TILLERING PROPENSITY AND CROP WATER USE OF DIFFERENT SORGHUM VARIETIES UNDER VARYING IRRIGATION REGIMES

BY

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DECLARATION

I, Mathatha Rifilwe, declare that the research project titled "*Tillering propensity and crop water use of different sorghum varieties under varying irrigation regimes*" is my original work. This dissertation submitted to the University of Limpopo for the degree of Master of Agricultural management (Plant production) has not been previously submitted by me or presented by anyone in any academic institution, and that all material contained herein has been duly acknowledged.

19/05/2025

MISS R MATHATHA Date

DEDICATION

Heartfelt dedication to my daughter (Reitumetse Kgomotso) for being my greatest motivation for completing this study. Additionally, I dedicate this work to my beloved late parents (Emma Messiah Mathatha and William Matome Tebjane), though you are no longer with me, your love continues to guide me. Lastly, to my aunt (Lebogang Dorosofa Makgato) for being my pillar of strength and for your unwavering support, love and encouragement.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

PREFACE

This dissertation aimed at assessing the tiller propensity and performance under the integration of water availability and cultivar selection to quantify the tiller contribution to yield, water use and water productivity. The study was broken down into five interconnected chapters. Chapter one provides a general background on the interlinked triple-threat challenges of food, water, and nutritional security; highlighting the difficulties and complexity of tiller quantification and prediction under varying irrigation regimes and cultivar selection. Chapter two provides a literature review on practices and factors that regulate tillering in sorghum. The review highlights the detrimental effects of neglecting tiller management practices, which can lead to increased competition for resources among the stem ranks, resulting in reduced yields and compromised food security. Chapter three presents the results of field experiment carried out to observe interactive effect of varying irrigation regimes and cultivar selection on quantifying sorghum tillering propensity and tiller contribution to growth and yield traits. Moreover, chapter 3 showcases tiller contribution to shoot dry biomass, harvest index and grain yield. Subsequently, chapter four addresses tiller contribution to water use and water productivity, assessing the effects of varying irrigation regimes on sorghum tiller and main stem contributions to water use and water productivity of different sorghum cultivars. Interesting to note, is that yield data from chapter three was used to derive water productivity in chapter four. Chapter five presents a comprehensive discussion and conclusion of the findings from chapters two, three, and four, aiming to address the overall study objectives. It provides practical recommendations for enhancing sorghum production under varying water availability conditions. Furthermore, chapter 5 outlines suggestions for future research, emphasizing the need for multi-location and more than one season planting studies to better understand tiller contributions and optimize management practices for improved yields and efficient water use.

GENERAL ABSTRACT

Tillering is one of sorghum's adaptive traits to water availability, which can 'make or break' crop yields depending on cultivar genetics. The complex interaction between water availability and genetic expression makes tiller contribution to yield difficult to be predicted and quantified. Additionally, contributions of sorghum tillers and main stem to 'yield per drop' and water use under different water availability and sorghum cultivars have not been quantified. Therefore, this study aimed to evaluate tillering propensity and water use of sorghum cultivars under complex tiller regulating practices, hence showcasing tiller contribution to sorghum yields and their water productivity under different sorghum cultivars and varying irrigation regimes. A literature review on practices and factors that regulate tillering was done to provide guidelines on the key practices and factors that regulate tillering in sorghum to enhance the productivity of tillers and yield. Highlighting the effective management practices that can improve grain yield by prioritising resource allocation hence minimizing competition among tillers. Moreover, the study emphasized that the dynamics of tillering must be understood under varying management practises to maximize the tiller contribution to yield and 'yield per drop'. As such, the field trial was conducted to quantify the tiller contributions to yield, water use, and water productivity at the University of Limpopo experimental farm. The study was carried out as a 3 x 4 factorial, laid out as a split-plot and arranged in a randomized complete block design (RCBD). The plots comprised of two irrigation regimes assigned as the main (full, deficit) which were compared to rainfed (unirrigated control), and four sorghum cultivars as subplots (Mr Buster, PAN606, Macia, and a local landrace) replicated three times. For addressing the tiller contributions to yield, water use and water productivity, phenological development, maximum canopy cover, plant height, stem width, biomass accumulation, number of tillers and fertile tiller percentage, harvest index, grain yield, soil water content, evapotranspiration, water productivity and the tiller contributions were collected during the growing season. The interactive effects of cultivar selection and irrigation regimes significantly influenced shoot dry biomass, grain yield, water use, and water productivity. Significantly higher shoot dry biomass (5.70 ton/ha), grain yield (7.10 ton/ha), and water productivity (2.58 kg/m^3) were recorded from the local landrace when it was cultivated under deficit irrigation. On the contrary, the lowest sorghum yield (3.04 ton/ha), shoot dry biomass (1.78 ton/ha), and

