CP inter-row intercropping during the 2017/18 growing season. During the

2018/19 growing season, plant height and the number of leaves after 80 DAE showed a positive correlation with 50% and 100% weeding frequency and SS/CP intra-row intercropping. Also, plant height and the number of leaves after 60 DAE had a strong association with SS/DB inter-row intercropping and SS/CP inter-row and intra-row intercropping.



**Fig 2.9.** Principal component analysis denoting the association of intercropping pattern and weeding frequency with °Bx, dry biomass, fresh biomass, plant height, and the number of leaves during the 2017/18 and 2018/19 growing season. Measured variables are represented by the vectors from the first and second axes SOLSS = sole SS, SSCPTRA = SS/CP inter-row

intercropping, SSCPTRA = SS/CP intra-row intercropping, SSDBTER = SS/DB inter-row intercropping, SSDBTRA= SS/DB intra-row, WF0= 0% weeding frequency, WF50 = 50% weeding frequency and WF100 = 100% weeding frequency, BRIXA= °Bx, DRYBI = dry biomass, FREBI = fresh biomass, 60DLE = 60 DAE number of leaves, 80DLE = 80 DAE number of leaves, 60DHE = 60 DAE plant height, 80DHE = 80 DAE plant height.

## 2.5 Discussion

Despite various advantages, SS is still regarded as an underutilized crop and limited weed management strategies are associated with its production (Peerzada et al., 2017). Furthermore, selecting suitable weed management strategies to achieve an eco-friendly outcome is a daunting task (Gholami et al., 2013). The study evaluated intercropping pattern and weeding frequency with their interaction on SS °Bx, dry and fresh biomass, plant height, and the number of leaves. This study's findings are of interest in biomass production to better understand the critical weed-free period, particularly in an intercropping system to maximize biomass production.

The observed results of weeding frequency suggest that the more the weeding frequencies increased, the more the °Bx declined, meaning that uncontrolled weed plots accumulated higher °Bx than controlled weed plots (Fig 2.2a). The Brix values were generally low (4.12–5.43% during the 2017/18 growing season and 5.42–7.62% during the 2018/19 growing season) compared with what has been reported in literature. According to Xavier et al. (2017), sorghum seed heads' detachment significantly increased °Bx in the stalks and leaves which could explain the low Brix values. The °Bx content depends on the variety, and it has been estimated to range from 14 to 23% (Vinutha et al., 2014), hence, one-degree Bx is equal to 1 g of sugar per 100 g of juice (Mathur et al., 2017). The results of this study reaffirm Silva et al. (2014) findings that SS coexistence with weeds caused an increase in total °Bx compared with the hoed controlled

(Silva et al., 2014). The authors further stated that increasing the number of plants per linear meter increased soluble solids' content; thus, an increase in intraspecific competition may have adverse effects on water absorption, increasing the soluble solids concentration. Different varieties contain different °Bx content, and these depend on several factors viz, internode position, time of the year, stage of harvesting, and environmental conditions,(Qazi et al., 2012), day length, global radiation, fertilization, or soil fertility (Silva et al., 2014). The radiation usage efficiency, photosynthetic rate, and water absorption are regulated by leaf morphology and root architecture, translating into °Bx's quality (Mathur et al., 2017). The information about the physiological mechanism around sugar accumulation in SS is still scanty (Shukla et al., 2017). Sugar content varies inversely with biomass yield within SS germplasm, i.e., high sugar content with lower biomass or low sugar content with high biomass (Disasa et al., 2017). However, the most favorable genotypes would have higher biomass with high sugar yields (Mathur et al., 2017).

As expected, uncontrolled weed plots had the lowest dry biomass accumulation, whereas the biomass increased as weeding frequency increased (Fig. 2.2b). Therefore, it is worth noting that dry biomass accumulation remained insignificant as weed frequencies further increased from 50 to 100% weeding frequency (Fig. 2.2b). Also, dry biomass accumulation doubled during the 2018/19 growing season compared to the 2017/18 growing season (Fig. 2.2b). The 2017/18 growing season received high rainfall of 703 mm than the 2018/19 growing season of 253 mm which could expound the biomass difference between the two seasons. Similar results were reported by Rad et al. (2020), where different precipitation levels over seasons could explain the different sorghum and forage legumes yield accumulation between the growing seasons, However, the authors further stated that the high level of ambient temperature, particularly the minimum temperature, accelerated and increased leaf area and plant growth and, finally, enhanced the forage yield. Moreover, there were also likely nutrient and soil

quality improvements between the growing seasons. However, unpredictably SS managed to accumulate higher dry biomass under moisture stress conditions. Under low-rainfall conditions, it could be that the temporal use of radiation by the cropping system was increased by increasing biomass production (Chimonyo et al., 2016). Under a water-limited environment, SS plants become dormant but can resume growth following favourable conditions. In contrast, excessive moisture usually reduces overall biomass and stalk juice quality and yield (Zhang et al., 2016). Thus, high biomass quantities are needed to aid a bio-based economy while maintaining sufficient food production levels and preserving natural resources, and environmental quality is indispensable (Cassman & Liska, 2007).

The significant effect of weeding frequency on sweet sorghum fresh biomass accumulation during the 2017/18 growing season showed that uncontrolled weeds had a detrimental effect on SS biomass accumulation (Fig. 2.3). The results showed that SS biomass accumulation increased as weeding frequency increased. However, the insignificant difference between 50 and 100% weeding frequency reflects that SS biomass accumulation is not influenced by further weed control events (Fig. 2.3).

The highest SS dry biomass was observed in SS/CP intercropping during the 2018/19 growing season. This could be associated with the CP complete canopy cover; hence it denied weeds the light needed for germination (Fig. 2.4). Contrary, Chimonyo et al. (2016) reported that intercropping insignificantly affected sorghum growth and development and hence, high biomass.

The significant interaction between intercropping pattern  $\times$  weeding frequency showed that uncontrolled weeds had a tremendous impact on SS fresh biomass accumulation during the 2018/19 growing season (Fig. 2.5). The intercropping patterns  $\times$  0% weeding frequency during the crop cycle was negatively affected (Fig. 2.5), with a reduction of approximately 55%

compared to 50 and 100% weeding frequency. Light interception by a crop canopy is determined by the species' leaf area index and the leaf light absorption characteristics (Bastiaans & Kropff, 2003). Thus presumably, high weed density and diversity in uncontrolled weed treatments affected light interception, which plays a crucial role in crop biomass production. Graham et al. (1988) reported that high weed density negatively affected leaf area and light absorption, resulting in affected crop yield. These results support Dille et al. (2020), who reported that approximately 47% of sorghum total yield was lost due to weed interference. As different climatic conditions are considered, weeds are a significant hurdle on sorghum growth and yield, with 18-97% losses reported due to weeds (Peerzada et al., 2017). A constant increase in atmospheric CO<sub>2</sub> negatively affects vegetative growth in most C4 crops; therefore, this puts C4 crop in a susceptible position to compete against counterparts C3 weeds and yield potential declines (Ziska, 2001).

Moreover, increasing concerns about environmental and human health reduced reliance on agrochemicals to control weeds worldwide (Zhang et al., 2015). Research focusing on combining cultural weed control strategies with mechanical and chemical methods could reduce herbicide use, thus improving sustainable weed control strategies (Hozayn et al., 2012). With different environmental conditions in mind, a competitive cultivar in one region would not be as competitive as in other regions (Peerzada et al., 2017). The lack of modern technology and implements in developing countries exacerbates the intra-row weed control hurdle faced by farmers who typically use handheld hoes and spades (Hussain et al., 2018). However, it is difficult to control weeds within intra-rows without injuring the crop (Tillett et al., 2008).

The insignificant differences observed between intermediate and high weeding frequencies (Fig. 2.6a, b) could be that crop canopy cover due to high plant population and uniform crop distribution affect the weeds' light interception through shading (Forcella et al., 1992).

Therefore, the filtered light quality of solar radiation reaching the ground surface affects weed seed germination (Moomaw & Martin, 1984). The shading provisioned by faster canopy cover reduces weed germination, growth, and establishment (Locke et al., 2002). The highest plant height in SS/CP inter-row intercropping could be due to the crops harmoniously utilizing the environmental resources with less competition for water, nutrients and light (Fig. 2.7a), which could also explain the SS/CP intra-row intercropping having the highest number of leaves per plant (Fig. 2.7b). The appropriate selection of legumes in the intercropping system and increasing diversity can reduce weeds' ability to compete for resources (Rad et al., 2020). There is a direct relationship between plant height and biomass (Mathur et al., 2017). The 80 DAE plant height obtained during the 2017/18 growing season showed that SS height under uncontrolled weed plots were significantly affected by SS/CP intra-row intercropping  $\times$  0% weeding frequency interaction. However, the other treatment combinations remained insignificant (Fig. 2.8a). These results agreed with Silva et al. (2014) who reported that uncontrolled weeds during the crop cycle negatively affected sorghum's plant height. Intercropping pattern and weed interference affected the number of leaves (Fig. 2.8b). Hence, these results also agreed with the findings of Shukla et al. (2017) that competition reduces the number of leaves present. The authors further stated that the more sorghum plant remains vegetative, the more the number of leaves; thus, the internode length and maturity influence the plant height.

Intercropping pattern and weeding frequency influenced the LER values, however, the intra-row intercropping pattern had greater values than the inter-row intercropping pattern (Table 2.4). Moreover, all the intercropping treatments had LER above 1.0 except on 0% weeding frequency, signifying that intercropping was advantageous over sole cropping.

The PCA ordination highlighted crucial information on the intercropping pattern and weeding frequency concerning the sweet sorghum's agronomic traits. The PCA ordination showed that

°Bx was consistent and had a strong association with SS/DB intra-row in both growing seasons. The different amounts of rainfall received within the two seasons could have contributed to the inconsistency of the number of leaves and plant height relation with SS/CP intra-row intercropping, SS/CP inter-row intercropping, and other variables.

## 2.6 Conclusion

Sweet sorghum low biomass production was found to be associated with the 0% weeding frequency, resulting in higher sugar content °Bx. Based on the observed results, after eight weeks of crop emergence, the weed control applications were not necessarily beneficial. Since SS biomass yield and °Bx remained insignificant at 50 and 100% weeding frequencies, high crop injuries were noted. Intercropping pattern × weeding frequency interaction effect showed that fresh biomass, plant height, and the number of leaves per plant remained low at 0% weeding frequency; however, they ascended as weeding frequency increased across all the intercropping patterns. The fresh biomass accumulation improved under intercropping with legumes than sole cropping. Furthermore, dry biomass was highest under intra-row intercropping compared to other cropping arrangements. Therefore, looking at the difference in biomass yield between the two growing seasons, SS could be drought-tolerant and perform better in moisture-limited conditions, as this can be explained by the different amounts of rainfall received between the growing seasons. In general, the LER results showed that intra-row intercropping performed better compared with inter-row inter-cropping plots. The PCA analysis ordination proved that Brix was consistently associated with SS/DB intra-row intercropping over the seasons.

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## CHAPTER 3

### WEEDING FREQUENCY EFFECTS ON DRY BEAN INTERCROPPED WITH SWEET SORGHUM AND COWPEA UNDER DRY LAND CONDITIONS

#### 3.1 Abstract

A better understanding of the dry bean (*Phaseolus vulgaris* L.) growth and yield response to weed competition under intercropping system is critical for improving sustainable weed management strategies. A two-year trial was conducted with three types of crop arrangement (sole cropping, inter-row, and intra-row intercropping) combined with weeding frequency (no weeding, weeding over the first 50 days of crop growth, and weed-free) at Ukulinga Research and Training farm of the University of KwaZulu-Natal in Pietermaritzburg, during 2017/18 and 2018/2019 growing season. Effects of the treatments were tested on dry bean agronomic indicators viz: 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, plant height, number of leaves per plant, and chlorophyll content. The intercropping pattern significantly affected dry bean pods per plant, height and chlorophyll content, while weeding frequency significantly affected all dry bean measured agronomic indicators except for chlorophyll content during the 2017/18 growing season. The results showed that the significant measured agronomic indicators were lowest under no weed control; however, they increased as weeding frequency increased. The 2018/19 growing season followed a similar trend; however, the interaction effect significantly affected dry bean 100-grain weight, dry biomass, and 40 days after emergence number of leaves per plant. The dry bean/ sweet sorghum or cowpea intra-row intercropping and intermediate weeding frequency had optimum productivity.

**Keywords:** dry bean, intercropping pattern, weeding frequency.

### 3.2 Introduction

Dry bean (*Phaseolus vulgaris* L.) is a vital grain pulse and one of the plant protein sources in South Africa, yet there is approximately 49% dry bean production deficit annually (Mathobo et al., 2017). However, like any other crop, dry beans are sensitive to weed competition, especially at the early growth stage. Therefore, a dry bean production shortfall in South Africa could be exacerbated by weed interference. It is essential to develop sustainable weed control strategies for sustainable crop production by which weeds can be controlled effectively (Weisany et al., 2016) to curb environmental degradation. Herbicides and tillage are tools primarily used to control weeds, and the ramifications brought by these tools are growing severe environmental concerns and increasing herbicide resistance (MacLaren et al., 2020). In response to the echoing calls for intensifying sustainable agriculture, intercropping has been advocated as a sustainable cropping system to reduce conventional agriculture's negative impact on the environment (Fung et al., 2019). Therefore, sustainable weed control strategies are critical.

There are several challenges associated with weeds in agricultural fields, mainly reducing crop yield and quality (Fernandez et al., 2019; Fernando et al., 2019). The growth and yield of French beans are significantly reduced by weed competition for growth factors (Stagnari & Pisante, 2011). However, integrating cultural weed control methods such as a spatial arrangement or intercropping with new strategies is essential to achieve a sustainable agricultural ecosystem (Owen et al., 2014). Narrow rows in intercropping systems are linked with greater uniformity in leaf and root distribution, allowing the crop to intercept more radiation and efficiently utilize the soil resources, thus impeding weed establishment and growth (Dusabumuremyi et al., 2014; Weisany et al., 2016).

Controlling intra-row weeds can be laborious, mainly through manual weeding in slow-growing row crops such as dry beans with less competitive traits against weeds (Van Der Weide et al.,

2008). Van Der Weide et al. (2008) also stated that intra-row weeding is expensive, time-consuming, and challenging to organize. In this view, a critical period for weed control (CPWC) was developed and defined as a period in the crop's growth cycle during which weed control is imperative to shun unacceptable yield losses (Knezevic et al., 2002). Early weed control is imperative to achieve optimum crop yield since prolonged weed interference affects crop yield, reduces crop quality, and increases production costs (Sardana et al., 2017). The mechanism behind the impact of weed interference during CPWC on crop growth, development, and yield is partially unknown (McKenzie-Gopsill et al., 2020).

The magnitude of weed-related dry bean yield loss due to weed interference can be variable in different growing areas or seasons, mainly attributable to weed species present, weed density, and environmental conditions (Soltani et al., 2018; Tursun et al., 2016). Understanding agronomic technologies that are profitable and practical to adopt is an important research area, as the semi-arid and marginal lands require judicious use of inputs and zonal management to optimize nutrients restoration (Buerkert & Schlecht, 2013).

Intercropping is defined as growing more than one crop species simultaneously in the same area (Rosa-Schleich et al., 2019) and not necessarily sown or harvested simultaneously (Fung et al., 2019). The potential benefits of intercropping are increasing crop yield and quality via efficient use of land, sunlight, soil nutrients and moisture (Brooker et al., 2016), thus improving resilience to current and future climate changes, pests, disease, and weed damage (Altieri et al., 2017). The addition of legumes in intercropping systems is supported globally to improve soil fertility, protein-rich plant products and livestock fodder (Snapp et al., 2018). Dry beans are frequently used as intercrops, thus ensuring sustainable cropping systems by intensifying production and soil fertility enhancement through their ability to fix atmospheric nitrogen biologically (Buruchara et al., 2011). It enhances phosphorous biological turnover thus, making

them relevant for sustainable agriculture (Snapp et al., 2018) in the context soil fertility management.

Information about the potential and feasibility of dry bean performance with sweet sorghum (*Sorghum bicolor* L.) or cowpea (*Vigna unguiculata* L. Walp) intercropping is not widely available in literature. Moreover, the sweet sorghum or cowpea as a companion of dry bean in intercropping under weed interference has been poorly reported. There is a need for sustainable weed control strategies for poor rural farmers to increase the adoption of grain legumes, such as agronomic practices to reduce weed pressure, particularly spatial arrangement and critical periods for weed control in different grain legume species. Therefore, the current study was designed to evaluate dry bean performance and determine the optimum spatial arrangement in dry bean/sweet sorghum or cowpea intercropping system compared to sole cropping under different weeding management levels.

### **3.3 Materials and methods**

#### ***3.3.1 Description of the experimental site***

A two-season trial was conducted at Ukulinga Research and Training farm of the University of KwaZulu-Natal in Pietermaritzburg, South Africa latitude 29°39'56.6"S and longitude 30°24'26.2"E, altitude 791 m amsl during the 2017/18 and 2018/19 growing seasons. Three types of crop arrangement (sole cropping, inter-row, and intra-row intercropping) were combined with three types of weeding frequency (no weed control (NWC), 50 days weeding after crop emergence (50 DWACE) and weed-free (WF) and subjected to physical weed control treatments (section 3.3.2 below). All treatment combinations were planted using 0.60 m inter-row and 0.30 m intra-row spacing (55 555.6 plants ha<sup>-1</sup>) to achieve uniformity for both sole crops and intercrops. The dry bean (*Phaseolus vulgaris* L.) (optimum 8 plants m<sup>-2</sup>) was intercropped with sweet sorghum (*Sorghum bicolor* L.) (optimum 7.41 plants m<sup>-2</sup>) and cowpea

(*Vigna unguiculata* L. Walp) (optimum 10 plants m<sup>-2</sup>). A split-plot design in a randomized complete block design (RCBD) was used, comprising of twenty-seven treatments replicated three times totalling 81 plots. Generally, treatments, plot layout, soil analysis, and climatic were done according to a previously published study (Baker et al., 2021). During crop growing season, five manual (hand hoe) weeding frequencies were executed every 10 days up to 50 days of weed control after crop emergence (50 DWACE), and eight hand hoe-weeding frequencies were applied for the weed-free treatment, while no weeding was done for the control.

### 3.3.2 Data and yield collection

Effects of the treatments were tested on various dry bean agronomic indicators: 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, plant height, number of leaves per plant, and chlorophyll content. To determine dry bean biomass production, whole plants were harvested from 1.44 m<sup>2</sup> then sun-dried for dry biomass weight. Plant height was based on the average height of four plants per plot. Eight (8) plants were sampled per plot on sole cropping on the dry bean, amounting to an area of 1.44 m<sup>2</sup> on sole and intercropping systems. The grains were removed from the dry pods at 12% moisture content determined using a moisture meter (Halogen Moisture Analyzer HX204) and their mass was recorded (Mettler Toledo) to obtain grain yield. A handheld soil plant analysis development (SPAD) chlorophyll meter was used to measure chlorophyll content.