water productivity (1.19 kg/m^3) was obtained by Mr Buster with high water use (239.9 mm). However, it had statistically comparable water use and water productivity with PAN606 (225.5 mm and 1.34 kg/m^3) and Macia (226.2 mm and 1.24 kg/m^3), respectively. The great performance of landrace was attributed to longer maturity, number of tillers produced and the adaptability to local environment. The landrace had high percentage of fertile tillers (81%) compared to Mr Buster (51%). This suggest that landrace is good at using low water to produce reasonable yield and can be planted to maximize yield with less water used. Tillers made a substantial contribution to both overall grain yield and water productivity, accounting for 57% of the total yield compared 43% contribution of the main stem. Similarly, tillers contributed 53% to water productivity, while the main stem contributed 47%. Despite this, the main stem remained the statistically dominant yield contributor across different irrigation regimes and cultivars. The early-emerging tillers T1 (27 %), T2 (15 %), and T3 (9 %) proved to be the most productive due to better access to plant available assimilates. In contrast, the later-emerging tillers T4 (4 %) and T5 (2 %) were less competitive and had a minimal impact on yield, as they had low access to the resources needed by the plant. The reported tiller contributions to yield ranges from 5 – 78 %, hence, the conclusion was drawn that tillers contributing less than 5% to yield are considered non-significant. Additionally, tiller 1 to tiller 3 consistently contributed within a range of 5 – 78% across all irrigation regimes and cultivars. Therefore, it is suggested that farmers prioritize harvesting tillers up to tiller 3, as tillers beyond this point (tiller 4 and tiller 5) do not contribute significantly to overall yield. It is then recommended that cultivating landrace under deficit irrigation and focusing on tillers up to tiller 3, could achieve sustainable yields and maximize the contributions of productive tillers. However, the study was limited to a single site and season planting. Therefore, it is recommended that future research include multi-location trials and multiple growing seasons to capture the spatial and temporal variability of environmental conditions. Furthermore, additional research should explore specific agronomic practices designed to selectively boost the productivity of tillers while reducing the presence of unproductive ones.

Keywords: evapotranspiration, food security**,** irrigation regimes, sorghum cultivar, tiller contributions, water productivity, yield

CHAPTER 1: GENERAL INTRODUCTION

1.1 Problem statement

In Sub-Saharan African countries, food and nutritional insecurity remains a major challenge with a population of about 85% relying on small-scale rainfed agriculture for their livelihoods (FAO, 2013; Ali, 2019; Wudil *et al.,* 2022). South Africa is a semi-arid country that has limited water resource, and provision of adequate agricultural water supply remains a challenge (Botai *et al*., 2018; Schneider *et al.,* 2017). As a result, challenges of food, nutrition, and water security to be intrinsically linked, therefore requiring an integrated approach to address (Hadebe *et al*., 2021). To this triple-threat challenge, one possible integrated solution is growing drought tolerant, nutrient dense crops in order to produce considerably high yields and nutrition under water-limited conditions. Sorghum is among staple cereal crops that fit that mould of a traditional, drought-tolerant suited for production under water-limited conditions where alternative cereal crops like maize may fail (Belton and Taylor, 2002; Hadebe *et al.,* 2016). Moreover, sorghum is dense in nutrients that are deficient in Sub-Saharan African populations such as proteins, zinc, and iron (Nyoni *et al.,* 2020; Hadebe *et al.,* 2021). Tillering is one of sorghum's adaptive traits to water availability, which may reduce or increase grain yield and nutrition compensation under water stress depending on cultivar genetics (Wenzel *et al.,* 1999; Kim *et al.,* 2010; Hossain *et al.,* 2022). Sorghum tiller fertility has been shown to range between 7 – 91%, corresponding to 5 – 78% yield contribution from tillers (Lafarge *et al*., 2002; Wang *et al.,* 2020). This highlights how tillering ability in sorghum can 'make or break' crop yields, where low contribution can result in crop failure while high contribution can result in yield boost under marginal environments. This is further complicated by varied yield contribution that can be achieved from the main stem, where the likelihood of the main stem failing increases with decreasing water availability. Given the vastness in sorghum cultivars and differences in their tillering ability, it is critical to develop evidence-based guides of selecting the correct cultivar to be produced under varying water availability conditions as a tool to improve food, nutrition and water security in the region. To this end, there is a lack of research that has evaluated the contribution of tillers to sorghum 'yield per drop' and 'nutrition per drop' under different interactions of water availability and sorghum cultivars.