Land equivalent ratio (LER) was determined using the equation below.

$$\text{LER} = \text{ID}/\text{SD} + \text{IS}/\text{SS} \dots \dots \dots (1)$$

Above-ground dry biomass was used to determine LER for dry bean and sweet sorghum intercropping, where ID denotes intercropping dry bean, SD denotes sole dry bean cropping, and IS denotes intercropping sweet sorghum, SS denotes sole sweet sorghum cropping.

$$\text{LER} = \text{ID}/\text{SD} + \text{IC}/\text{SC} \dots\dots\dots (2)$$

Grain yield was used to determine LER dry bean and cowpea intercropping, where ID denotes intercropping dry bean, SD denotes sole dry bean cropping, and IC denotes intercropping cowpea, SC denotes sole cowpea cropping.

### 3.3.3 Statistical analysis

Analysis of variance (ANOVA) was used to compare the effects of intercropping pattern and weed frequency on dry bean 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, plant height, number of leaves per plant and chlorophyll content using GENSTAT statistical software version 18. The standard error of the difference (S.E.D) and least significant difference (LSD) were used for mean separation when treatments were significantly different ( $P < 0.05$ ).

## 3.4 Results

### 3.4.1 Analysis of variance of dry bean measured traits

The significant analysis of variance (ANOVA) results are shown in Table 3.1 and Table 3.2 for the 2017/18 and 2018/19 growing seasons, respectively. Intercropping pattern had significant ( $P < 0.01$ ) effect on dry bean pods per plant, 60 days after emergence (DAE) plant height, and 80 DAE chlorophyll content. Also, the results showed that weeding frequency had a significant ( $P < 0.01$ ) effect on dry bean 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, 60 and 80 DAE plant height (Table 3.1). Moreover, the intercropping pattern  $\times$  weed frequency interaction effects was significant ( $P < 0.05$ ) on 80 DAE plant height; however, other treatments remained insignificant (Table 3.1)

**Table 3.1.** Analysis of variance of dry bean measured attributes during the 2017/18 growing season

Source of variation	Intercropping pattern	Weeding frequency	Intercropping pattern × weeding frequency	Residual	CV	
						df
	4	2	8	28		
	ms					
100-grain weight	81 ns	3974***	145.8 ns	102.1	28.2	
Dry biomass	0.26 ns	4.4***	0.16 ns	0.10	40.1	
Grain yield	15350 ns	240969***	18336 ns	8411	53.6	
Grains per pod	0.80 ns	10.86***	0.82 ns	0.37	19.9	
Pods per plant	219.11**	2920.69***	40.3 ns	44.96	30.0	
Plant height	60 DAE	55.73**	368.36***	7.09 ns	10.34	8.2
	80 DAE	20.35 ns	111.96***	21.63*	9.12	13.1
Chlorophyll	80 DAE	146.96 **	127.18 ns	18.01 ns	44.77	4.7

ns: not significant; \*, \*\*, \*\*\* significant at 0.05, 0.01, 0.001 probability levels, respectively; ms=- mean square; df= degree of freedom; CV= coefficient of variation.

During the second growing season, intercropping pattern had a significant ( $P < 0.01$ ) effect on dry biomass, pods per plant, 40 and 80 DAE plant height (Table 3.2). Weeding frequency had significant ( $P < 0.01$ ) effect on dry bean 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, plant height, number of leaves per plant, and chlorophyll content (Table 3.2). The intercropping pattern  $\times$  weeding frequency interaction had significant ( $P < 0.05$ ) effect on dry bean 100-grain weight, dry biomass and 40 DAE number of leaves per plant (Table 3.2).

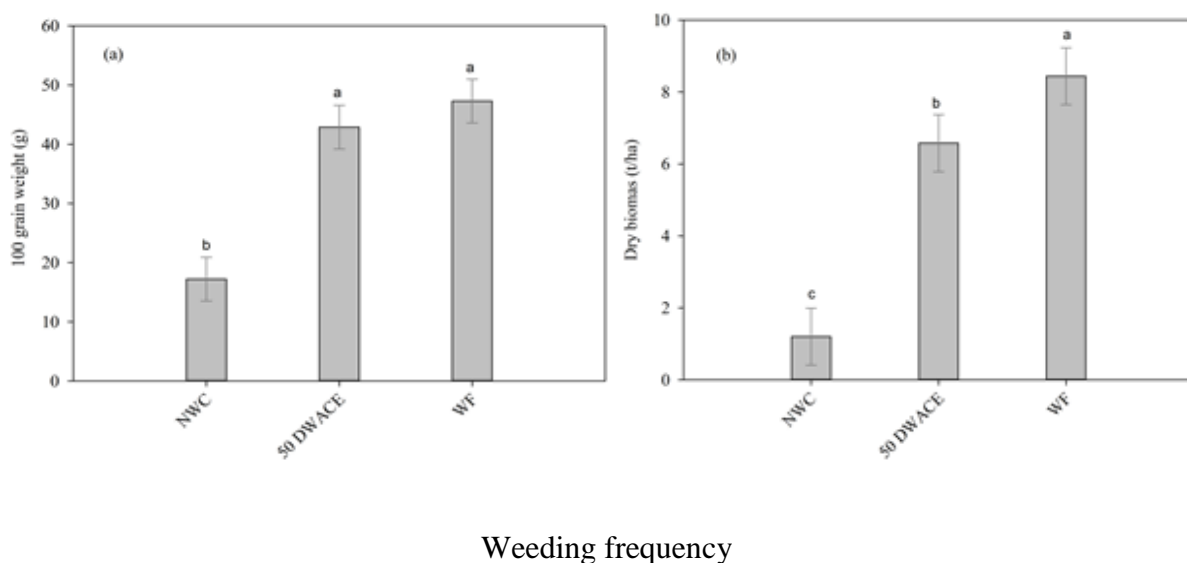
**Table 3.2.** Analysis of variance of dry bean measured attributes during the 2018/19 growing season

Source of variation		Intercropping pattern	Weeding frequency	Intercropping pattern × weeding frequency	Residual	CV
		df	df	df		
		4	2	8	28	
		ms				
100-grain weight		58.82 ns	8812.18***	68.33*	29.74	18.1
Dry biomass		0.04**	0.35***	0.02*	0.01	45.6
Grain yield		4201 ns	55951***	2385 ns	1670	26.1
Grains per pod		0.98 ns	75.71***	1.34 ns	0.71	31.7
Pods per plant		42.78*	1037.95***	21.4 ns	11.45	2.0
Plant height	40 DAE	140.44*	211.65***	94.73 ns	49.07	49.8
	60 DAE	140.75 ns	533.99***	131.90 ns	62.70	32.8
	80 DAE	453.9 **	1513.9***	106.9 ns	120.7	4.2
Number of leaves	40 DAE	9.44 ns	114.83***	24.52 *	10.63	31.7
	60 DAE	26.39 ns	70.04***	20.94 ns	18.74	54.2
	80 DAE	30.73 ns	203.05**	23.61 ns	24.75	65.2
Chlorophyll	40 DAE	150.15 ns	425.48*	118.6 ns	89.76	49.6
	80 DAE	219.5 ns	4061*	131.8 ns	160.9	45.8

ns: not significant; \*,\*\*,\*\*\* significant at 0.05, 0.01, 0.001 probability levels, respectively; ms= mean square; df= degree of freedom; CV= coefficient of variation.

### 3.4.2 Weeding frequency effect on measured dry bean traits

The weeding frequency significantly affected 100-grain weight; no weed control had significantly lower 100-grain weight; however, the 100-grain weight increased not significantly as weeding frequency increased from 50 DWACE to weed-free in the 2017/18 growing season (Fig 3.1a). For dry biomass, the difference was observed between 50 DWACE and weed-free based on (Fig. 3.1b), grain yield (Fig. 3.2a), number of grains per pod (Fig. 3.2b), number of pods per plant (Fig. 3.2c), chlorophyll content index (Fig. 3.2d).



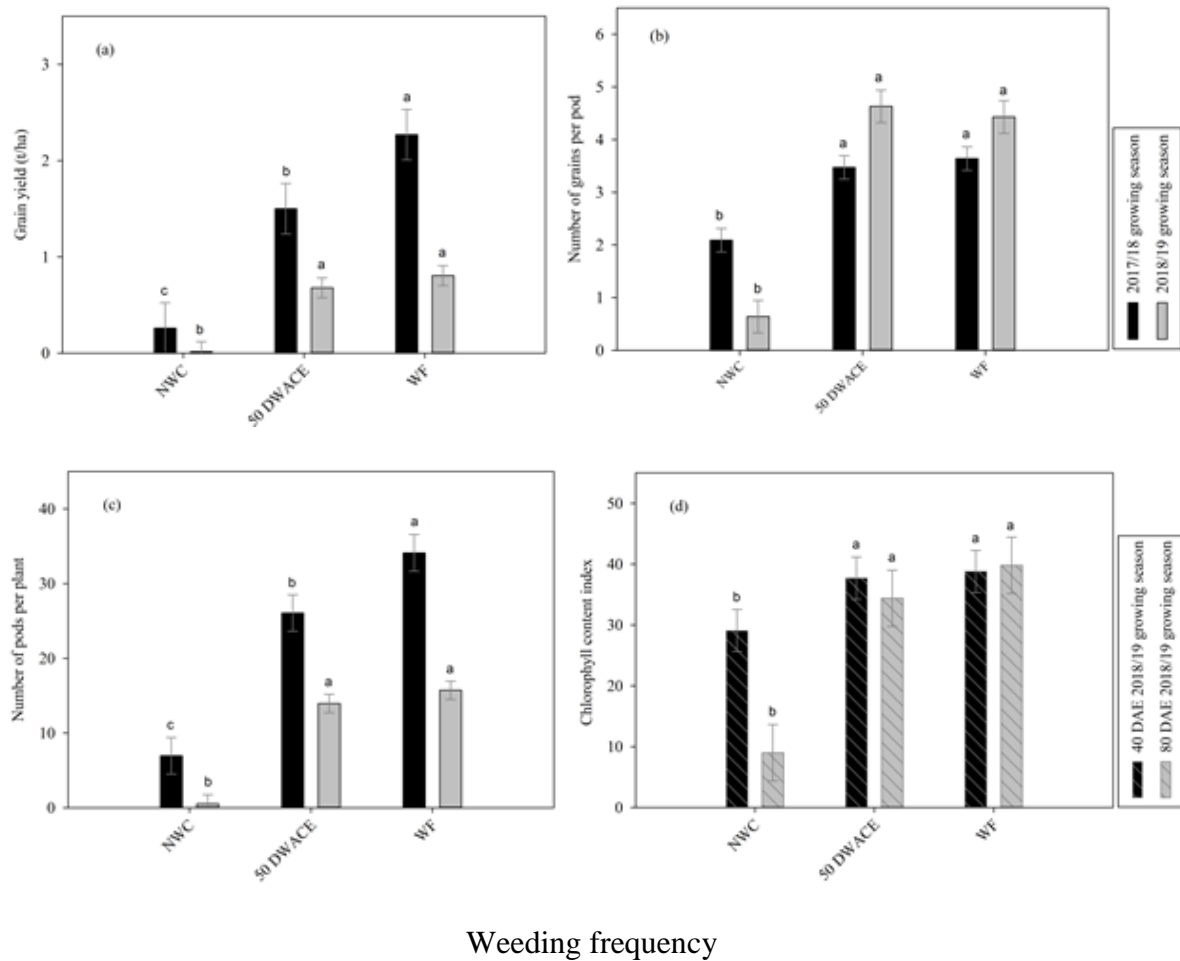
**Fig 3.1.** Weed frequency effect on dry bean (a) 100-grain weight, (b) dry biomass during 2017/18 growing season. The error bars denote S.E.D.

In the 2018/19 growing season, dry bean grain yield was significantly lower at no weed control and increased as weeding frequency increased; however, it showed no significant effect between 50 DWACE and weed-free compared to the 2017/18 growing season (Fig 3.2a).

The number of grains per pod was significantly influenced by weeding frequency. The grains per pod increased as weeding frequency increased. However, it remained insignificant between intermediate weeding frequency and weed-free over the growing seasons (Fig 3.2b).

The lowest number of pods per plant was observed at no weed control, which increased as the weeding frequency increased (Fig 3.2c). The number of pods per plant during the 2017/18 growing season showed a significant difference between 50 DWACE and weed-free; however, the 2018/19 growing season showed no significant difference between 50 DWACE and weed-free (Fig 3.2c). Due to increased weeding frequency, the high number of dry bean pods per plant differed between the growing seasons.

The weeding frequency significantly influenced dry bean leaf chlorophyll content at 40 DAE and 80 DAE during the 2018/19 growing season (Fig 3.2d). The no-weed control had a significantly lower dry bean leaf chlorophyll content and significantly increased as the weeding frequency increased at 40 DAE and 80 DAE but remained not significant at intermediate weeding frequency in the 2018/19 growing season (Fig 3.2d).



**Fig 3.2.** Weeding frequency effect on dry bean (a) grain yield, (b) grains per pod, (c) pods per plant during the 2017/18 and 2018/19 growing season, and (d) dry bean leaf chlorophyll content during the 2018/19 growing season. The error bars denote S.E.D.

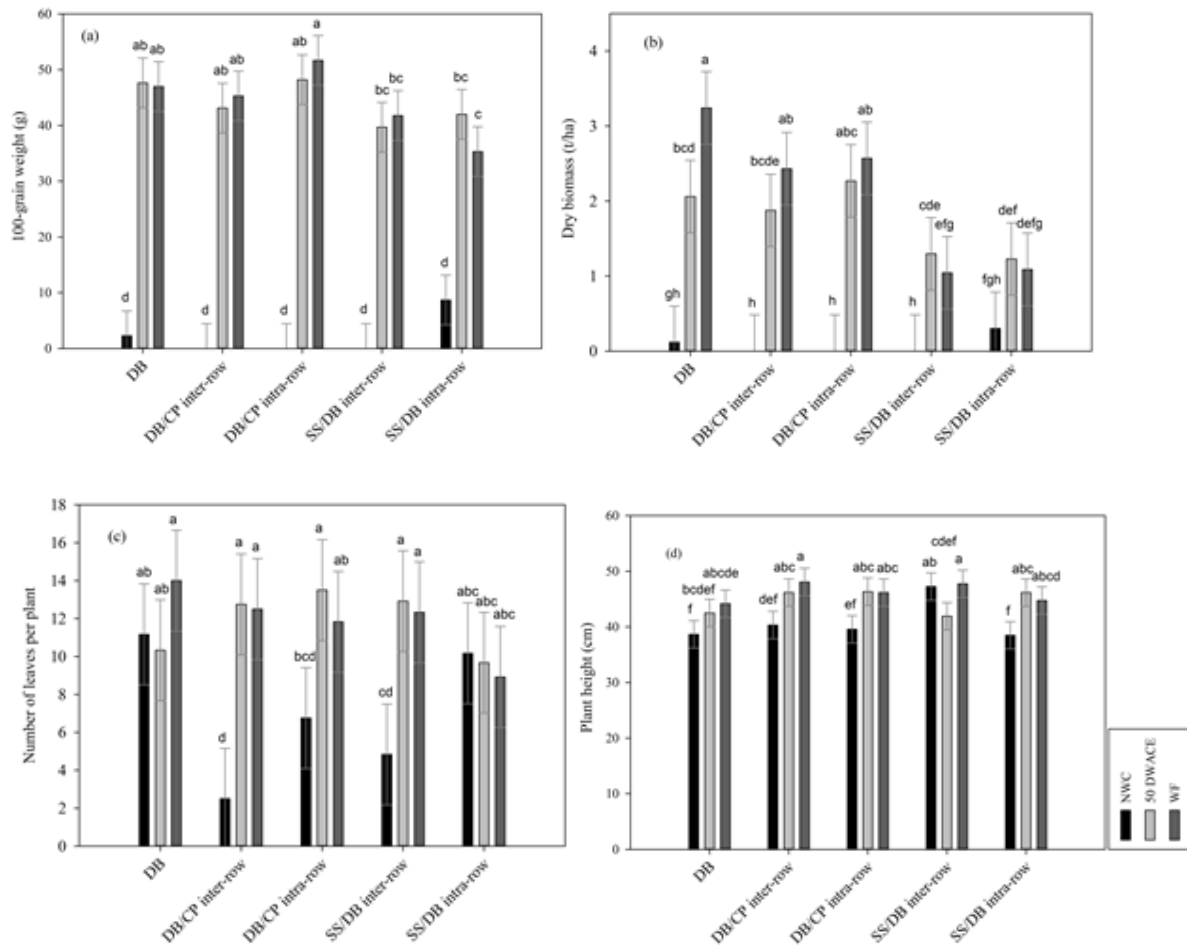
### 3.4.2 *Intercropping pattern* × *weeding frequency* interaction effects on measured dry bean yield traits

During the second growing season, interaction effects between intercropping pattern × weeding frequency were significant on dry bean 100-grain weight (Fig. 3.3a). The DB/CP intra-row × weed-free had the highest 100-grain weight compared to other treatments; however, the 100-grain weight remained significantly lower at no weed control throughout the intercropping patterns (Fig. 3.3a).

The two-way interaction showed a significant effect regarding dry bean biomass; sole DB × weed-free had significantly higher dry biomass. However, the no-weed control had the lowest dry biomass across all the intercropping patterns (Fig 3.3b). The SS/DB inter-row and intra-row intercropping had the least dry bean dry biomass across all weeding frequencies compared to sole DB, DB/CP intra-row, and inter-row intercropping.

At 40 DAE during the 2018/19 growing season, there was a significant interaction regarding the dry bean number of leaves per plant (Fig 3.3c). The sole DB × weed-free interaction had the highest dry bean number of leaves per plant, while DB/CP inter-row had the lowest dry bean number of leaves per plant (Fig. 3.3c). There was no significant interaction effect on dry bean number of leaves per plant between DB/CP inter-row, DB/CP intra-row, and SS/DB inter-row intercropping × no weed control interaction; however, the number of leaves per plant significantly increased as weeding frequency increased (Fig 3.3c).

At 80 DAE in the 2017/18 growing season, the intercropping pattern × weeding frequency had a significant interaction where the DB/CP inter-row and SS/DB inter-row intercropping × weed-free had the highest plant height while SS/DB inter-row and sole DB × no weed control and 50 DWACE had the lowest plant height (Fig 3.3d).