1.2 Rationale

South Africa's sorghum agricultural system consists of commercial farmers and smallholder farmers, with three broad sorghum seed selection categories available for farmers which are landraces, open-pollinated varieties, and hybrids (Hadebe *et al*., 2020). Sorghum yield can be influenced by improper water and cultivar genetics management strategies, whereby not having clear knowledge on the relationship between water use and cultivar genetics based on their tillering ability will compromise the production (Kallen *et al*., 2021). Landraces are preferred by smallholder farmers for high tillering and year-on-year vigour retention, reducing dependency on the seed market. Open-pollinated varieties, bred by ICRISAT and CGIAR, offer nutritional benefits, biotic stress tolerance, and market-related needs but are prone to tillering. Hybrids are preferred by commercial farmers due to their high seed vigour and low tillering propensity (Kumar *et al*., 2021). Sorghum crops tend to experience various tiller regulating factors during their growing cycle, with a significant impact on yield production. Predicting sorghum tiller contribution to yield and water use becomes more complex as the number tiller regulating variables increases within an agricultural system, where incorrect analysis can lead up to a 91% error in predicting tiller fertility (Lafarge *et al*., 2002; Wang *et al.,* 2020). This can translate up to a 78% error in yield prediction, which is a costly exercise for sorghum growers and by extension to the sorghum value chain (Wang *et al.,* 2020). Our work therefore aims to integrate at least two sorghum tiller-regulating variables (water availability and cultivar genetic differences) in order to provide empirical evidence for future predictions of tiller success, fertility and nutrition under complex management systems. It is important to focus on improving the understanding of the cultivar genetic differences and how they are influenced by environmental management (water use) interactions to bridge the yield gap and increase sorghum productivity (Kisekka *et al*., 2016). Results from this study will help supplement sorghum production guidelines by providing the required empirical evidence by growers to select the correct genotypes under different water availability scenarios for high yields and nutrition. Furthermore, study results will refine prediction of tiller propensity, fertility, and yield contribution under multivariable scenarios. This will be pivotal in maximising sorghum yields and nutrition under scarce water resources.

1.3 Aim

This study aimed to improve food and water security in semi- and arid regions through quantifying and assessing sorghum tiller contribution to yields, water use and water productivity. To achieve this, the aim was broken down into two objectives:

1.3.1 Objectives

i. To investigate the effect of varying irrigation regimes on tillering propensity, performance and yield parameters of selected sorghum varieties.

ii. To investigate the effect of varying irrigation regimes on crop water use and water productivity from tillers and main stems of selected sorghum varieties in semi-arid region of Limpopo, South Africa.

1.3.2 Null hypotheses

i. Irrigation regimes will not have an effect on tillering propensity, performance and the yield parameters of the three selected sorghum varieties.

ii. Irrigation regimes will not have an effect on crop water use and water productivity from tillers and main stem of selected sorghum varieties.