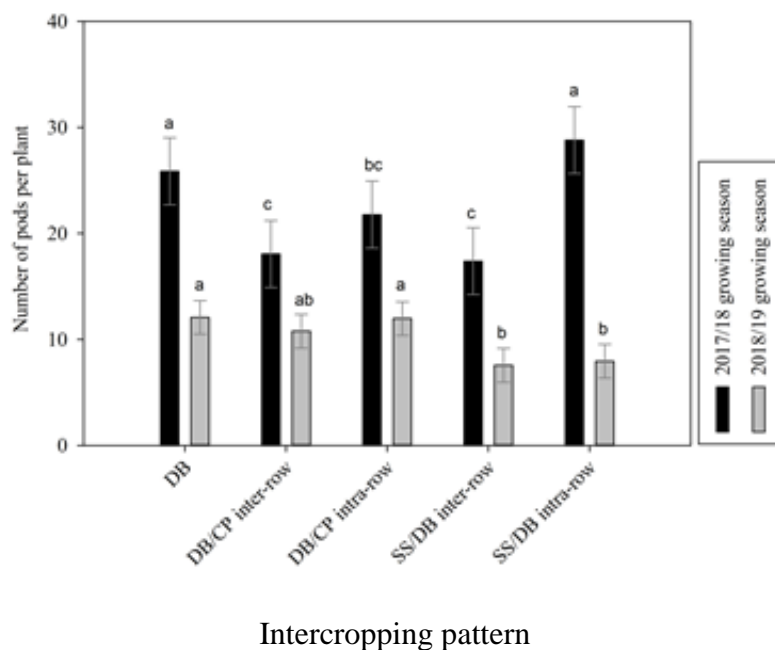


Intercropping pattern

**Fig 3.3.** Intercropping pattern and weeding frequency interaction effect on (a) 100-grain weight, (b) dry biomass, (c) 40 DAE number of leaves per plant during the 2018/19 growing season and (d) 80 DAE plant height during the 2017/18 growing season. The error bars denote S.E.D.

### 3.4.3 Intercropping pattern effect on dry bean pods per plant

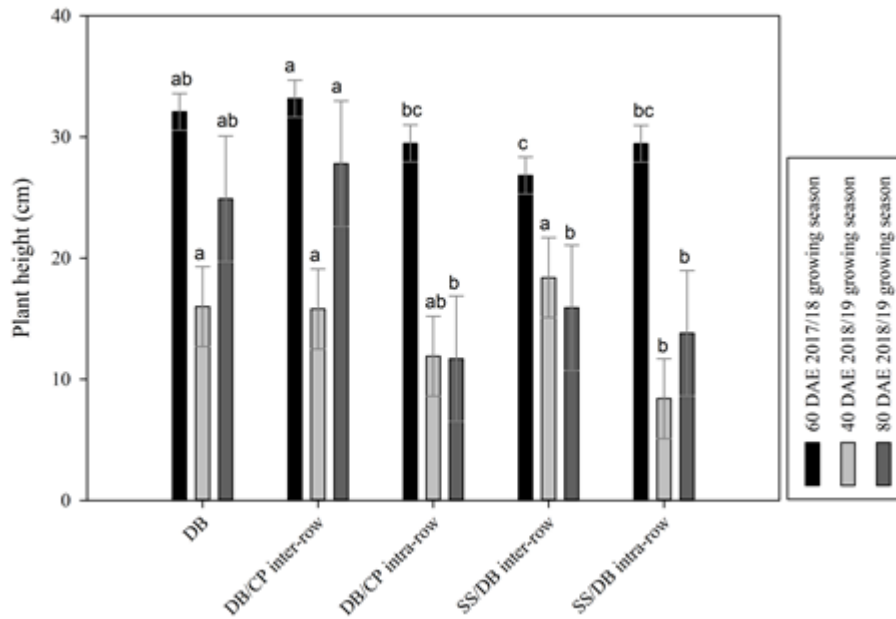
The intercropping pattern effect on the number of dry bean pods per plant was highest on SS/DB intra-row intercropping, whereas SS/DB inter-row and DB/CP had the lowest number of pods per plant during the 2017/18 growing season (Fig 3.4). There was no significant impact of DB/CP intra-row, DB/CP inter-row, and SS/DB inter-row intercropping during the 2017/18 growing season (Fig 3.4).



**Fig 3.4.** Intercropping pattern effect on the number of dry bean pods per plant during the 2017/18 and 2018/19 growing seasons. The error bars denote S.E.D.

#### 3.4.4 Intercropping pattern effect on dry bean growth parameters

The intercropping pattern significantly impacted dry bean plant height at 60 DAE during the 2017/18 growing season and at 40 DAE and 80 DAE in the 2018/19 growing season (Fig 3.5). The highest plant height was recorded for DB/CP inter-row intercropping, and the lowest plant height was observed for SS/DB inter-row intercropping at 60 DAE during the 2017/18 growing season (Fig 3.5). The intercropping pattern significantly influenced dry bean height at 40 DAE and 80 DAE in the 2018/19 growing season (Fig 3.5). The SS/DB inter-row had the highest plant height, whereas SS/DB intra-row had the lowest plant height, DB/CP intra-row, and SS/DB intra-row showed not significant difference at 40 DAE during the 2018/19 growing season (Fig 3.5). At 80 DAE during the 2018/19 growing season, the highest plant height was recorded on the DB/CP inter-row and the lowest on the DB/CP intra-row; however, SS/DB inter-row, SS/DB intra-row, and DB/CP were not significant amongst the treatments (Fig 3.5).



Intercropping pattern

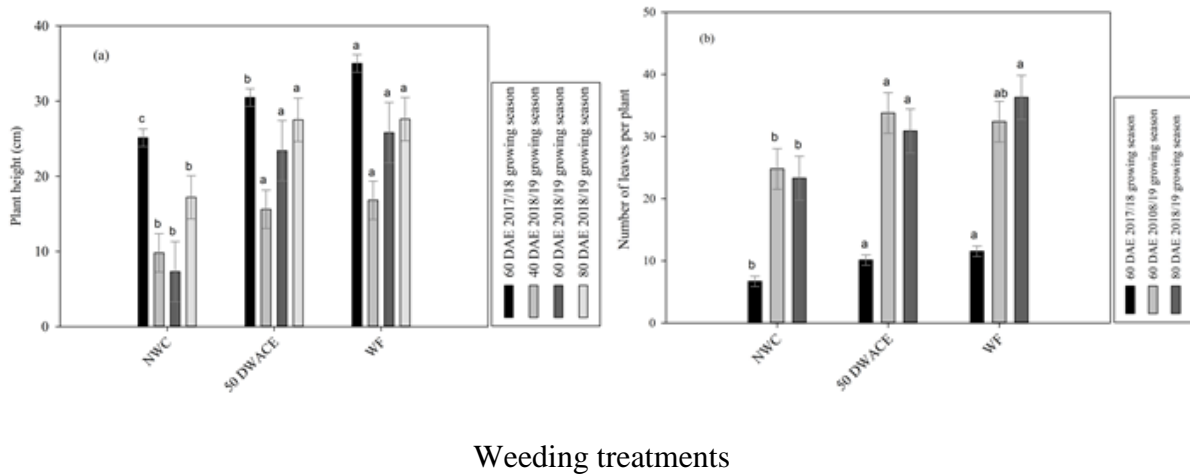
**Fig 3.5.** Intercropping pattern effect on dry bean plant height during 2017/18 and 2018/19 growing season. The error bars denote S.E.D.

### 3.4.5 Weeding frequency effect on dry bean height and number of leaves per plant

The results showed that weeding frequency significantly impacted 60 DAE dry bean height. The highest plant height was observed for weed-free treatment and declined as weeding frequency reduced during the 2017/18 growing season (Fig 3.6a). Weeding frequency effect on dry bean height was not significant at 40 DAE during the 2017/18 growing season, whereas, at 40 DAE during the 2018/19 growing season, a significant effect was observed (Fig 3.6a). However, the highest 40 DAE dry bean height was observed at weed-free and declined as weeding frequency reduced during the 2018/19 growing season (Fig 3.6a). The same was noted for the 60 and 80 DAE during the 2018/19 growing season; moreover, no significant differences were observed between intermediate and weed-free frequencies.

Dry bean number of leaves per plant responded significantly to weeding frequency, the no-weed control had the lowest number of leaves per plant, and the number of leaves per plant

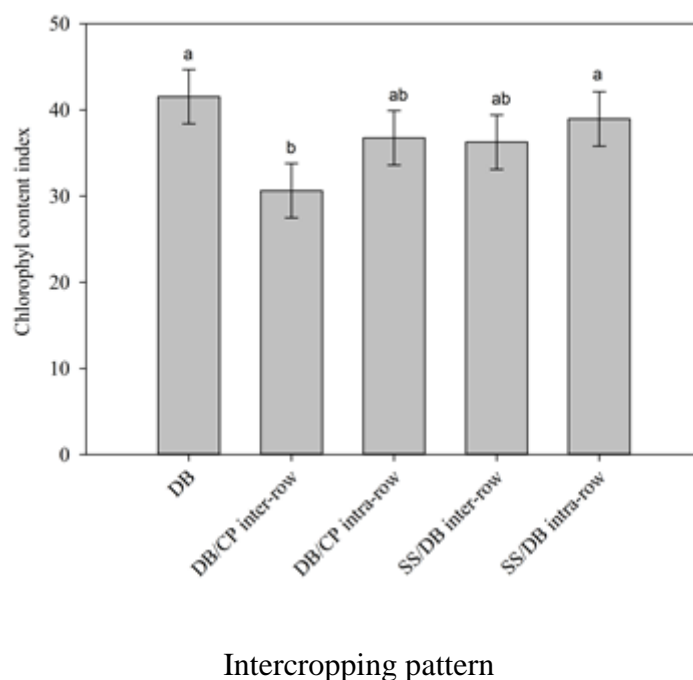
increased as weeding frequency increased at 60 DAE during the 2017/18 growing season, and only for 60 and 80 DAE during the 2018/19 growing season (Fig. 3.6b).



**Fig 3.6.** Weeding treatment (NWC = no weed control; 50DWACE = cultural weeding 50 days after emergence; WF = weed free) effect on dry bean (a) plant height, and (b) the number of leaves per plant 2017/18 and 2018/19 growing season. The error bars denote S.E.D.

### 3.4.6 Intercropping pattern effect on dry bean pods per plant

The intercropping pattern significant effect on dry bean leaf chlorophyll was observed at 80 DAE in the 2017/18 growing season only and the highest chlorophyll content was observed on sole DB, whereas DB/CP inter-row intercropping had the lowest chlorophyll content (Fig. 3.7).



**Fig 3.7.** Intercropping pattern (DB = dry bean only; CP = cowpea; SS = sweet sorghum) effect on dry bean leaf chlorophyll content 80 DAE during the 2017/18 growing season. The error bars denote S.E.D.

### 3.4.7 LER values and PCA analysis of intercropping under weed interference

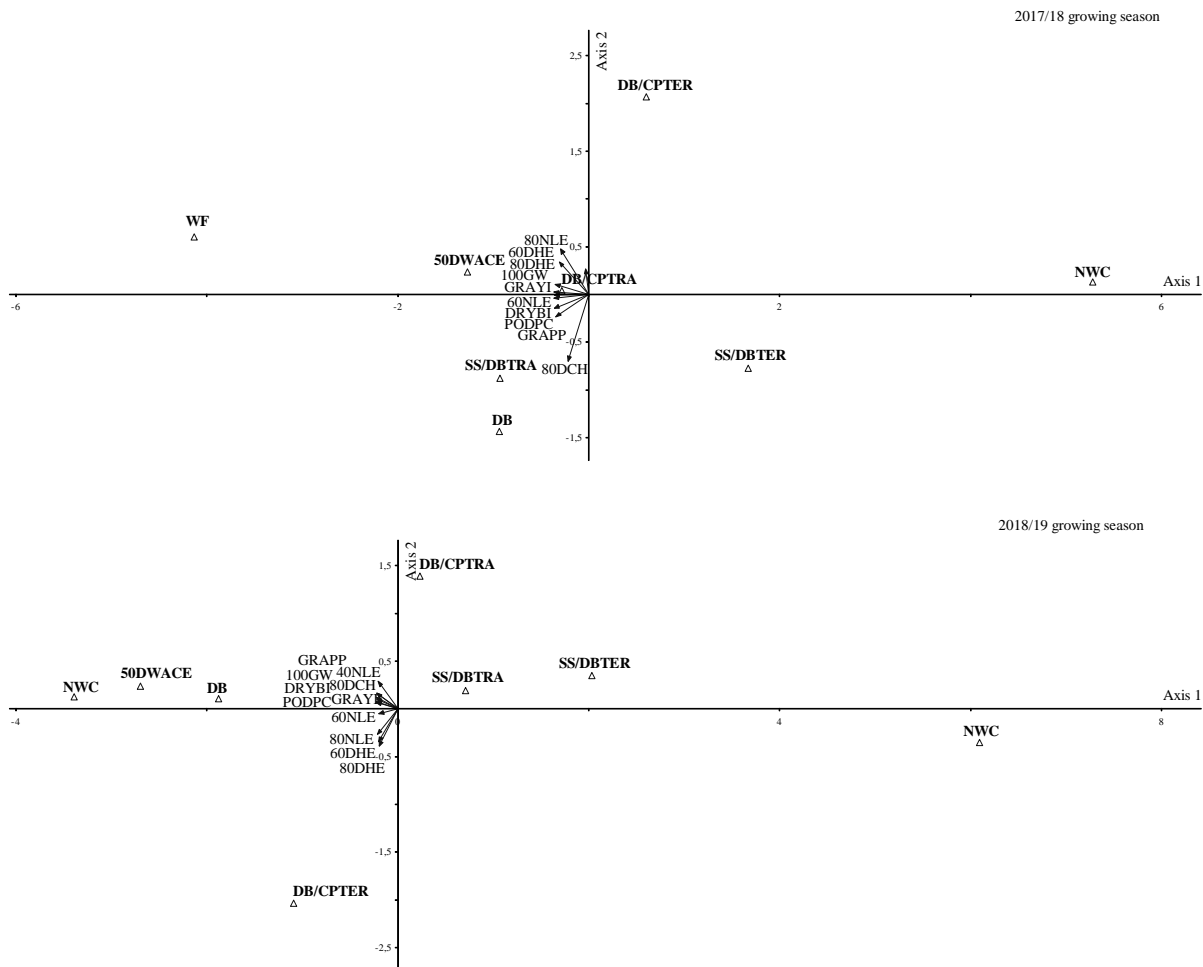
The intercropping pattern and weeding frequency showed effects on dry bean/ sweet sorghum or cowpea intercropping performance regarding the LER value (Table 3.3). During the 2017/18 growing season, the LER value ranged between 0.91 and 3.75, whereas, in the 2018/19 growing season LER value ranged between 0.10 and 2.65 (Table 3.3). The 2017/18 growing season showed that DB/CP intra-row combined with 50 DWACE resulted in greater LER 3.75 than other treatments, while in the 2018/19 growing season, SS/DB intra-row together with no-weed control resulted in higher LER 2.65 than other treatments (Table 3.3). The intercropping pattern and weeding frequency influenced the LER values; however, the intra-row intercropping pattern had greater LER values than the inter-row intercropping pattern (Table 3.3). Moreover, all the intercropping treatments had an LER above 1.0 except no weed control, signifying that intercropping was advantageous over sole cropping.

**Table 3.3.** Dry bean, sweet sorghum, and cowpea LER for the 2017/18 and 2018/19 growing seasons.

Growing season	Intercropping pattern	Weeding frequency			Total plot	Yield type t/ha
		NWC	50 DWACE	WF		
2017/18	DB/ CP inter-row	-	1.72	1.03	1.60	Grain
	DB/ CP intra-row	1.15	3.75	1.43	2.13	
	SS/ DB inter-row	0.91	2.03	1.70	1.66	Dry biomass
	SS/DB intra-row	1.12	2.78	2.1	2.19	
2018/19	DB/ CP inter-row	0.13	2.27	1.67	1.71	Grain
	DB/ CP intra-row	0.10	2.38	1.67	1.73	
	SS/ DB inter-row	1.27	1.65	1.82	1.96	Dry biomass
	SS/DB intra-row	2.65	1.84	1.60	1.75	

Note: NWC, no weed control; 50 DWACE, 50 days weed-control after crop emergence; WF, weed-free; DB, dry bean; CP, cowpea; SS, sweet sorghum

The principal component analysis was used to evaluate correlations between 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, 60 and 80 DAE plant height, 60 and 80 DAE number of leaves per plant, 80 DAE chlorophyll and sole DB, DB/CP inter-row intercropping, DB/CP intra-row intercropping, SS/DBN inter-row intercropping, SS/ DB intra-row intercropping, no weed control, 50 DWACE, weed-free (Fig. 8). The first and second principal components explained 73.55 and 11.65% for the 2017/18 growing season; 84.81 and 8% for the 2018/19 growing season of the data variation, respectively (Fig. 3.8).



**Fig 3.8.** The principal component analysis of intercropping pattern and weeding frequency on dry bean performance under sweet sorghum or cowpea intercropping. Vectors indicate measured variables from the first axis and second axis 100GW= 100 grain weight, 80DCH= 80 DAE chlorophyll, DRYBI = dry bean biomass, GRAYI= dry bean grain yield, 60DHE= 60 DAE height, 80DHE= 80 DAE plant height, GRAPP= grains per pod, 60NLE=60 DAE number of leaves, 80NLE = 80 DAE number of leaves, PODPC= pods per plant. NWC = no weed control, 50 DWACE = 50 days weed control after crop emergence, WF = weed-free, DB = sole dry bean, DB/CPTER = dry bean /cowpea inter-row intercropping, DB/CPTRA = dry bean/cowpea intra-row intercropping, SS/DBTER = sweet sorghum/dry bean inter-row intercropping, SS/DBTRA = sweet sorghum/ dry bean intra-row intercropping.

### 3.5 Discussion

Changes in precipitation and other crop growth factors may affect weed species distribution and competitive ability between the weed population and the crop (Amare, 2016). This could explain the fewer weeding frequencies in the second season. Inconsistent progress has been observed in exploring the intercropping pattern and weeding frequency on dry bean performance growth and productivity in dry bean/sweet sorghum or cowpea intercropping over the seasons. The current study evaluated intercropping pattern and weeding frequency with their interaction on dry bean 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, plant height, number of leaves per plant and chlorophyll content. The current research results align with the findings of (Saberli & Mohammadi, 2019), who also reported the reduction in 100-grain weight under weed-infested conditions. However, contrary to Nassary et al., (2020b), the results found that 100-seed weight was affected by different precipitation over seasons. There is support that the findings that sole legumes had greater above-ground biomass yields than the associated intercrops (Michael Kermah et al., 2017; Nassary et al., 2020b). The different bean varieties and the cereal used could expound the 100-grain weight contradictions.