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CHAPTER 2: PRACTICES AND FACTORS THAT REGULATE TILLERING IN SORGHUM: A REVIEW

ABSTRACT

Tillering is a crucial trait in sorghum, significantly contributing to yield under water stressed environments. However, neglecting the tiller management practices in sorghum cultivation can increase competition for resources, negatively affect yields which compromise food security and economic returns. This then leads to challenges of predicting the contribution of sorghum tillers to production due to the growing number of tiller regulating factors and management practices within the agricultural system. This study investigated the key practices and factors regulating tillering in sorghum to optimize productivity and yield. The findings emphasize the importance of selecting cultivars based on specific environmental conditions to ensure optimal growth. Additionally, adjusting planting population is identified as a critical management practice where high planting population tend to suppress tillering due to intensified competition, while low planting population promotes tiller development by enhancing resource availability. Adopting low planting population not only supports higher tiller production but also creates favorable conditions for overall plant growth and development, ultimately improving crop yields. Understanding these dynamics allows for informed sorghum management strategies that maximize tillering and yield potential across diverse environments.

Keywords: competition, management practices, tillering, water stress, yield.

2.1 Introduction

Tillering is a sorghum adaptive feature to water stress, where side-plants can appear to compensate for yield loss in case the main stem fails (Kim *et al*., 2010; Hossain *et al*., 2022). Tillering plays a crucial role in crop yield, particularly by contributing to biomass accumulation and influencing plant architecture (Hammer, 2006; Kuraparthy *et al*., 2008; Kim *et al*., 2010). It is regulated by a complex interplay of genetic, hormonal, and environmental factors, making it a highly adaptable trait that allows cereals to thrive in diverse conditions (Li and Bangerth, 2003; McSteen, 2009; Kebrom *et al*., 2013; Shang *et al*., 2021). The development of tillers is largely driven by the

availability of assimilates, and when there are no limiting environmental or genetic constraints, it could lead to an increase in yield (Lafarge and Hammer, 2002). Tillering can vary significantly depending on the genotype and environmental conditions. For instance, under favorable conditions, sorghum is capable of producing up to ten productive tillers with each contributing to the plant's overall architecture and enhancing its potential yield (Hammer *et al*., 1993; Kouressy *et al*., 2008). This adaptability allows tillering to serve as an essential mechanism for maximizing productivity in varying environments.

Fertile tillers can contribute from 5 to 78% to overall yield depending on the prevailing environmental conditions and the crop management practices (Lafarge *et al*., 2002). In marginal conditions, low tillering can result in significant yield losses potentially leading to crop failure, while high contributions from fertile tillers can enhance yields. The fertility of sorghum tillers varies from 7 to 91%, indicating their significant role in crop yields. However, predicting the contribution of sorghum tillers to production becomes more challenging due to the growing number of tiller regulating factors and management practices within the agricultural system. Incorrect analysis can result in a 91% error in estimating tiller fertility and a 78% error in yield prediction (Lafarge *et al*., 2002; Wang *et al*., 2020). This then highlights the importance of understanding and optimizing the tiller managing and regulating factors that influence tiller development and fertility, as they play a crucial role in maximizing sorghum productivity and yield contribution (Lafarge *et al*., 2002; Kim *et al*., 2010; Bean, 2018).

Sorghum is one of the most vital cereal crops globally, particularly in semi-arid and arid regions, where its resilience to harsh environmental conditions makes it a staple food and a crucial component of agricultural systems (Mwadalu and Mwangi, 2013; Hadebe *et al*., 2017). Its adaptability to wide range of climatic conditions has established it as a crop of choice in regions where other cereals may fail (Reddy *et al*., 2013; Hossain *et al*., 2022). The capability of sorghum to produce tillers is an important trait that greatly contributes to its adaptability and productivity in semi-arid regions. The development of tillers in plants can be controlled by the balance of hormones and competition for assimilates throughout the plant's growth processes (McSteen and Leyser, 2005; Beveridge, 2006; Ongaro and Leyser, 2008; McSteen, 2009). The phytohormones cytokinin and auxin work antagonistically in determining the branching whereby the auxin favours the apical dominance whereas cytokinin stimulates the

growth of the lateral branching (Ongaro and Leyser, 2008). Cytokinin stimulate cell division and differentiation in plants, and in the context of tillering, they counteract the inhibitory impact of auxins on axillary bud extension and promote the development of buds into lateral shoots or tillers. (Cortleven *et al*., 2018; Koprna *et al*., 2021). This literature review aimed at providing guidelines on the key practices and factors that regulate tillering in sorghum to enhance the productivity of tillers and yield.