Biomass yields declined with decreasing soil fertility status, but this decline varied among legume species and sites (Michael Kermah et al., 2017). Resource limitation during weed-crop interaction is a significant yield-reducing factor (McKenzie-Gopsill et al., 2020). The nearby weeds negatively affect common bean yield more than prolonged weed interference or resource limitation, particularly in vegetative stages (McKenzie-Gopsill et al., 2020). Dry bean's poor performance due to weed interference could be linked to their short and shallow root system, affecting their competitive capabilities for nutrient resources (Karuma et al., 2016).

The grain yield difference between the 2017/18 and 2018/19 growing seasons could be explained by the drastically different rainfall distributed between the growing seasons, triggering a high interspecific competition between the crops. The lower rainfall received during the second season could have contributed to limited moisture hence low yields (Michael Kermah et al., 2017). The reduction in grain yield in the presence of weeds can be attributed to interspecific competition between crop and weed growth factors (Esmaeilzadeh & Aminpanah, 2015). This might probably be due to shade provided by weed canopy on the dry bean, which might have filtered sun radiation for photosynthesis (Ghamari & Ahmadvand, 2012) or the shade provided by the sweet sorghum.

Simultaneously sowing of cereal and a grain legume might affect the performance of the legume biomass and the grain yield (Nassary et al., 2020b). Delayed growth before flower setting is one of the bean traits rather than delayed development, pods production, smaller seed size, particularly during adverse environmental conditions (Nassary et al., 2020a). Weed interference throughout the vegetative growth stages of common bean prompts the shade avoidance response, which negatively affects the bean performance, resulting in irretrievable depleted CO<sub>2</sub> assimilation, photosynthesis efficiency, and yield. The inhibition of photosynthesis is attributed to the biochemical limitation to the Calvin Cycle (McKenzie-Gopsill et al., 2020). McKenzie-Gopsill et al. (2020) further stated that all these could be avoided given that the common bean is kept weed-free throughout the vegetative growth stages. Moreover, the depletion in photosynthesis and gas exchange correlates with common bean yield during vegetative growth stages.

It is worth noting that dry bean was diseased in the 2018/19 growing season; this could be the other reason for the difference of the measured variables between the two seasons. Past research showed that flowering, pod setting, and maturation of grain legume as intercrops could coincide

with high precipitation resulting in high diseases and pest pressure, thus reducing grain yield due to early planting, whereas poor grain yields of the grain legume were the outcome of late planting due to the late onset of rainfall (Kermah et al., 2018). Bean pods produced per plant influence grains and yield; hence, cropping systems are supposed to be a pivotal factor to consider in each agro-ecological zone (Nassary et al., 2020a). Depending on weeds severity, the greater light competition in high weed density explains bean grain reduction compared to low weed density (Tollenaar et al., 1994). The increase in the crop productivity of incompatible crop species in an intercropping system is linked with facilitation, sharing, and complementarity in resource acquisition and efficient utilization (Brooker et al., 2015).

The current study results support Esmailzadeh & Aminpanah (2015) who reported that grains per pod and pods per plant were lower under weed-infested environments than weed-free environments. Tapetal degeneration for the dry bean is common, particularly in higher temperatures where photosynthesis declines with excessive flower drop and pollen sterility, negatively affecting grains per pod and pods per plant (Muñoz-Perea et al., 2006). In all weed pressure levels, bean leaf area and leaf chlorophyll increased linearly with an increase in N rate application (Saberli & Mohammadi, 2019). Shading affects far-red radiation than red-radiation hence high plant height under weed interference (Röhrig & Stützel, 2001). Smith (1986) reported that neither cell division nor node formation rate changes were observed under weed interference on stem elongation but increased cell division.

The provisioned shade by weeds or sweet sorghum canopy on dry beans might have reduced sun radiation for photosynthesis (Ghamari & Ahmadvand, 2012). Furthermore, most C3 plants, such as dry beans, are sensitive to limited moisture stress, especially under weed interference (Bukun, 2004). As a result, it affects the development of leaves and causes a reduction in the dry bean leaf area index; it probably minimizes the capacity to photosynthesize, consequently

decreasing its production capability, affecting yield components (Ghamari & Ahmadvand, 2013).

Land equivalent ratio (LER) values were affected by intercropping and weeding frequency. The intercropped treatments had above one LER value than sole cropping treatments except for some treatments under no weed control, which means intercropping was superior to sole cropping. Legumes intercropped with legumes or legumes intercropped with cereals yielded higher LER values, which could suggest that the crop species complement each other by efficiently acquiring growth resources or soil phosphorus (P) (Latati et al., 2016). Higher LER for grain yield was reached in the P-deficient than P-sufficient soil (Latati et al., 2016), which indicates that intercropping is more advantageous under low soil fertility conditions (Michael Kermah et al., 2017).

The PCA ordination clustered the measured dry bean attributes accordingly with the treatments. Moreover, it showed a consistent relationship between 100-grain weight, grain yield and 50 DWACE over seasons. The diseased dry bean during the 2018/19 growing and the difference amount of rainfall received over the seasons might have contributed to the inconsistency of the number of leaves per plant, plant height, dry biomass, pods per plant, and chlorophyll content with DB/CP inter-row intercropping, 50 DWACE, and sole dry bean.

### **3.6 Conclusion**

Dry bean growth traits were significantly affected by intercropping patterns and weeding frequency. Intercropping patterns significantly affected the dry bean height and pods per plant. The impact of weeding frequency on dry bean's significant measured attributes showed an increasing trend as weeding frequency increased but somehow remained not significant between intermediate weeding frequency and weed-free, particularly during the second growing season. Weed control for 50 DAE is critical for maximizing dry bean production under dry bean/ sweet sorghum or cowpea intercropping. Further implementation of weed control after 50 days after crop emergence could increase crop injury, thus affect dry bean growth performance or increase unnecessary labour costs. However, it is recommended that future research should focus on more long-term trials in different regions to observe the dry bean performance in sweet sorghum or cowpea intercropping under weed interference. More growing seasons are needed to answer the questions about which dry bean agronomic traits stabilizes in intercropping pattern and weed interference after a certain period.

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## CHAPTER 4

### INTERACTION OF WEED MANAGEMENT TIMING AND AGRONOMIC PERFORMANCE INDICATORS FOR COWPEA

#### 4.1 Abstract

The effects of an intercropping pattern on cowpea [*Vigna unguiculata* (L.) Walp.] growth and grain yield were studied in sweet sorghum or dry bean intercropping under weed interference. A Randomised Complete Block Design (RCBD) with a split-plot treatment structure replicated three times was used for the study at Ukulinga Research and Training farm of the University of KwaZulu-Natal in Pietermaritzburg, South Africa during 2017/18 and 2018/2019 growing season. Each plot consisted of three cropping systems (sole crop cropping, inter-row, and intra-row intercropping) and three weed management levels (no weeding, weeding during the first 50 days of crop growth, and weeding over the whole period of crop growth). Results indicated that intercropping pattern had significant ( $P < 0.05$ ) effects on cowpea dry biomass and the number of pods plant<sup>-1</sup> during the 2017/18 growing season and grain yield during the 2018/19 growing season. Weeding frequency significantly ( $P < 0.05$ ) affected cowpea 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, height, and the number of leaves per plant during the 2017/18 growing season and chlorophyll content during the 2018/19 growing season. All the significant measured cowpea attributes increased as weeding frequency increased; however, remained insignificant between intermediate and high weeding frequency. No significant interaction effect was observed in each of the seasons. Intra-row intercropping significantly improved cowpea dry biomass, pods plant<sup>-1</sup> than inter-row intercropping and sole cropping. The intra-row intercropping and intermediate weeding frequency are entirely adequate for maximizing cowpea production.

Keywords: cowpea, dry biomass, intercropping pattern, weeding frequency

## 4.2 Introduction

Cowpea (*Vigna unguiculata* (L.) Walp.) is an essential and nutritious grain legume mostly grown and consumed by smallholder farmers in tropical and temperate zones (Raina & Khan 2020). The nutritious leaves are harvested and consumed as a fresh vegetable or dried and consumed later (Namatsheve et al., 2020; Owade et al., 2019). However, the harvesting of the leaves significantly affects grain yield (Owade et al., 2019). It is also valued as a multipurpose crop with significant grain and fodder quality yields (Samireddypalle et al., 2017; Snapp et al., 2018). Cowpea (CP) is often grown in interspersed rows with widely spaced sorghum (*Sorghum bicolor* L. Moench) within the same row or alternate rows (Snapp et al., 2018). Its drought tolerance trait makes it a critical and resilient legume crop useful for overcoming food security constraints caused by climate change (Santos et al., 2020). Despite all the potential economic returns of cowpea as a subsistence and commercial crop, several constraints, such as weeds, diseases and insect pest, limit its production (Tadele, 2017). Generally, cowpea is susceptible to weed interference, particularly during the first few weeks after emergence (Osipitan et al., 2016).

Over-reliance on agrochemicals for weed and pest control is an obstacle to sustainable agriculture; hence, the ramifications threaten the environment and human health (Zhang et al., 2018). Sustainable weed control strategies such as intercropping are critical. Intercropping is the interaction of two or more different crop species grown in the same land simultaneously for a significant part of the crop cycle (Maitra et al., 2021) in the inclusion of legumes. Although intercropping can be utilized as a potential chemical-free strategy to manage weeds, optimum weed control cannot be achieved by relying on a single method (Weerarathne et al., 2017). Due to high variability in soil type, climate condition, growth habits, and weeds' morphology, no sole weed control strategy is feasible in alleviating problematic or resistant weeds; however, integrating more than two weed control strategies is likely to be effective (Osipitan, 2017). Therefore,

intercropping's positive impact on weed suppression occurs when spatial and temporal compatibility of the intercrop integration is achieved (Weerarathne et al., 2017). Moreover, the adoption of intercropping helps to utilize resources needed by weeds, which leads to reduced weed growth (Brooker et al., 2015), consequently minimizing herbicide application. Adopting appropriate weed management strategies is pivotal for improved technologies' potential benefits to materialize (Mishra & Talwar 2020).

Hand weeding is the preferred weeding technique to control weeds in small-scale farming, but it is very labour-intensive (Hussain et al., 2018). Therefore, it is vital to integrate hand weeding with other weed control mechanisms, particularly agronomic methods such as intercropping. Integrating intercropping at optimum row spacing and hand hoe weeding has been demonstrated to provide feasible weed control (Jabran et al., 2017). Crop-weed competition is determined by the crop's growth habit, where a rapid canopy cover of a crop reduces weed density (Weerarathne et al., 2017). The effects of weeds on crop yield depends on the duration of the interference and the life history stage of the weed-crop system at which the interaction occurs (Knezevic et al., 2003). The idea of a critical period of weed control emerged to determine the duration at which weed-free must be maintained in a growing season to avert undesirable yield loss (Knezevic et al., 2002). Several factors such as unimproved local varieties, low soil fertility, limited moisture and other biotic and abiotic stresses (Horn & Shimelis 2020), low moisture, and various insect pests, diseases, and weeds (Tadele, 2017) are linked to low yield. Weeds compete with the crops for limited growth resources such as moisture, nutrients and light (Mishra & Talwar 2020).

Likewise, it has been reported that fertilizer application significantly affects weed composition, density, and biomass (Yin et al., 2005); however, nitrogen (N) deficiency is one of the renowned hurdles of soil characteristics that leads to yield reduction (Stewart et al., 2019). The inclusion of biological N fixing legumes such as CP in an intercropping system is critical for soil fertility improvement. As estimated, CP can fix 240 kg ha<sup>-1</sup> of atmospheric N with approximately 60–70

kg ha<sup>-1</sup> N replaced for the following growing season (Kebede and Bekeko 2020). The previous study showed that CP monocropping systems had a high 57 kg N ha<sup>-1</sup> total fixed N due to higher biomass production than intercrops 36 kg N ha<sup>-1</sup> (Namatsheve et al., 2020).

Weed interference significantly affects the growth and yield of any crop; thus, a better understanding of crop-weed interaction would improve weed management options, especially in the intercropping systems. It is worth noting that CP and sweet sorghums (SS) are underutilized legumes and cereal crops in South Africa, yet both have capabilities required for weed suppression. A better understanding of the effects of intercropping pattern and weeding frequency on CP and SS or dry bean (DB) in an intercropping system is vital, particularly in response to sustainable agriculture echoes. The study objectives were to assess inter-row and intra-row intercropping effects on CP growth performance in CP/ SS or (DB) intercropping under different weed pressure.

## 4.3 Materials and methods

### 4.3.1 *The experimental site, design and trial management*

A field experiment was conducted at Ukulinga Research and Training farm of the University of KwaZulu-Natal in Pietermaritzburg, South Africa (29°39'56.''S 30°24'26.2''E), altitude 791 m. The research farm received an annual rainfall of 644–838 mm and had an average temperature of 18.4°C during 2017/18 and 2018/2019 growing seasons.

A randomized complete block design (RCBD) with a split-plot treatments structure comprising 27 treatments replicated three times totalling 81 plots, was used for the experiment. The crops used were: cowpea (*Vigna unguiculata* L. Walp.) variety Agrinawa, dry bean (*Phaseolus vulgaris* L.) cultivar Ukulinga, and sweet sorghum (*Sorghum bicolor* L. Moench) variety Supasweet II. Twenty-seven treatment combinations composed of three subplot intercropping patterns (sole crops, inter-row, and intra-row) and three main plot weeding frequencies (no weeding after emergency = 0%; weeding during the first 50 days of crop growth = 50% and weeding over the whole period of crop growth =100%) were tested. A complete description of land preparation, sowing treatments, plot layout, soil analysis, field procedures and climatic conditions was described by (Baker et al., 2021).

### 4.3.2 Data collection

The data collected were the total 100-grain weight, dry biomass, number of grain yield grains per pod, number of pods per plant, plant height, number of leaves per plant and chlorophyll content. To determine biomass production, whole plants were harvested from 1.44 m<sup>2</sup> then sun-dried for three weeks for dry biomass weight. Plant height was based on the average height of four plants plot<sup>-1</sup> using a meter ruler.

Eight plants were sampled per plot on sole cropping on the cowpea, amounting to an area of 1.44 m<sup>2</sup> on sole and intercropping systems. Grain yield was determined by removing the dry pods from

plants and air-drying them. The grains were removed from the dry pods (12% moisture content determined using a moisture meter), and their mass was recorded to obtain grain yield per square meter.

Land equivalent ratio (LER) was determined using the equation as shown below;

$$\text{LER} = \text{IC}/\text{SC} + \text{IS}/\text{SS} \dots\dots\dots (1)$$

Above-ground dry biomass was used to determine LER, where IC denotes intercropping cowpea, SC denotes sole cowpea cropping, and IS denotes intercropping sweet sorghum, SS denotes sole sweet sorghum cropping.

$$\text{LER} = \text{IC}/\text{SC} + \text{ID}/\text{SD} \dots\dots\dots(2)$$

Grain yield was used to determine LER, where IC denotes intercropping cowpea, SC denotes sole cowpea cropping, and ID denotes intercropping dry bean, SD denotes sole dry bean cropping.

### 4.3.3 Statistical analysis

Analysis of variance (ANOVA) was used to compare the effects of intercropping pattern and weed frequency on cowpea 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, plant height, number of leaves per plant and chlorophyll content using GEN STAT version 18. The standard error of the difference (SED) and least significant difference (LSD) were used for mean separation when treatments were significantly different ( $P < 0.05$ ).

#### **4.4 Results**

The results indicated that intercropping pattern had significant ( $P < 0.05$ ) effect on CP dry biomass and pods per plant during the 2017/18 growing season (Table 4.1). The results also showed that weeding frequency had significant ( $P < 0.05$ ) effect on CP 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, plant height, and the number of leaves per plant (Table 4.1). Moreover, intercropping pattern  $\times$  weed frequency interaction effects were not significant in all the treatments during the 2017/18 growing season (Table 4.1).

**Table 4.1.** Analysis of variance of cowpea measured variables during the 2017/18 growing season

Source of variation	Intercropping pattern	Weeding frequency	Intercropping pattern × weeding frequency	Residual	CV
	df				
	4	2	8	28	
	ms	ms	ms		
<b>100-grain weight</b>	17.2 ns	72.8 **	20.47 ns	10.36	21.4
<b>Dry biomass</b>	150,38 *	1291,02 **	43,42 ns	42,58	42.2
<b>Grain yield</b>	1,0855 ns	9,1983 **	0,8116 ns	0,6413	51.2
<b>Grains pod<sup>-1</sup></b>	8.824 ns	28.723 **	5.212 ns	5.073	20.4
<b>Pods plant<sup>-1</sup></b>	401.8 *	4774.1 **	208.5 ns	113.4	35.6
<b>80 DAE height</b>	72.65 ns	1504.91 **	18.69 ns	68.13	27.0
<b>60 DAE number of leaves</b>	5.12 ns	21.59 *	4.75 ns	5.71	19.5
<b>80 DAE number of leaves</b>	72.65 ns	590.41 **	18.69 ns	68.13	7.0

ns: not significant; \*,\*\* significant at  $P < 0.05$ ,  $P < 0.001$  probability levels, respectively; ms=- mean square; df= degree of freedom; CV= coefficient of variation.

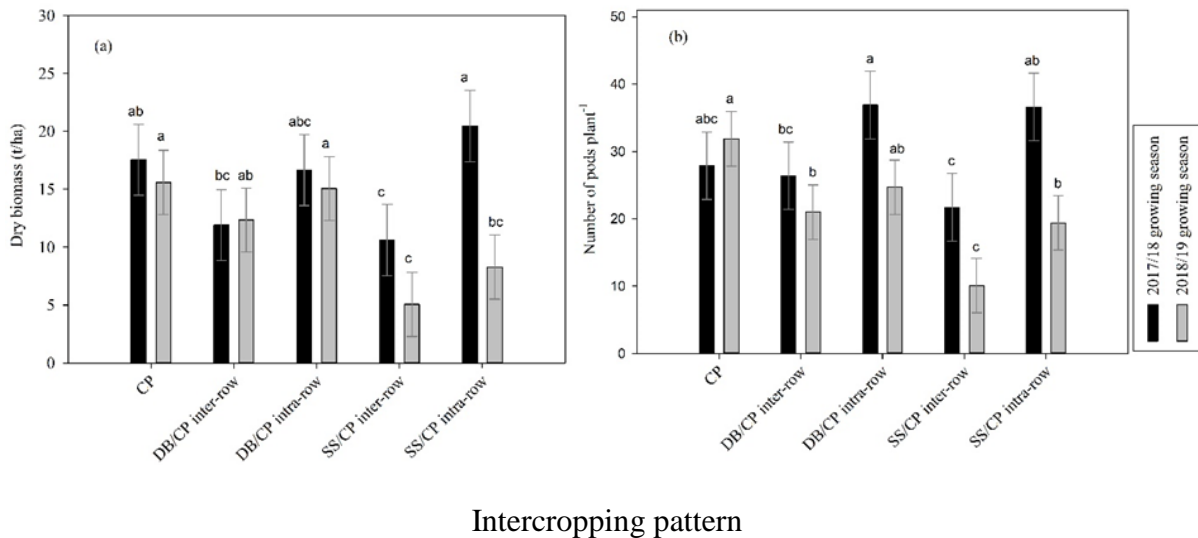
The findings of the analysis of variance show that intercropping pattern had a significant ( $P < 0.05$ ) effect on CP dry biomass, grain yield, pods per plant only during the 2018/19 growing season (Table 4.2). On the other hand, the weeding frequency had a significant ( $P < 0.05$ ) effect on CP 100-grain weight, dry biomass, grain yield, plant height, grains per pod, pods per plant, number of leaves per plant, and chlorophyll content during the 2018/19 growing season (Table 4.2). No significant interaction effect was observed during the 2018/19 growing season (Table 4.2).

**Table 4.2.** Analysis of variance of cowpea measured variables during the 2018/19 growing season

Source of variation	Intercropping pattern	Weeding frequency	Intercropping pattern × weeding frequency	Residual	CV
	df				
	4	2	8	28	
	ms	ms	ms		
<b>100-grain weight</b>	61.66 ns	181.03 **	23.41 ns	25.43	37.3
<b>Dry biomass</b>	184,01 **	995,07 **	54,46 ns	34,64	52.2
<b>Grain yield</b>	1,42 *	11,93 **	0,47 ns	0,36	47.0
<b>Grains pod<sup>-1</sup></b>	19.1 ns	107.14 **	8.99 ns	13.42	36.2
<b>Pods plant<sup>-1</sup></b>	572.22 **	2724.12 **	83.36 ns	73.47	40.0
<b>80 DAE height</b>	49.30 ns	207.74 *	40.67 ns	41.81	19.8
<b>60 DAE number of leaves</b>	35.99 ns	184.09	15.07 ns	19.03	29.2
<b>80 DAE number of leaves</b>	139.23 ns	353.90 *	66.77 ns	79.58	29.4
<b>40 DAE Chloro</b>	63.09 ns	250.49 **	31.09 ns	42.93	13.5

ns: no significant; \*,\*\* significant at  $P < 0.05$ ,  $P < 0.001$  probability levels, respectively; ms-= mean square; df= degree of freedom; CV= coefficient of variation.

Intercropping pattern had significant influence on CP dry biomass (Fig 4.1a). The CP/SS intra-row intercropping resulted in the highest dry biomass, and CP/SS inter-row intercropping had the lowest dry biomass during the 2017/18 growing season (Fig 4.1a). In the 2018/19 growing season, the highest dry biomass was observed on sole CP and DB/CP intra-row intercropping, whereas CP/SS inter-row intercropping had the lowest dry biomass (Fig 4.1a).



**Fig 4.1.** Effect of intercropping pattern on cowpea (a) dry biomass and (b) pods plant<sup>-1</sup> during the 2017/18 and 2018/19 growing seasons. The error bars denote SED.

The results showed a significant difference in the number of pods per plant (Fig 4.1b). The CP/DB and CP/SS intra-row intercropping had significantly higher number of pods per plant while the CP/SS inter-row had the lowest pods per plant during the 2017/18 growing season (Fig 4.1b). During the 2018/19 growing season, sole CP had the highest number of pods per plant, and CP/SS inter-row intercropping had the lowest number of pods per plant (Fig 4.1b).

Weeding frequency had a significant effect on CP 100-grain weight; the 0% weeding frequency had significantly lower 100-grain weight; however, the weight increased as the weeding frequency increased to 50% weeding frequency but remained insignificant between intermediate and high weeding frequency during the 2017/18 and 2018/19 growing seasons (Fig 4.2a).

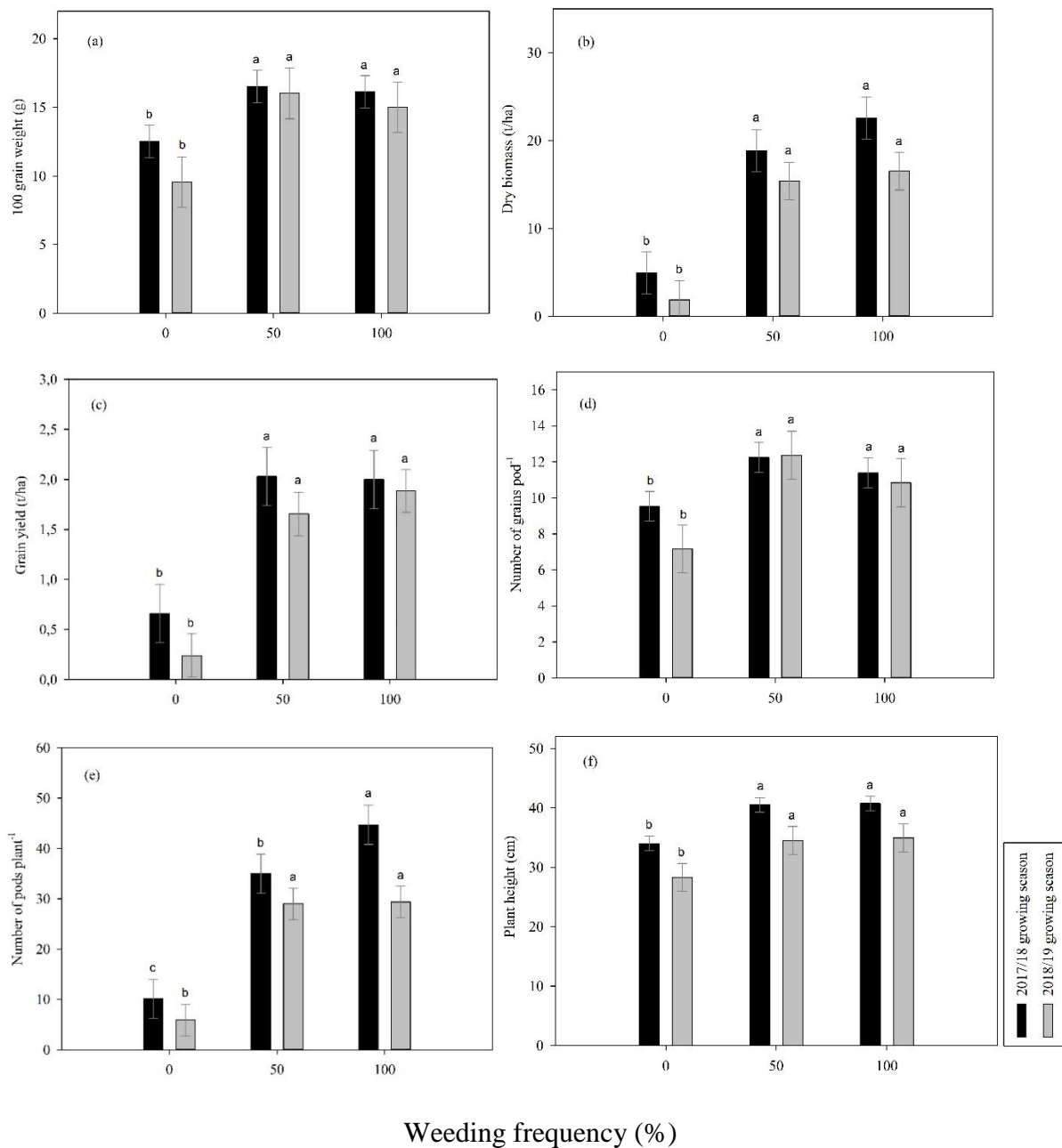
Weeding frequency significantly affected CP dry biomass as 0% weeding frequency had the lowest dry biomass, and the dry biomass increased as weeding frequency increased during the 2017/18 and 2018/19 growing seasons (Fig 4.2b).

The results indicated that weeding frequency significantly influenced grain yield; 0% weeding frequency had a significantly lower grain yield. However, grain yield increased as weeding frequency increased during the 2017/18 and 2018/19 growing seasons (Fig 4.2c).

Weeding frequency significantly affected CP grains per pod (Fig 4.2d). The 0% weeding frequency had the lowest number of grains per pod while the highest number of grains per pod was recorded at the 50% weeding frequency and slightly decreased at 100% weeding frequency over seasons (Fig 4.2d).

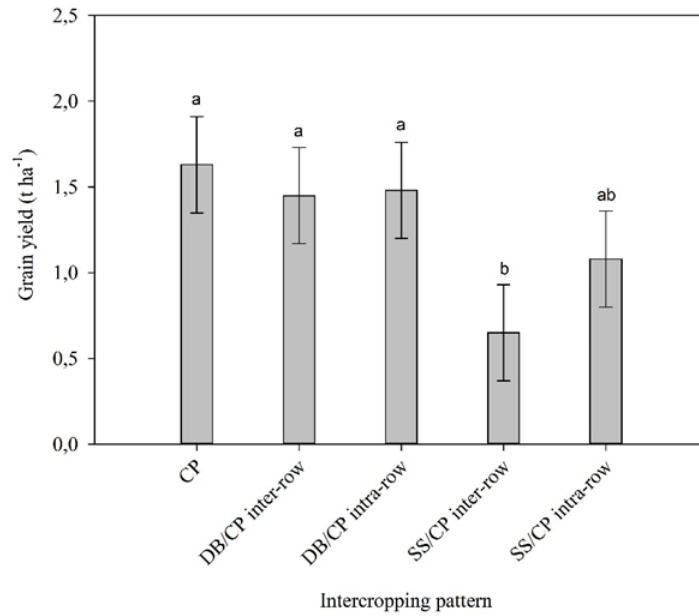
Furthermore, the weeding frequency affected the number of CP pods per plant; the number of pods per plant increased as weeding frequency increased from 0% to 50% and 100% weeding frequency during the 2017/18 and 2018/19 growing seasons (Fig 4.2e).

The results revealed that weeding frequency significantly affected CP height at 80 DAE during the 2017/18 and 2018/19 growing season only as such the highest CP height was observed in 50% and 100% weeding frequency and significantly declined as weeding frequency reduced (Fig 4.2f).



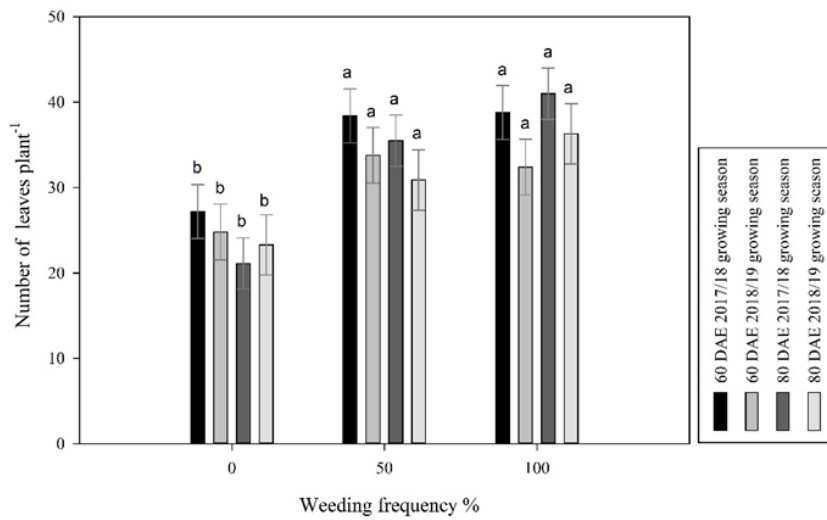
**Fig 4.2.** Weeding frequency effect on cowpea (a) 100-grains weight, (b) dry biomass, (c) grain yield, (d) grains per pod, (e) pods per plant, (f) plant height in the 2017/18 and 2018/19 growing season. The error bars denote SED.

The CP/SS inter-row intercropping had a significantly lower grain yield, while sole CP cropping, CP/DB inter-row, and intra-row intercropping had the highest grain yield (Fig 4.3).



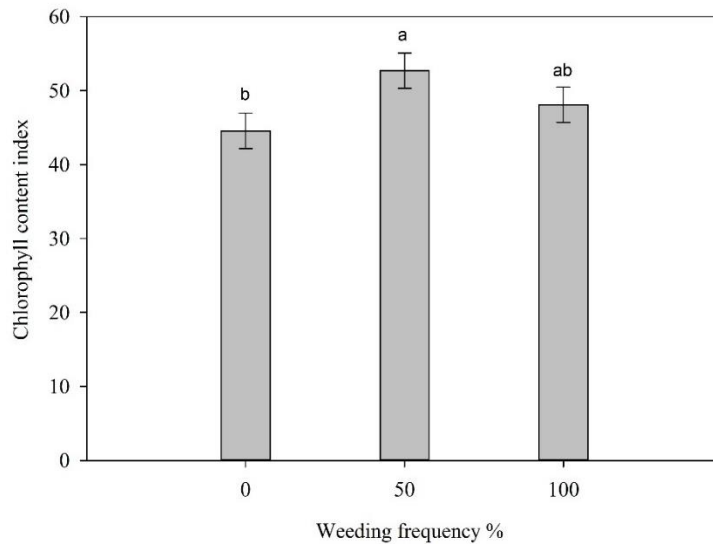
**Fig 4.3.** Intercropping pattern effect on cowpea grain yield under different weed interference. The error bars denote SED.

The number of leaves per plant significantly increased as weeding frequency increased but remained not significant between intermediate and 100% weeding frequency (Fig 4.4).



**Fig 4.4.** Weeding frequency effects on cowpea number of leaves per plant for 2017/18 and 2018/19 growing season. The error bars denote SED

The cowpea's chlorophyll content index increased as weeding frequency increased at 40 DAE during the 2018/19 growing season; however, the results showed not significant difference between 50% and 100% weeding frequency (Fig 4.5). The cowpea's chlorophyll content index across treatments remained insignificant after 40 DAE during the 2018/19 growing season.



**Fig 4.5.** Weeding frequency effect on chlorophyll content during the 2018/19 growing season. The error bars denote SED.

During the 2017/18 growing season, the LER value ranged between 0.97 and 3.75, whereas, in the 2018/19 growing season, the LER value ranged between 1.10 and 2.45 (Table 4.3). The 2017/18 growing season analysis showed that CP/DB intra-row combined with 50% weeding frequency resulted in a higher LER (3.75) than other treatments, while in the 2018/19 growing season, CP/SS intra-row together with 50% weeding frequency resulted in higher LER (2.45) than other treatments (Table 4.3). Intercropping pattern and weeding frequency influenced the LER values; however, the intra-row intercropping pattern had greater values than the inter-row intercropping pattern (Table 4.3).

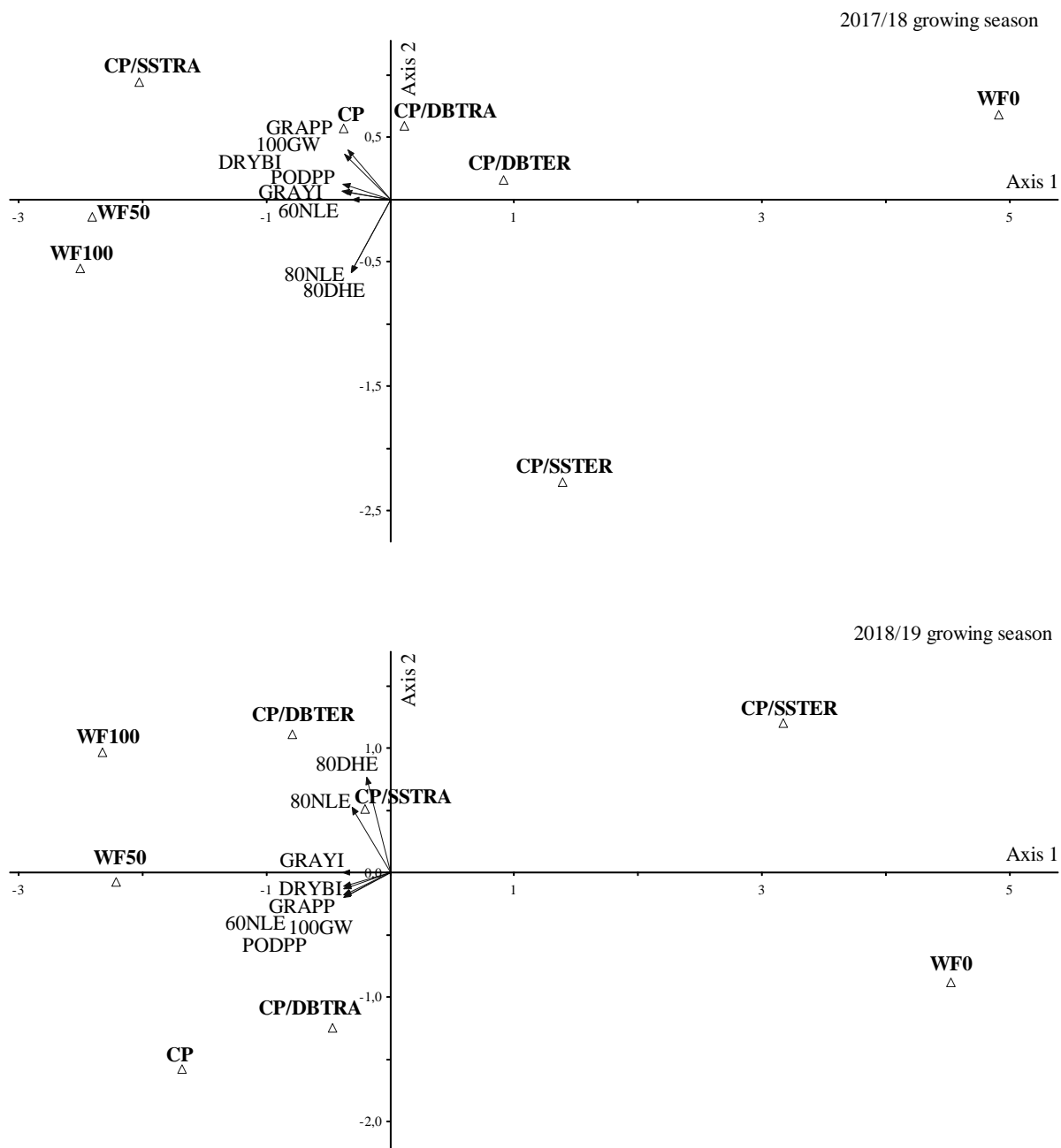
**Table 4.3.** Cowpea, sweet sorghum and dry bean, and LER for 2017/18 and 2018/19 growing season

Growing season	Cropping pattern	Weeding frequency %			Total plot	Yield type t/ha
		0	50	100		
2017/18	CP/DB inter-row	-	1.72	1.03	1.60	Grain
	CP/DB intra-row	1.15	3.75	1.43	2.13	
	CP/SS inter-row	0.97	1.91	1.51	1.61	Dry biomass
	CP/SS intra-row	1.48	2.69	2.29	2.26	
2018/19	CP/DB inter-row	0.13	2.27	1.67	1.71	Grain
	CP/DB intra-row	0.10	2.38	1.67	1.73	
	CP/SS inter-row	1.16	1.60	1.28	1.36	Dry biomass
	CP/SS intra-row	1.65	2.45	1.85	2.47	

CP, cowpea; DB, dry bean; SS, sweet sorghum

The principal component analysis (PCA) provides a better insight into the impact of intercropping pattern and weeding frequency on cowpea 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, plant height, number of leaves per plant (Fig 4.6). These findings provide an essential indication of the factors to be considered to increase CP yield as cultivated in intercropping under weed interference. The PCA was used to assess correlations between 100-grain weight, dry biomass, grain yield, grains per pod, pods per plant, 60 and 80 DAE plant height, 60 and 80 DAE number of leaves, 80 DAE chlorophyll and 0%, 50%, and 100% weeding frequency, sole CP, CP/SS inter-row intercropping, CP/SS intra-row intercropping, CP/DB inter-row intercropping, CP/DB intra-row intercropping. The first and second principal components explained 74.30% - 13.06% and 77.78% - 15.35% during the 2017/18 and 2018/19 growing season of the data variation, respectively (Fig 4.6).