2.2 Cultivar selection

The selection of cultivar influences tillering, which is viewed as a key determining factor in yield contribution (Lafarge *et al*., 2002; Kim *et al*., 2010). Sorghum cultivars exhibit significant differences in tillering behaviour, influenced by genetic, physiological, and environmental factors (Kebrom *et al*., 2013; Shang *et al*., 2021). Genetic variability plays a crucial role in determining the propensity to tiller, with some genotypes showing a higher tendency to tiller than others (Alam *et al*., 2010; Alam, 2013; Alam *et al*., 2014). The cultivars are normally selected based on their adaptability to environmental conditions in order to optimize the yield production. For instance, high tillering cultivars are selected under favourable environmental conditions because they thrive better and are able to use resources efficiently. Moreover, high tillering hybrids develop more tillers in favorable conditions because they have a lower source-to-sink threshold (Naoura *et al*., 2019). Conversely, in harsh environments with limited water for transpiration, the stay-green and low tillering cultivars are recommended to reduce plant size and maximize post-anthesis water availability and grain yield (Hammer, 2006). Furthermore, stay-green and low tillering hybrids may offer yield advantages in low yielding environments, as these traits are often linked to better resource efficiency and drought tolerance (Jordan *et al*., 2012; Tolk *et al*., 2013). These stay-green cultivars can maintain photosynthetic activity for longer periods while low tillering reduce competition for resources, potentially leading to improved yields under marginal conditions (Galyuon *et al*., 2019; Rotili *et al*., 2021). South Africa's agriculture system consists of commercial farmers and smallholder farmers, with three broad sorghum seed selection categories available for farmers which are landraces, open-pollinated varieties, and hybrids (Hadebe *et al*., 2020).

Tillering in these genotypes vary depending on genetic characteristics and breeding background. Landraces are traditional, locally adapted cultivars that have not

undergone intensive breeding and frequently hold onto traits characteristic of the wild type, such as tillering patterns (Villa *et al*., 2005; Newton *et al*., 2011; Marone *et al*., 2021). Contrastingly, hybrids are the consequence of crossing two genetically separate inbred lines, resulting in hybrid vigour and possibly changed tillering traits when compared to open-pollinated cultivars (Lohn *et al*., 2021). They are preferred by commercial farmers due to their high seed vigour and low tillering propensity (Upadhyaya and Vetriventhan, 2018). Open-pollinated varieties are populations of plants that are permitted to freely cross-pollinate, maintaining genetic variation within the population and can alter tillering patterns (Kutka, 2011). Hybrids and open-pollinated varieties in some cases have been bred for low tillering and this could be attributed to sbTB1(sorghum bicolor teosinte branched1) and sbDRM1(sorghum bicolor dormancy-associated1) genes being slightly expressed or repressed, while landraces still retain their wild-type teosinte branching nature due to lack of deliberate breeding efforts (Upadhyaya and Vetriventhan, 2018; Nagesh Kumar *et al*., 2021). Hybrids tend to perform well in both narrow and wide row layouts, making them appropriate for both irrigated and dryland fields (Smith, 2006). For yield optimization under varying environmental conditions the modern hybrids should be selected since they are known to produce from zero to four fertile tillers accounting for 80% yield contribution (Hammer *et al*., 1993; Lafarge *et al*., 2002). Hybrids have superior high yield potential and stress tolerance surpassing the landrace by 12% (Haussmann *et al*., 2006).