The PCA analysis showed that grains per plant and 100-grain weight correlated with sole CP and SS/CP intra-row intercropping during the 2017/18 growing season (Fig 4.6). Grain yield and dry biomass, pods per plant and 60 DAE number of leaves per plant were more correlated with the 50% weeding frequency. During the second growing season 2018/19, 80 DAE number of leaves per plant and height correlated with CP/SS intra-row intercropping and CP/DB intercropping. Grain yield was associated with 50% weeding frequency. Grain per plant, dry biomass, pods per plant, 60 DAE number of leaves, and 100-grain weight were associated with sole CP cropping (Fig 4.6).



**Fig 4.6.** The principal component analysis of intercropping pattern and weeding frequency on cowpea growth performance under CP/SS or DB intercropping. Measured variables are indicated by vectors from the first axis and second axis 100GW= 100 grain weight, 80DCH= 80 DAE chlorophyll, DRYBI = dry biomass, GRAYI= DB grain yield, 60DHE= 60 DAE height, 80DHE= 80 DAE plant height, GRAPP= grains per pod, 60NLE=60 DAE number of leaves, 80NLE = 80 DAE number of leaves, PODPP= pods per plant. WF0 = 0% weeding frequency, WF50 = 50% weeding frequency, WF100 = 100% weeding frequency, CP = sole cowpea,

CP/DBTER = cowpea/dry bean inter-row intercropping, CP/DBTRA = cowpea/dry bean intra-row intercropping, CP/SSTER = cowpea/sweet sorghum inter-row intercropping, CP/SSTRA = cowpea/sweet sorghum intra-row intercropping.

#### **4.5 Discussion**

Sustainable weed control strategies are critical to meeting agriculture's potential to feed the world's growing population while conserving ecosystems and biodiversity (MacLaren et al., 2020). In simplified agroecosystems such as intercropping, crop and weed competition is possible mainly in an environment where growth factors are limited (Kocira & Staniak 2021). Many plants require the same growth factors to blossom; however, various plants utilize growth factors at different developmental stages rather than simultaneously, hence coexistence. Nonetheless, in abundant environmental resources, there could be minimal competition between crops and weeds. However, abundant environmental resources also benefit weeds to produce more biomass, thus boosting weeds to become severer competitors against crops as weed canopies and root zones overlap (MacLaren et al., 2020).

The significant dry biomass accumulation and the number of pods plant<sup>-1</sup> could be attributed to CP and SS compatibilities for growth factors such as light, moisture, and nutrients. The removal of weeds within the first 45 days could have put the cowpea on the advanced level to become a stronger competitor against weeds; hence higher cowpea biomass was achieved at intermediate and 100% weeding frequency. The findings suggest that CP could have utilized the available growth resources, possibly with little interplant competition (Legwaila et al., 2019). According to Sogoba et al. (2020) high biomass is achievable with long season varieties and early planting dates. Therefore, the selection of competitive cultivars or varieties and the use of increased plant densities negatively influence light interception by weeds (Gholami et al., 2013).

The grain yield results contrast with those of Sogoba et al. (2020), who reported that cowpea as an intercrop had low yields, and 75% were below 500 kg ha<sup>-1</sup>. These different findings could be due to different soil fertility, climatic zones, plant density, cultivars or varieties. Caution should be taken as hand hoe weeding after ground cover and during the reproductive stage could lead to yield reduction due to physical injury to CP (Adigun et al., 2014). Past research showed that taller crops in intercropping affect the understorey legumes' photosynthetic rate, leading to low yield (Namatsheve et al., 2020). However, other studies have shown that cultivating CP in association with cereals in arid and semi-arid zones leads to competition for soil nutrients, water, and light, leading to decreased crop productivity (Nelson et al., 2018).

Muthusankaranarayanan & Pandian (2017) pointed out that weeds deplete active photosynthesis radiation, affecting photosynthesis and shortening the lives of lower leaves; furthermore, the understorey crops then produce thin pale green leaves with reduced vascular bundles and meristem cells due to shading by taller crops or weeds.

The significant increase of chlorophyll as weeding frequency increased could probably be due to reduced competition for resources. According Hakim et al. (2013), these results indicate that the chlorophyll content (SPAD value) declined as weed interference prolonged.

The LER's and PCA analysis outcomes showed inconsistent LER values and correlation between the measured cowpea attributes as affected by intercropping and weeding frequency. This could probably be due to the different rainfall over the season. Past research showed that rainfall positively correlated to crop yields (Rossato et al., 2017). Moreover, all the intercropping treatments had LER above 1.0 except 0% weeding frequency, signifying that intercropping was advantageous over sole cropping.

## 4.6 Conclusion

Cowpea responded to intercropping patterns and weeding frequency. The SS/CP and DB/CP intra-row intercropping had the highest dry biomass accumulation and the number of pods plant<sup>-1</sup> compared to other treatments; however sole CP had the highest number of pods plant<sup>-1</sup> during 2018/19 growing. The study showed that the intermediate weeding frequency positively influenced cowpea's 100-grains weight, dry biomass, grain yield, grains per pod, pods per plant, and plant height increased over the growing seasons. The intra-row intercropping was more advantageous than inter-row and sole cropping since intra-row intercropping had above 2 LER values. The intercropping pattern and intermediate weeding frequency are essential for maximizing cowpea production.

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## CHAPTER 5

### RESPONSE OF WEED BIOMETRIC INDICATORS TO INTERCROPPING AND WEEDING FREQUENCY

#### 5.1 Abstract

The extensive use of herbicides to control weeds has led to herbicide resistance, environmental pollution, and human health issues. Therefore, intercropping has been advocated as an alternative sustainable weed control technology to reduce weed pressure on crop yield. To assess the effects of intercropping pattern and weeding frequency on growth and diversity of weed species, a randomized complete block design with a split-plot treatment structure consisting of three cropping systems (sole cropping, intra-row and inter-row intercropping) and three weeding frequencies (no weed control, weeding during the first 50 days after emergence and weeding throughout the crop growth), replicated three times were used. Results showed that during the 2017/18 growing season, weed frequency significantly ( $P < 0.05$ ) affected weed biomass while other treatments remained insignificant. During the second growing season 2018/19, intercropping pattern significantly ( $P < 0.05$ ) affected weed dry biomass, density, species diversity, species evenness, and richness. These significant measured variables were also observed in weeding frequency. Furthermore, intercropping pattern x weeding frequency interaction was significant ( $P < 0.05$ ) on weed dry biomass and species evenness. Sole cowpea and dry bean/cowpea intercropping had the highest weed species diversity and species evenness. On the other hand, weed species diversity and richness decreased as weeding frequency increased. As anticipated, weed dry biomass and density decreased as weeding frequency increased. The interaction effect of sweet sorghum with either dry bean or cowpea and intermediate weeding frequency was significantly beneficial to weed suppression.

Keywords: intercropping, weeding frequency, weed diversity, weed biomass, weed density

## 5.2 Introduction

Weeds are a significant cause of crop production losses, and the intensive reliance on herbicides for their control causes significant environmental and health issues. Therefore, sustainable approaches to reducing reliance on herbicide for weed control are imperative (Petit et al., 2018) before irreversible damage to the environment and humans (Sharma et al., 2021). Intercropping, the simultaneously growing two or more crops in the same area throughout the crop cycle, is a possible solution (Engbersen et al., 2021). Intercropping has been advocated as a sustainable agricultural practice that can control weed pressure by reducing the resources available for weeds (Stefan et al., 2021; Stomph et al., 2020).

Past research demonstrated that intercrop biomass and weed biomass are inversely propositional; as intercrop biomass accumulation increased, weed biomass declined; moreover, weed density was lower under intercropping than sole cropping with many weed species (Cheriere et al., 2020; Sharma & Banik, 2013). Several factors influence weed dynamics in intercropping systems, viz planting density, row spacing, and crop species selection (Bainard et al., 2020). The choice of the intercropped species and the spatial arrangement are critical aspects that influence the level of competition between weeds and crops for weed control (Cheriere et al., 2020). The positive effects of intercropping on weed suppression were found in the dryland areas (Sharma et al., 2021), with relatively high nitrogen availability than lower nitrogen availability (Stoltz & Nadeau, 2014). Pest and disease control is possible under intercropping (Nur Arina et al., 2021) by creating a microclimate that changes host morphology and physiology; and direct pathogen inhibition (Boudreau, 2013), thus helps to reduce disease intensity. Despite the potential benefits of intercropping on weed suppression, no single weed control method is sufficient to control weeds effectively due to high weed species diversity and survival strategies; thus, weeds adapt very well when controlled with a single weed control strategy (Knezevic et al., 2017).

Therefore, flexible strategies are required, particularly involving the basic agronomical logic of cropping systems and the production context and other potential strategies that could enhance biological weed control (Petit et al., 2018). It would be very beneficial to integrate the efficacy of intercropping on weed suppression with the hand hoe weeding approach. To ease the weed control pressures caused by increasing urbanization, increased labour costs, and decreasing workforce in agriculture, particularly in developing countries where weeding is mainly done manually (Chauhan, 2020; Sharma et al., 2021), thus, adopting certain sustainable agronomic practices such as intercropping is critical. The yield advantages in intercropping systems are primarily attributed to complementary utilization of resources; however, few studies examined nutrient acquisition and biomass production (Engbersen et al., 2021). Focusing on which weed species grow better in which crop combination could be pivotal to more targeted weed control approaches (Stefan et al., 2021).

Above- and below-ground are the two-mode of competition within the crop-weed competition, with the former crops compete for light; thus, shading provided by taller plants affect the quantity and quality of light transmitted into the canopy while the latter weeds can be impacted by competition for nutrients and water, altogether can affect the root and shoot production (Petit et al., 2018). Growth of shoots results in a higher competitive ability for light, whereas growth of roots results in a higher competition ability for nutrient and water uptake (Petit et al., 2018). Understanding these dynamics could help to improve the perception to predict successful species combinations for intercropping systems and maximize the advantages of intercropping as a realistic alternative to current monoculture-based agricultural systems (Engbersen et al., 2021).

The study explored the potentials of cultural and mechanical weed control approaches by combining two aspects intercropping pattern and weeding frequency on weed growth. Understanding the weed population's abundance and distribution could aid in determining weed population shifting over a given period in response to selected pressures applied by certain

agronomic practices (Nkoa et al., 2015). Thus, mitigating and eradicating ecological, environmental, and social externalities associated with the over-reliance on herbicide use could be pivotal to design and advocate alternative sustainable weed management strategies (Sharma et al., 2021). The selection of crops that vary in the exploitation of environmental resources could optimize intercropping systems while maximizing compatibility and minimizing competition (Stomph et al., 2020). Cultural weed control through intercropping systems remains a difficult hurdle (Andert, 2021). The objective of this study was to assess the integrated effects of intercropping patterns and weeding frequency on weed growth.

### **5.3 Materials and methods**

#### **5.3.1 Study site**

Field experiments were conducted during the summer of 2017/18 and 2018/19 growing seasons at Ukulinga Research and Training farm of the University of KwaZulu-Natal in Pietermaritzburg, South Africa (29°39'56.6"S 30°24'26.2"E), altitude 791 m. The average annual rainfall ranged from 644 mm to 838 mm and had an average temperature of 18.4°C.

A randomized complete block design (RCBD) in a split-plot treatment structure comprising 27 treatments replicated three times, totalling 81 plots, was used for the experiment. The crops used were cowpea (CP) (*Vigna unguiculata* L. Walp.) variety Agrinawa, dry bean (DB) (*Phaseolus vulgaris* L.) cultivar Ukulinga, and sweet sorghum (SS) (*Sorghum bicolor* L. Moench) variety Supasweet II. Twenty-seven treatment combinations composed of three intercropping patterns (sole crops, inter-row, and intra-row) and three weeding frequencies (no weeding after emergency=0%; weeding during the first 50 days of crop growth=50% and weeding over the whole period of crop growth=100%) were tested. A complete description of land preparation, sowing treatments, plot layout, soil analysis, and climatic conditions were epitomized (Conrad Baker et al., 2021).

### 5.3.2 Data collection, analysis for weed flora and diversity

After crop harvest, two quadrats of 1 m<sup>2</sup> were randomly placed in each plot to determine weed density and biomass. All weed species inside the quadrat were cut at the soil surface, counted and classified by species. The weed samples were oven-dried at 50 °C for five days to attain constant dry weight (Baker et al., 2018).

The assessment of weed species response to intercropping pattern and weeding frequency was achieved through relative importance value (%) (RIV) expressed as a percentage. The relative importance value was determined by the sum of relative frequency and relative density divided by the sampled unit. Relative frequency was determined as the number of target weed species in the sampling unit divided by the total number of weed species sampled in the sampling unit as expressed as a percentage. Relative density was calculated as the number of individuals of target weed species sampled divided by the surface area of the sampling unit (Travlos et al., 2018). The RIV was achieved through the following equation:

$$\text{RIV} = \frac{\text{relative frequency} + \text{relative density}}{2}$$

The RIV of 10 or less are classed as outstanding (Chikoye & Ekeleme, 2001). Species diversity, usually described by two essential constituents (richness and evenness), denotes the different species within a community. Species richness, the number of species present, whereas evenness, reveals how the existing species dominate the community or whether these species are represented by approximately equal numbers (Nkoa et al., 2015). Shannon–Wiener ( $H'$ ) and Pielou ( $E$ ) indices were calculated using the following equations (Pielou, 1975).

$$H' = \frac{N \ln N - \sum(n \ln n)}{N}$$

where  $H'$  is species diversity through the proportion of the abundance of species, with a higher value suggesting greater diversity,  $N$  is the total number of individual weed species per quadrat, and  $n$  is the population of individual of each weed species observed in the area.

Evenness index ( $E$ ) was computed as:

$$E = \frac{H'}{\ln N}$$

$E$  is the relationship between the observed number of species and the total number of species; for evenness, zero values indicate that the community is exceptionally uneven (dominated by one species). A value of one indicates that the community is even (maximum diversity exists, no single species dominates) (Nkoa et al., 2015)

### 5.3.3 Statistical data analysis

The weed density and biomass data were square root ( $x + 0.5$ ) transformed before analysis to homogenize variances. Analysis of variance (ANOVA) was used to compare intercropping pattern and weeding frequency effects on weed density, biomass, and weed species diversity using GENSTAT statistical software version 18. Mean comparison and separation were achieved by using the standard error of the difference (SED) and the significant ( $P < 0.05$ ). Principal component analysis (PCA) was used to evaluate the intercropping pattern and weeding frequency effects on weed measured variables. The PCA is a distance-based ordination method used mainly to display patterns in multivariate data, patterns recovered are solely a function of relationships between the dependent variables (Syms, 2019).

## 5.4 Results and discussion

The weeding frequency had a significant ( $P < 0.05$ ) effect on weed biomass only; however, the main effects of intercropping pattern, as well as the interaction between the two factors, were not significant during the 217/18 growing season (Table 5.1). Intercropping pattern and weeding frequency had a significant ( $P < 0.05$ ) effect on weed biomass, density, species evenness, and species richness during the 2018/19 growing season (Table 5.1). There was significant interaction ( $P < 0.05$ ) effects between intercropping pattern  $\times$  weeding frequency on weed biomass and species evenness during the 2018/19 growing season (Table 5.1).

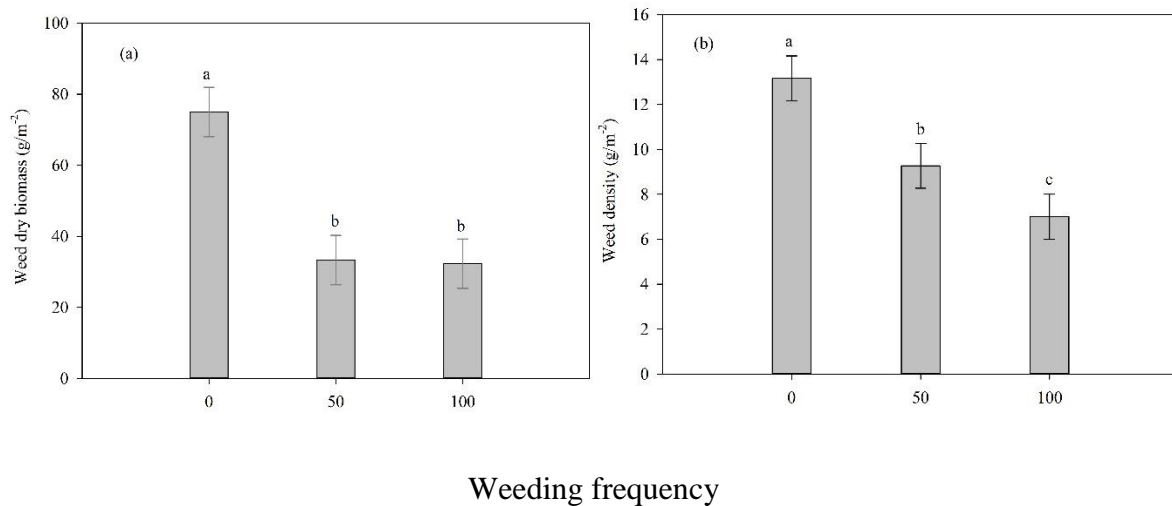
**Table 5.1.** Analysis of variance of weed dry biomass during the 2017/18 growing season and weed dry biomass, density, diversity, evenness, and richness during the 2018/19 growing season.