2.3 Water availability

Water availability is a crucial factor influencing sorghum growth and yield, particularly in semi-arid regions where rainfall is often variable and limited (Chauvin *et al*., 2012; Hossain *et al*., 2022). Sorghum cultivation in these regions often subjects it to water stress since the rainfall is erratic and sometimes does not meet the plant demand of about 450 – 650 mm during its growing season for optimal growth (Jewitt *et al*., 2009; Hadebe *et al*., 2017). The water saving strategy in water limited conditions is cultivation of low tillering varieties because it has been proven to enhance yield due to less competition of resources. This could be attributed to resource maximization and water use prioritization by the main stem for survival (Borrell *et al*., 2014; Hammer *et al*., 2014). A high number of tillers during the early stages of crop growth can compete with

the main stem for water, leading to increased water demand and crop transpiration (Elhani *et al*., 2007; Rotili *et al*., 2021). This competition reduces the soil moisture available for critical growth stages in sorghum, such as booting and flowering (Rao *et al*., 2011). As a result, these conditions can lead to significant tiller abortion, poor grain set, and smaller panicle sizes, ultimately reducing grain yield (Kariali and Mohapatra, 2007). Water stress in sorghum disrupts the allocation of carbon supply/demand to tillers, resulting in reduced photosynthetic rates and a disturbed hormonal balance.

Water availability influences the production and distribution of plant hormones such as auxins, cytokinins, abscisic acid (ABA), and gibberellins and they play a key role in regulating tiller initiation and growth, and some play a role in stress response (Wahab *et al*., 2022). Water stress can disrupt the hormonal balance in plants, negatively impacting tiller development by reducing photosynthetic rates, hindering nutrient absorption, and affecting the allocation of carbon to tillers (Assuero and Tognetti, 2010); Wahab *et al*., 2022). This interruption may result in fewer, smaller, and less fertile tillers, affecting overall crop development and output (Hussain *et al*., 2018; Prasad *et al*., 2021).

When plants experience water stress, whether due to insufficient soil moisture or other environmental factors, they often respond by synthesizing and accumulating ABA (abscisic acid). ABA acts as a signaling molecule, triggering adaptive responses to cope with water scarcity (Osakabe *et al*., 2014; Aslam *et al*., 2022; Kuromori *et al*., 2022). Water availability can have different effects on tillers depending on the crop and the conditions they face. Moreover, tillers are often encouraged to initiate and develop when there is sufficient water available (Lafarge *et al.*, 2002; Kim *et al.*, 2010). Although a lack of water may negatively impact seed germination and embryo growth rate hence several sorghum cultivars have successfully adapted to semi-arid regions (Patane *et al*., 2012). Drought during the tillering stage can reduce tiller size and suppress tiller production in rice (Hernán *et al*., 2021). The lack of water during this critical growth period disrupts normal plant development, limiting both the number and size of tillers, which can negatively affect overall yield. Under water-limited conditions, excessive tillering can lead to high tiller abortion, poor grain set and small panicle size, thereby reducing grain yield (Kariali and Mohapatra, 2007). The study of Wang *et al.* (2020) conducted on different sorghum hybrids reported that under adequate irrigation they had a smaller number of fertile tillers, and they had more tiller production under water stressed conditions and this can be due to hybrids that have been bred in some

cases for low tillering which are results of the branching genes being slightly expressed or repressed. When the crop is cultivated under favourable conditions and the agronomic management practices are accounted for, tillering propensity can be advantageous. However, if drought is likely to occur, reduced tillering may result in smaller plants and reduced water consumption before anthesis. This conservation of water can provide additional resources post-anthesis, potentially increasing grain yield (Hammer, 2006). Excessive soil moisture can decrease tiller number and restrict root growth, leading to reduced tillering (Kisaakye *et al*., 2015). An Open-pollinated variety (Macia) was recommended for production in water limited areas due to its high yields and water productivity stability in various rainfed conditions in a study by Hadebe *et al*. (2020). Sorghum landraces can tiller extensively when faced with water stress, which is viewed favourably by subsistence farmers who link tillering to yield compensation in difficult circumstances (Pandravada *et al*., 2013). Plants with fewer tillers tend to have higher grain yield and water use efficiency, possibly due to reduced water stress compared to freely tillering plants in barley plants (Kuromori *et al*., 2022). Water deficit stress can halt dry matter accumulation before physiological maturity (Borrell *et al*., 2014). It can lead to significant reductions in sorghum growth, with decreases of 42% in stem biomass, 37% in shoot dry weight, and reduced leaf dry weight (Nxele *et al*., 2017; Perrier *et al*., 2017). These reductions directly impact the plant's overall productivity and its ability to achieve optimal yields under water-limited conditions.

2.4 Temperature thresholds

Temperature is one factor that influences tiller development and survival, most likely through its effect on photosynthate availability at tiller emergence (Lafarge *et al*., 2002; Roozeboom and Prasad, 2019). Sorghum is a warm weathered crop that needs high temperatures to germinate and flourish. The minimum temperature for germination ranges from 7 to 10 °C (Emendack *et al*., 2021; La Borde *et al*., 2023). The lower temperature threshold limit for sorghum in South Africa is 7°C, while the higher temperature threshold limit for sorghum grown in semi-arid tropics is 38°C (Huda *et al*., 1984; Du Plesis, 2008). Temperature signals regulate the timing of multiple developmental processes and have drastic effects on plant architecture and biomass (Ding *et al*., 2020). The regulation of plant architecture by temperature appears to

involve the complex integration of multiple hormones signalling networks (Patel and Franklin, 2009; Bhattacharya, 2019). Temperature has a significant effect on tillering especially on the onset of tiller emergence that occurs after five leaf stage at a developmental stage 3 known as growing point differentiation. Temperature influences the timing of fertilizer application, the rate of nutrient uptake and utilization by plants (Bean, 2018). High temperatures above the optimum threshold of 32°C inhibit tillering in sorghum plants, preventing the expansion of buds into tillers by negatively impacting the emergence of tillers from lower axils, thereby affecting the subsequent fertility of these tillers, it can also induce heat stress which lead to overall reduced yield (Kim *et al*., 2010; Prasad *et al*., 2017; Tack *et al*., 2017; Prasad *et al*., 2019). Temperature changes affect plant endogenous hormone responses and their biosynthesis. High temperatures stimulate the biosynthetic pathways resulting in higher accumulation of hormones such as auxin and favours apical dominance (Li *et al*., 2021; Lu *et al*., 2021). High temperatures affect gas exchange and chlorophyll fluorescence in sorghum leaves, leading to a decrease in photosynthetic rate and changes in photosystem function (Yan *et al*., 2011). High temperature stress in sorghum plants leads to altered carbohydrate metabolism and starch deficiency, which is associated with reduced expression of genes related to sugar-to-starch metabolism (Jain *et al*., 2007; Prasad *et al*., 2021).

The low temperature below the threshold of 18 °C lowers the photosynthetic rate by reducing the plant size thus limiting the plant's ability to produce assimilates and this affect the endogenous hormone responses and their biosynthesis (Lafarge and Hammer, 2002). Cold stress can increase the endogenous ABA levels in plants and then improve their resistance to low temperatures (Liu *et al*., 2017). This increase in ABA content is a critical response mechanism that assists plants in coping with cold stress by regulating multiple adaptation mechanisms to improve their tolerance to low temperatures (Shi and Yang, 2014). Sorghum is sensitive to frost, and frost events during the 4 to 6 leaf stage can cause significant damage to developing tillers. Since there is low rate of photosynthetic activity this means that the hormone cytokinin responsible for tiller formation will be produced in less amounts and this affect its influence on the mobilization of nutrients to the axillary bud in order to promote tillering and this leads to tillering being inhibited (Tanaka *et al*., 2006; Sosnowski *et al*., 2023). Shimono *et al*. (2007) reported that low temperatures during the vegetative stage

reduce the plant's ability to produce tillers, extend the growth period, and consequently impact overall yield.

However, other studies referenced that low temperatures during the vegetative stage can hinder tiller emergence, leading to a slowdown in plant development. However, as temperature increases, tiller growth can pick up again, allowing plants to potentially return to normal levels of tiller production. This then highlights the resilience of crops such as sorghum, which can adjust to temperature variations throughout their growth cycle (Liu *et al*., 2008; Bhattacharya, 2022). High temperatures can induce water stress which in turn may delay the formation of tillers (El Sabagh *et al*., 2019). Simulation studies revealed that increasing temperature and decreased rainfall provided a greater risk of low yield than an increase in rainfall (Prasad *et al*., 2021). The temperature increase of 2°C, 4°C, and 6°C reduced grain production by 10% and a drop in rainfall by 25% and 50% resulted in yield decreases ranging from 5% to 37% (Akinseye *et al*., 2019). The effect of temperature on sorghum growth is also affected by the time of planting. Sorghum that is planted later and exposed to warmer temperatures often yields less fertile tillers than sorghum that is planted earlier (Maiga, 2012; Roozeboom and Prasad, 2019).