Source of variation	df	2017/18 growing season		2018/19 growing season			
		Dry biomass	Dry biomass	Density	Diversity	Evenness	Richness
		ms					
Intercropping pattern	8	1097.7 ns	197140 **	80.63 **	0.8078 **	0.001091 **	136.92 **
Weeding frequency	2	16049.6 **	2177412 **	261.91 **	2.6298 **	0.002631 **	164.33 **
Cropping pattern × weeding frequency	16	489.1 ns	49151 **	7.87 ns	0.0939	0.000465*	23.77 ns
Residual	52	655.7	26211	13.54	0.1247	0.000232	13.1
CV		54.7	58.7	37.5	19.6	3.7	36.9

ns: not significant; ms: means square; CV: Coefficient of variation; \* , \*\*, significant at 0.01 and 0.05 probability levels, respectively.

The results showed that weed frequency significantly affected weed biomass during the 2017/18 growing seasons (Fig 5.1a). The weed biomass was higher at 0% weeding frequency and decreased as the weeding frequency increased at 50% and 100%; however, there were no significant differences between intermediate and 100% weeding frequency during the 2017/18 growing season (Fig 5.1a). Similar trends were also observed between weed frequency; however, there were significant differences between intermediate and 100% weeding frequency (Fig 5.1b). The modification of N dynamics by mechanical weeding could probably affect plant growth (Gilbert et al., 2009), including weeds.

Setting up the crops on the advanced stage to acquire growth resources could probably limit resources available for weed, thus resulting in weed pressure reduction (Stefan et al., 2021). Above all, moisture availability could be the limiting factor for weed growth than light, affecting the efficacy of row spacing in a dry environment rather than a moisture-saturated environment (Bainard et al., 2020). Petit et al. (2018) explained that there is a dependence on crop-weed competition processes to acquire growth resources; any limited resource leads to other resources to be partially exploited, e.g. detrimental effects of moisture competition could be exacerbated by insufficient nutrient absorption.

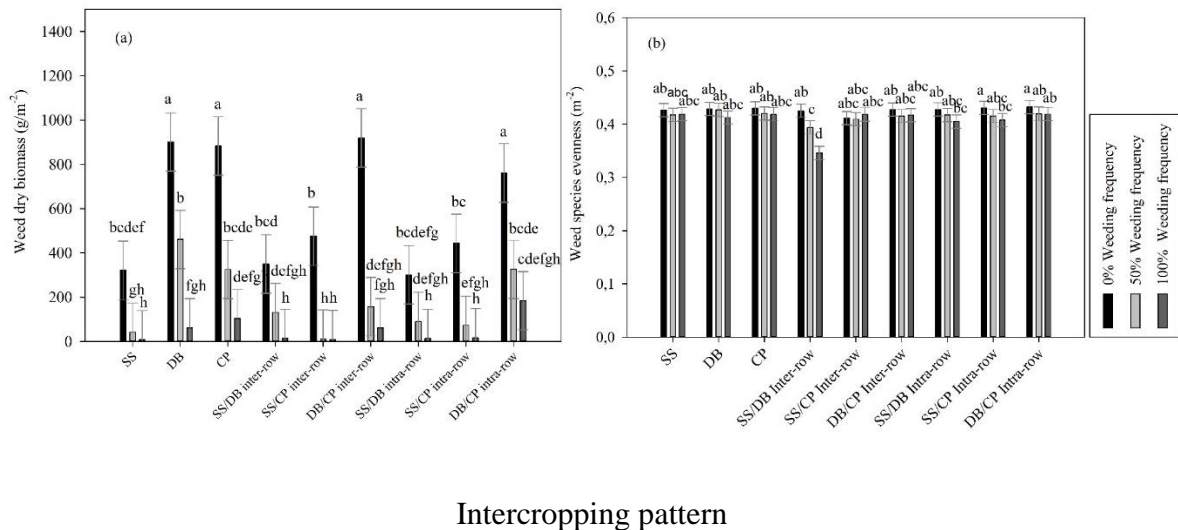


**Fig 5.1.** Weeding frequency effect on (a) weed biomass 2017/18 growing season and (b) weed density 2018/19 growing season.

The sole DB, CP and DB/CP inter-row, DB/CP intra-row intercropping had significantly high weed biomass compared to sole SS and SS/DB, SS/CP inter-row and intra-row intercropping at 0% weeding frequency (Fig 5.2a). The results showed that intercropping sweet sorghum with either dry bean or cowpea significantly reduced weed biomass compared to legume/legume intercropping, particularly at 0% weeding frequency (Fig 5.2a). These results reaffirm (Sharma & Banik, 2013) finding that the greater the crop biomass, the higher the weed suppression. Also, Cheriére et al. (2020) reported that high total intercrop biomass in the first part of the crop cycle was associated with low weed biomass. The high weed biomass on legume/legume intercropping could be explained by the legume's ability to fix N<sub>2</sub>; consequently, the large amount of soil N could be freely available for weeds utilization (Cheriére et al., 2020). Canopy height has been shown to be a pivotal factor in plant competition for light (Violle et al., 2009). This explains the efficacy of sweet sorghum/ legume intercropping on weed biomass. Crop height determines weed-crop competition when the weed community is dominated by tall weed species (Cheriére et al., 2020). Traoré et al. (2003) demonstrated that shading by sorghum decreased weed biomass due to a high leaf area index. The broad but low canopy of legumes

might also have reduced light levels for shorter weeds (Sharma & Banik, 2013). It was noted that weed density was higher in broader spatial arrangements due to unsuppressed weed growth by crop plants (Ali et al., 2017).

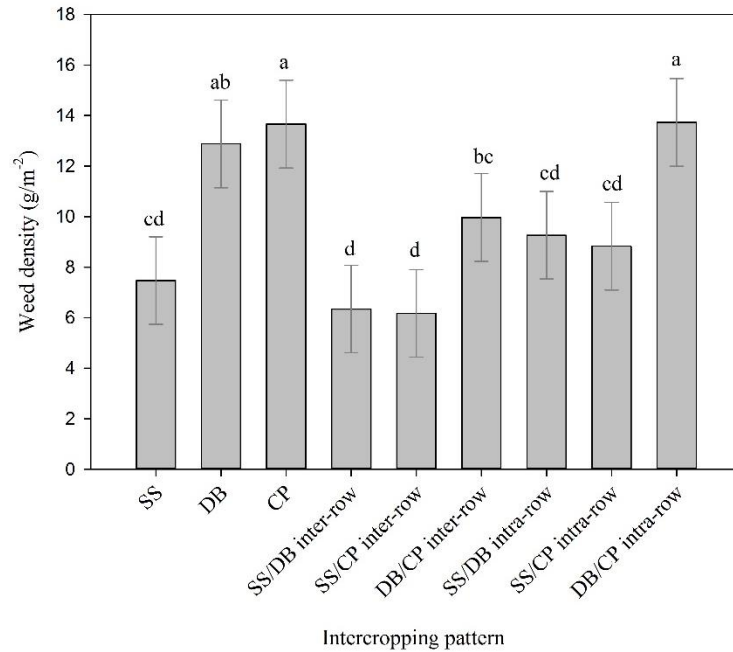
Intercropping pattern  $\times$  weeding frequency had a significant interaction effect on weed species evenness; thus, SS/DB inter-row intercropping had the lowest weed species evenness, particularly at 100% weeding frequency but increased as weeding frequency decreased (Fig 5.2b). The results align with (Sharma & Banik, 2013) findings that weed evenness was higher in intercrops than sole, however, in this study except for SS/DB inter-row intercropping.



**Fig 5. 2.** Intercropping interaction  $\times$  weeding frequency effects on weed biomass and weed species evenness 2018/19 growing season.

The intercropping pattern had a significant effect on weed density (Fig 5.3). Specifically, weed density was lower on SS treatments than a sole DB, CP, or DB/CP intercropping (Fig 5.3). Sole cropping had a significant high weed density compare to intercrops (Sharma & Banik, 2013). Thus, sweet sorghum is an appropriate plant species to suppress weeds when intercropped with dry bean or cowpea. Stoltz and Nadeau (2014) reported that weed incidence was reduced under intercropping systems than sole cropping. Hauggaard-Nielsen et al. (2001) found increased

efficiency of intercropping for the utilization of environmental resources for plant growth and better competitive ability towards weeds compared with sole crops. The involvement of cereals as intercrop could boast the potential benefits of intercropping on weed suppression (Stefan et al., 2021).



**Fig 5. 3.** Intercropping pattern effect on weed density during the 2018/19 growing season.

The DB/CP intra-row intercropping, sole DB, and CP had significant higher weed species diversity compared to sole SS and SS/DB, SS/CP inter-row and intra-row intercropping (Table 5.2). The SS/legume intercropping significantly affected weed species diversity compared to legume/legume intercropping (Table 5.2). Intercropping pattern significantly affected weed species richness; the highest weed species richness was observed in sole cowpea and DB/ intra-row intercropping only (Table 5.2). The lowest weed species richness was observed in sweet sorghum/cowpea inter-row intercropping (Table 5.2). The restriction of incident photosynthetic active radiation (PAR) reaching weeds might also explain the decreased species diversity of weed communities in intercropping systems (Sharma & Banik, 2013). Shading by dominant crop produces thinning or mortality effects on individuals of subordinate weed

species, consequently reducing richness in weed species (Goldberg & Miller, 1990). Shading may also inhibit the germination of some species by inducing secondary dormancy in seeds, which could be caused by modifying either the light quality by the canopy or the amplitude of the soil temperature (Arnold et al., 1988). Species diversity of weed community was modified differently by crop treatments. Species number decreased significantly, but evenness increased in intercropping systems than their respective sole cropping systems. The results agree with Stefan et al. (2021) that Shannon's diversity index was lower in the presence of cereals.

**Table 5.2.** Intercropping pattern effect on weed species diversity and richness 2018/19 growing season.

<b>Intercropping pattern</b>	<b>Weed species diversity</b>	<b>Weed species richness</b>
SS	1.63 cde	6.58 d
DB	2.07 ab	12.69 ab
CP	2.16 a	15.55 a
SS/DB inter-row	1.37 e	6.20 d
SS/CP inter-row	1.42 de	5.13 d
DB/CP inter-row	1.89 abc	10.73 bc
SS/DB intra-row	1.76 bc	7.72 cd
SS/CP intra-row	1.73 cd	8.40 cd
DB/CP intra-row	2.18 a	15.13 a

SS: sweet sorghum; DB: dry bean; CP: cowpea; means with different letters denote significant different

Weeding frequency significantly affected weed species diversity; the highest weed species diversity was observed at a 0% weeding frequency and declined as weed frequency increased (Table 5.3). Furthermore, the highest weed species evenness was observed at 50% weeding frequency and significantly declined at 100% weed frequency (Table 5.3).

**Table 5.3.** Weeding frequency effect on weed species diversity and weed species evenness during the 2018/19 growing season

Weeding frequency %	Weed species diversity	Weed species richness
0	2.12 a	10.34 a
50	1.78 b	11.96 a
100	1.50 c	7.11 b

Means with different letters denote significant different

Relative importance value explored the composition of the most dominant weed species in the intercropping pattern and weeding frequency. A total of 18 weed species were identified during the 2017/18 growing (Table 5.4) and 17 weed species during the 2018/19 growing season (Table 5.5). Out of the identified 18 weed species across the treatments, only eight weed species (*Commelina benghalensis*, *Bidens pilosa*, *Ipomoea purpurea*, *Alternanthera pungens* Kunth, *Tagetes minuta*, *Cyperus rotundus*, *Ribes uva-crispa*, *Stenotaphrum secundatum*) were dominant, whereas, the other weed species were less dominant with RIV <10% (Table 5.4). These weed species dominance were also observed during the second growing season but with higher values. The *Commelina benghalensis* had the highest relative importance value RIV 31.68% in SS/DB intra-row intercropping (Table 4), whereas during the second growing season 2018/19, *Biden pilosa* had the highest RIV of 261.81% in DB/CP intra-row intercropping (Table 5.5). Interestingly, *Commelina benghalensis*, *Alternanthera pungens* Kunth and *Datura stramonium* were absent during the second growing season; however, there were substituted by *Portulaca oleracea*, *Amaranthus hybridus* and *Schkuhria pinnata* (Lam.) Kuntze ex Thell (Table 5.5). The *Bidens pilosa*, *Ipomoea purpurea*, *Galinsoga parviflora*, *Tagetes minuta*, *Cyperus rotundus*, *Ribes uva-crispa* and *Amaranthus hybridus* were much more evenly distributed, indicating the absence of a distinct dominant weed species. These weeds species dominated sole legume cropping and legume/legume intercropping than cereal/legume

intercropping as indicated by higher values of RIV% (Table 5). The degree to which a crop reduces species diversity, abundance and the number of propagules produced by the survivor weeds during its growing period would be reflected in the following crops or seasons (Sharma & Banik, 2013). Generally, weed species that grow in the field at high densities and frequencies have a high potential to cause crop yield losses (de Mol et al., 2015).

**Table 5.4.** The relative importance value (RIV %) of the aboveground weed species observed under intercropping pattern and weeding frequency during the 2017/18 growing season

Common name	Scientific name	Sole cropping			Inter-row intercropping			Intra-row intercropping		
		SS	DB	CP	SS/DB	SS/CP	DB/CP	SS/DB	SS/CP	DB/CP
Benghal wandering jew	<i>Commelina benghalensis</i>	21.2	14.7	21.3	14.9	22	13.7	31.7	18.2	13.7
Black nightshade	<i>Solanum nigrum</i>	0	3.1	4.4	7.4	3.4	0	1.5	4.6	6.3
Bobbin weed	<i>Leonotis martinicensis</i> (Jacq.)	0	0	1.5	1.7	2.2	1.5	1.5	1.5	0
Common blackjack	<i>Bidens pilosa</i>	11.3	12.8	15.1	13.5	10.6	10.8	10.3	17.5	7.5
Common morning glory	<i>Ipomoea purpurea</i>	19.8	27.2	23.4	18.4	18.2	22.5	17.5	8.5	22.7
Gallant Soldier	<i>Galinsoga parviflora</i>	6.8	7.4	1.5	4.8	1.5	2.9	3.9	2.4	0
Khaki burr weed	<i>Alternanthera pungens</i> Kunth	9.6	6.3	1.7	13.6	13.2	4.3	8.7	7.7	3.4
Khaki weed	<i>Tagetes minuta</i>	21.1	19.2	13.4	13.3	12.5	11.3	14.1	15.1	8.4
Purple nutsedge	<i>Cyperus rotundus</i>	21.9	23.9	6.4	15	17.4	14.9	20.2	5.5	17.2
Small mallow	<i>Malva parviflora</i>	0	1.5	0	1.9	0	0	3.3	0	0
Thorn apple	<i>Datura stramonium</i>	0	0	0	1.5	2.9	0	1.5	0	0
White goosefoot	<i>Chenopodium album</i>	0	0	0	2.4	0	0	0	0	0
Wild gooseberry	<i>Ribes uva-crispa</i>	10.8	8.9	7.7	10.8	12.5	7.9	13.5	10.4	4.1
Spiny Sowthistke	<i>Sonchus asper</i>	0	0	0	1.7	0	0	1.7	0	0
Arrow-leaf sida	<i>Sida rhombifolia</i>	1.5	2.4	4.8	1.5	1.9	1.9	6	0	1.7
Narrow-leaved ribwort	<i>Plantago lanceolata</i>	0	1.9	0	0	0	0	0	0	0
Common buffalo grass	<i>Stenotaphrum secundatum</i>	19.1	18.4	10.3	12	10.1	8.9	7.7	10.9	8.8
Perennial pigweed	<i>Amaranthus deflexus</i>	2.2	9.3	2.6	6	3.6	2.2	3.1	8.1	4.8
Other		0	0	0	0	1.7	0	0	0	0

**Table 5.5.** The relative importance value (RIV %) of the aboveground weed species observed under weed interference and intercropping pattern system during the 2018/19 growing season.

Common name	Scientific name	Sole cropping			Inter-row intercropping			Intra-row intercropping		
		SS	DB	CP	SS/DB	SS/CP	DB/CP	SS/DB	SS/CP	DB/CP
Black nightshade	<i>Solanum nigrum</i>	6.2	13.3	2.9	5.5	4.8	5.5	0	7.9	10.1
Bobbin weed	<i>Leonotis martinicensis</i> (Jacq.)	0	0	0	1.5	0	0	0	0	2.2
Common blackjack	<i>Bidens pilosa</i>	53.5	109.9	157.8	32.7	9.3	105	131.1	94.2	261.8
Common morning glory	<i>Ipomoea purpurea</i>	10.8	63.5	52.2	12.3	9.6	31.4	10.6	16.2	38.3
Gallant Soldier	<i>Galinsoga parviflora</i>	36.2	64.1	72.1	22.4	24.1	46.7	51	42.7	66.6
Khaki weed	<i>Tagetes minuta</i>	27.3	48.3	43.6	4.3	15.5	10.2	24.2	12.2	34.2
Purple nutsedge	<i>Cyperus rotundus</i>	20.5	42.4	80.5	13.6	18.2	19.3	28.5	16.4	18.5
Purslane	<i>Portulaca oleracea</i>	0	0	2.9	0	0	0	0	0	0
Small mallow	<i>Malva parviflora</i>	1.5	0	6.1	2.4	0	6.5	0	4.1	3.4
White goosefoot	<i>Chenopodium album</i>	0	34.5	6.9	1.5	8.8	5.5	1.7	1.5	1.5
Wild gooseberry	<i>Ribes uva-crispa</i>	6.7	24.7	36.3	38.3	20.4	32.3	13.5	19.2	7.4
Spiny Sowthistle	<i>Sonchus asper</i>	0	6.6	0	0	0	0	0	0	0
Arrow-leaf sida	<i>Sida rhombifolia</i>	0	1.5	6	0	1.7	4.3	7.2	9	2.4
Narrow-leaved ribwort	<i>Plantago lanceolata</i>	2.2	10.8	8.2	5	0	9	8.4	9.8	10.5
Common buffalo grass	<i>Stenotaphrum secundatum</i>	1.9	12.3	11.4	5.8	1.7	1.7	3.9	3.6	12.5
Smooth pigweed	<i>Amaranthus hybridus</i>	8.1	19.8	34.4	2.9	20	17.9	3.9	2.4	34.3
Dwarf marigold	<i>Schkuhria pinnata</i> (Lam.) Kuntze ex Thell.	0	0	0	0	0	0	0	0	1.5
Other		4.3	18.3	10.8	9.4	3.9	4.6	4.8	13.6	19.3

Principal component analysis (PCA) was performed for data exploration. The PCA first and the second axis had the percent of total variation explained as 23.34% and 18.63% and 30.89% and 20.67% during the 2017/18 and 2018/19 growing seasons, respectively (Fig 5.4). Direction cosines are critical to interpreting PCA results because they indicate the relative contribution of each variable to the significant structural trends (ordination axes) underlying the data (Kenkel et al., 2002). The PCA outcome showed a nonreciprocal effect between intercropping pattern, weeding frequency and weed species composition over the growing seasons. The SSDB/TER correlated with *Alternanthera pungens* Kunth, *Sonchus asper* and *Chenopodium album*, whereas WF100 was associated with *Galinsoga parviflora*, *Amaranthus deflexus*, *Stenotaphrum secundatum* and *Cyperus rotundus* during 2017/18 growing season. Moreover, *Leonotis martinicensis* and *Commelina benghalensis* had a strong relationship with SSDBTRA and SSCPTER. The DBCPTER intercropping was the only variable that was found to be at least marginally associated with *Ipomoea purpurea*, *Portulaca oleracea*, *Chenopodium album*, *Malva parviflora*, *Plantago lanceolata*, *Cyperus rotundus* and *Sida rhombifolia*, during the second growing season (Fig 5.4). The different amounts of precipitation received over the growing seasons could have contributed to the PCA outcome's inconsistency.

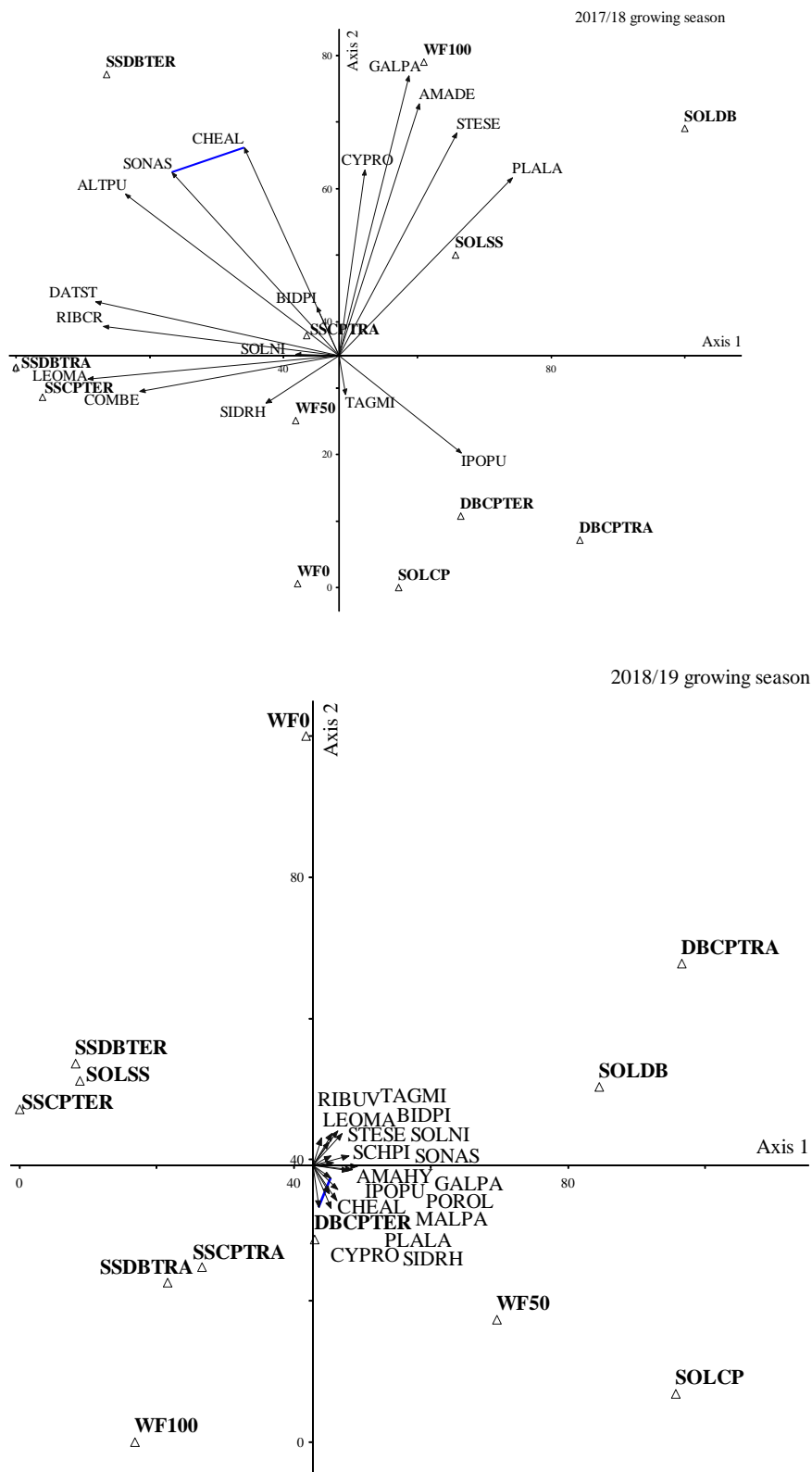


Fig 5. 4 Principal component analysis (PCA) ordination diagram representing the association of aboveground weed species with intercropping pattern and weeding frequency. Measured variables are indicated by vectors on the first and second axis. SIDRH= *Sida rhombifolia*,

COMBE = *Commelina benghalensis*, SOLNI = *Solanum nigrum*, LEOMA = *Leonotis martinicensis* (Jacq.), BIDPI = *Bidens pilosa*, STESE = *Stenotaphrum secundatum*, IPOPU = *Ipomoea purpurea*, GALPA = *Galinsoga parviflora*, ALTPU = *Alternanthera pungens* Kunth, TAGMI = *Tagetes minuta*, PLALA = *Plantago lanceolata*, AMADE = *Amaranthus deflexus*, CYPRO = *Cyperus rotundus*, SONAS = *Sonchus asper*, DATST = *Datura stramonium*, CHEAL = *Chenopodium album*, RIBCR = *Ribes uva-crispa*, SCHPI = *Schkuhria pinnata* (Lam.) Kuntze ex Thell, AMAHY = *Amaranthus hybridus*, POROL = *Portulaca oleracea*, MALPA = *Malva parviflora*; WF0 = 0% weeding frequency, WF50 = 50% weeding frequency, WF100 = 100% weeding frequency; SOLSS = sole sweet sorghum, SOLCP = sole cowpea, SOLDB = sole dry bean, DBCPTER = dry bean/cowpea inter-row intercropping, DBCPTRA = dry bean/cowpea intra-row intercropping, SSCPTER = sweet sorghum/cowpea inter-row intercropping, SSCPTRA = sweet sorghum/cowpea intra-row intercropping, SSDBTER = sweet sorghum/dry bean inter-row intercropping, SSDBTRA = sweet sorghum/ dry bean intra-row intercropping

## 5.5 Conclusion

The efficacy of intercropping on weed suppression was apparent in sweet sorghum/ dry bean or cowpea intercropping than in sole cropping systems. Intercropping dry bean/cowpea was an unsuitable combination for weed suppression, and the biological fixed N could have benefited weeds, thus high weed biomass. The sweet sorghum/ dry bean or cowpea intercropping and intermediate weeding frequency significantly reduced weed biomass. The sole cowpea and dry bean/cowpea intercropping had the highest weed species diversity and richness; however, weed species diversity and species richness declined as weeding frequency increased.

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## CHAPTER 6

### GENERAL DISCUSSION AND RECOMMENDATIONS

#### 6.1 Introduction

The mounting concerns about environmental and human health issues associated with over-reliance on pesticides are strong motivations for research on how to manage weeds with less or no herbicides while optimizing crop productivity (Colbach et al., 2020). Weeds are detrimental to agricultural activities. However, the small-scale farmers' economic limitation has led to the reliance on hand hoe for weed control. Therefore, redesigning cropping systems for sustainable weed control is pivotal to ease the intensive reliance on herbicides while maximizing crop production. This study was able to confirm the importance of adopting certain sustainable agronomic practices such as intercropping combined with mechanical weed control methods such as hand hoeing in an integrated system. However, any strategy in which a crop is used to manage weeds is considered a sustainable weed control practice, and such strategies need to be integrated with other tools to achieve sustainable weed management effectively (Chauhan, 2020). Intercropping, as one of the sustainable weed control technologies, and it has been emphasized that intercrops were associated with greater yields and pest and weed control compared with sole crops (Szumigalski & Acker, 2005). Most cropping system experiments were designed to examine the feasibility of the systems with various objectives such as reducing pesticide use or increasing crop diversity while maintaining profitability and decreasing impact on soil structure with the exclusion of weed assessment (Giuliano et al., 2016). However, a good understanding of particular cropping system impact on weed dynamics in the inclusion of weed assessment is pivotal for improving sustainable weed control.

## **6.2 Sweet sorghum response to legume intercropping under weed interference**

### *Intercropping pattern effects on sweet sorghum*

The manipulated environmental resources in crop production also benefit weeds; however, a successful weed management strategy aims to put crops on the advantage level to utilize the optimal environmental resources over weeds (Dille, 2017). It has been stated in (Chapter 5) that all the treatment combinations remained insignificant except for the weeding frequency impact on dry biomass during the 2017/18 growing season. During the second growing season 2018/19, the results showed that intercropping pattern significantly affected weed density; however, sole sweet sorghum, sweet sorghum/dry bean intercropping, and sweet sorghum/cowpea inter-row intercropping had the lowest weed density during the 2018/19 growing season (Chapter 5). On the other hand, sole dry bean, sole cowpea and dry bean/cowpea intra-row intercropping had the highest weed density. Past research showed that weed diversity mitigates winter wheat yield loss and that not all weed communities are detrimental to crop productivity (Adeux et al., 2019).

Moreover, the projection of yield loss based on weed density is futile since yield loss positively correlates with weed variables influencing crop-weed competition than weed density (Colbach et al., 2020). Simple weed metrics are not sufficient to explain yield loss, as recent research studies reported that yield loss decreases with increasing diversity and richness in the weed community (Adeux et al., 2019). This research study showed that in the presence of sweet sorghum, all intercropping treatments reduced weed species diversity and richness (Chapter 5). These could explain the impact of sweet sorghum on weed suppression. By the end of this two-year study, the intercropping pattern and weeding frequency influenced the weed community, leading to different weed communities. The significant differences in weed species diversity and richness found indicated that while the weed community may change due to differential

crops and weeding frequencies, the total number of weed species and relative abundance remained changed. After the first growing season, the shift observed in the weed community seemed to be driven by the crop's competitive ability and characteristics, including the weeding frequency.

The two-way ANOVA results indicated that intercropping pattern x weeding frequency interaction significantly affected weed biomass and weed species evenness (Chapter 5). All the sole components and intercropping treatment combinations had high weed biomass at 0% weeding frequency; however, the weed biomass declined as weeding frequency increased but remained insignificant between intermediate weeding frequency and 100% weeding frequency. Furthermore, the results showed that sweet sorghum could suppress weed as the sole component and intercrop; as revealed in Chapter 5, in the absence of sweet sorghum, all legume treatments had the highest weed biomass, particularly at 0% weeding frequency. The findings also showed that sweet sorghum fresh biomass was lowest at 0% weeding frequency; however, it increased as weeding frequency increased throughout the treatment combinations, excluding sweet sorghum/ dry bean intra-row intercropping (Chapter 3). This could emphasize the importance of early weed control; hence, a complete canopy cover impedes weed growth, negatively affecting weed biomass or seeds production (Chauhan, 2020). The combinations of inter or intra-row intercropping and 50% weeding frequency were more effective in reducing weed biomass, as can be evidenced in (Chapter 5). Despite attaining higher yields on measured crop variables under 100% weeding frequency, this treatment achieved similar results in reducing weed density and biomass with 50% weeding frequency. Therefore, under unpredictable and variable site conditions, increasing crop diversity, even with only three common field crops, allows for a more flexible response to the environment, more consistency in grain yield, and enhanced weed suppression ability and reliability (Szumigalski & Acker, 2005).

### *Weeding frequency effect on sweet sorghum*

The statistically significant response of variables measured for sweet sorghum and weed as affected by weeding frequency showed that the high weed biomass accumulation or density resulted in higher Brix % content, lower sweet sorghum's dry and fresh biomass, lower plant height and the number of leaves. The weed diversity and species richness observed at 0% weeding frequency could also explain the high accumulation of Brix content. Understanding the ecological processes that drive weed density or biomass and influencing these is an essential element in an ecological weed management framework (MacLaren et al., 2020).

### **6.3 Intercropping pattern and weeding frequency effects on legume yield and growth**

The combination of sweet sorghum/ dry bean intra-row intercropping x 50% or 100% weeding frequency tended to produce more significant weed suppression than sole component crops, indicating synergism among crops within intercrops on weed suppression (Chapter 3). These increased dry beans 100-grain weight, dry biomass, the number of leaves per plant, and plant height as weeding frequency increased. The higher dry bean dry biomass accumulation was observed at sole dry bean and significantly increased as weeding frequency increased (chapter 3). Nevertheless, the results showed that sole cowpea and cowpea/ dry bean intra-row had higher dry biomass and the number of pods per plant (Chapter 4). Sole crops can differ spatially, resulting in more complementary and efficient use of resources than when grown in monocultures (Liebman & Dyck, 1993). In the absence of sweet sorghum, dry bean dry biomass accumulation was significantly higher on legume-to-legume treatments. On average, weed biomass was highest in the legume-to-legume intercrop treatments and highest in the 0% weeding treatment. Gaps in the canopy cover and height might have allowed for high weed growth in the legume treatments, generally having lower light interception values than the other intercrop treatments (Szumigalski & Acker, 2005). Lower weed biomass in intercrops

compared with sole crops with similar crop production would provide further evidence that the component crops of an intercrop produce a synergistic effect concerning weed suppression (Mohler & Liebman, 1987). However, the study revealed that sole legume components and dry bean/cowpea intra-row intercropping had higher weed species diversity and richness. Facilitation (Vandermeer, 1989) is a term used to represent the suite of possible mechanisms for the weed suppression effect of intercropping, which might not be directly related to the enhanced productivity of the intercrops. Given the generally low weed biomass accumulation in the uncontrolled weed plots, the effect of crop treatments on weed biomass likely uninfluenced weed-crop interference, however, could affect weed seed return and weed dynamics in the longer term (Grundy et al., 2004).

#### *Weeding frequency effect on dry bean and cowpea*

The low weed dry biomass, weed species diversity and weed species diversity as affected by 50% and 100% weed frequency could explain significant higher dry bean 100-grain weight and dry biomass and cowpea 100-grain weight, dry biomass, grain yield, number of grains per pod, number of pods per plant and plant height. The effect of weeding frequency on dry bean measured variables, and weed biomass varied considerably; as weed biomass accumulation increased with the reduction of weeding frequency, the significant measured dry bean variables increased as weeding frequency increased (Chapter 3).

#### *Cereal/ legume biomass LER's*

Based on biomass LERs, the 50% and 100% weeding frequency significantly produced high crop biomass with low weed biomass over the growing seasons; these could explain the reasonably low LER values at 0% weeding frequency. The results indicated that intercrops could enhance both weed suppression and crop production compared with sole crops. Surprisingly, the sweet sorghum/ dry bean intra-row intercropping and 0% weeding frequency

outperformed the other treatments, particularly during the second growing season 2018/19. Although the LERs were also higher for many intercrops in the 50% and 100% weeding frequency, there appeared to be no consistent trend of increased land-use efficiency in the 0% weeding frequency, except for sweet sorghum/ dry bean intercropping.

Based on grain yield LERs, the dry bean/ cowpea intra-row intercropping produced the highest LER value at 50% weeding frequency. The intercropping treatments performed better at 50% and 100% weeding frequency than with 0% weeding frequency. However, the LER's value for all the legume to legume intercropping treatments declined as weeding frequency increased from 50% to 100% weeding frequency over the seasons. In this respect, (Vandermeer, 1989) emphasized that simply comparing the LERs of weedy vs weed-free intercrops might not determine whether an intercrop advantage related to yield or biomass production was due to enhanced weed control. Applying weeding frequency at 50% and 100% showed that the overall grain yield stability was most remarkable for the dry bean/ cowpea intra-row intercropping.

Under uncontrolled weed plot, intercropping treatments such as sweet sorghum/ dry bean inter-row and intra-row intercropping, sweet sorghum/ cowpea inter-row and intra-row intercropping produced more significant weed suppression compared with sole component crops, indicating synergism among crops within intercrops about weed suppression. However, the intercrop effect on weed suppression was never comparable to the weed control between 50% and 100% weeding frequency. This suggests that the implementation of annual intercrops might be a suitable option for low-input production systems. However, more research is required to determine the mechanisms of weed suppression in intercrops and under which cropping environments they are most likely to be successful. Intercropping treatments increased crop production compared with sole component crops in both 50% and 100% weeding frequency. For treatments in which 50% and 100% weeding frequency were applied,

the treatment tended to be the most consistent intercrop treatment in terms of increased land-use efficiency as measured by the frequency of overyielding.

In comparison between grain and biomass yield on LER values, the application of 50% weeding frequency, the legume-to-legume treatments tended to produce the most consistent overyielding for grain yield  $<2$  LER value, but not for biomass  $>2$  LER value; however, the application of 100% weeding frequency, overall grain yield were  $>2$  LER value in both biomass and grain yield. However, judicious selection of component crops and proper field management will increase the probability of over- yielding in intercrops. The investigation of weed impacts on yield loss is overwrought with methodological difficulties, and weeds are a major biotic constraint to crop production in different cropping systems (Chauhan, 2020).

The study evaluated weed community responses to intercropping and weeding frequency in a two-year study where weeds were managed manually (hand hoe weeding). The results suggest that increased crop biomass is associated with more significant weed suppression, and the infestation of weeds can be managed sustainably by integrating intercropping patterns and 50% weeding frequency. Understanding how cropping systems modify weed communities is necessary to shift from reactive weed control approaches to predictive management strategies (Barroso et al., 2015).

The major recommendations from the study are:

- i. Intercropping sweet sorghum with legumes (dry bean and cowpea) can be considered as a major contributor to crop yield based on relatively low competition for crop growth and development traits and yield in terms of total biomass and grain yield.
- ii. Increasing plant density by using intercropping has the advantage of replacing weeds that would compete for soil and aerial resources by transferring these to a harvestable product in an integrated weed management system. This finding is crucial for small-

scale farmers who have limited land and other resources to increase production capacity under conditions where water and soil fertility may be serious limitations. This aspect requires further investigation beyond this study, suggesting that the study created an opportunity for further research into sustainable agriculture practices.

- iii. It is possible to generate data that are focused on one crop or a combination of three crops in one trial for conclusive indication of how intercropping and/or weeding frequency will affect sorghum, dry beans or cowpeas. This is an important consideration for advice to farmers.
- iv. The principal component analysis is a useful statistical tool to indicate the crop-weed association in a cultural weed control system. In this study, broadleaf weeds were linked with a crop and their predominance could be confirmed based on the intercropping and weed removal frequency. This finding suggests a great opportunity for innovative biophysical profiles of crop species in the context of potential or existing weed and other agronomic stresses in future research.

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