2.5 Nitrogen availability

Tiller emergence and growth are not only affected by temperature but also by nutrient levels, particularly nitrogen (Zhong *et al*., 2003; Wang *et al*., 2017). Nitrogen is one of the most critical and limiting nutrients for plants which are essential for cell division and growth (Hirel *et al*., 2011; Ostmeyer *et al*., 2022), especially in maintaining environmental homeostasis under stress situations (Jackson *et al*., 2008). The form in which the nitrogen is applied or absorbed as affect tillering, sorghum absorbs nitrogen from the soil by root transporters in a form of ammonium ion (NH^{4+}), nitrate ion (NO^{3-}), and other mineral ions from the soil (Wang *et al*., 2017; Luo *et al*., 2020). Nitrogen influences tillering initiation and development; however, it reduces tillering initiation in excess or deficiency (Wang *et al*., 2017, Peng *et al*., 2015). Since nitrogen is essential for promoting vegetative growth and tiller initiation (Hirel *et al*., 2011; Ostmeyer *et al*., 2022), its management must be carefully balanced to avoid the adverse effects of both deficiency and excess. Nitrogen deficiency affects the cell wall properties, carbon supply-demand balance, and growth phase transition, leading to a reduction in tillering

in sorghum (Alam *et al*., 2009). Excessive nitrogen application can suppress the initiation and outgrowth of axillary buds, which are responsible for tiller formation. The axillary buds may remain dormant or have limited growth due to the plant's focus on allocating resources to the main stem (Zhao *et al*., 2022). The excess can further lead to imbalances in nutrient availability, which can negatively affect overall plant health and tiller development (Wang *et al*., 2017).

Nitrogen fertilizers are usually applied to enhance the number of tillers, especially in fields with low plant density; it can compensate for the yield reduction of low planting density (Peng *et al*., 2015; Ju *et al*., 2009). Nitrogen fertility can also influence the density and spacing of tillers within the sorghum canopy. Higher nitrogen levels may lead to more tillers being produced, resulting in a denser canopy with closely spaced tillers. This can impact light penetration and airflow within the canopy, which can have consequences for disease susceptibility and grain formation (Dembele *et al*., 2021; Ostmeyer *et al*., 2022). Adequate nitrogen availability promotes vegetative growth and can encourage the initiation and development of tillers in sorghum. Sorghum plants often respond to increased nitrogen availability by producing more tillers, especially during the early vegetative stages of growth (Mahama *et al*., 2014). Application of nitrogen fertilizer can accelerate the growth and increase the number of rice tillers, whereas excessive application can decrease the number of effective tillers (Haque and Haque, 2016).

Tiller generation is dependent on a sufficient nitrogen supply; generation rate and quantity of tillers rise as plant nitrogen concentration increases within a particular range (Zhong *et al*., 2003; Wang *et al*., 2017). A study on grain sorghum over a wide range of population densities found that assimilate supply in the plant seems likely to have been a key driver of tiller emergence and fertility, and light quality a key determinant of tiller leaf area development and fertility (Lafarge *et al*., 2002). Therefore, optimizing nitrogen fertilization for sorghum tillering requires considering these factors and finding a balance between nitrogen supply and plant demand. Tomlinson and O'Connor (2004) investigated the role of nitrogen availability in tiller formation, suggesting that nitrogen plays a significant regulating role in tiller formation through root cytokinin production. The production of cytokinins influence the concentration of nitrogen in the root, because it is responsible for nitrogen absorption from the soil and seasonal reallocation of tissues. The levels of cytokinin in the roots

rise in response to nitrate and the transport of this raised cytokinin may serve as a long-distance signal to regulate the development of the shoot and the root (Miyawaki *et al*., 2004; Takei *et al*., 2004).

2.6 Photoperiod thresholds

Sorghum is a short-day photoperiod-sensitive crop, which means that it progresses towards flowering when day length is within the optimal threshold of 10 to 11 hours, while longer photoperiods promote vegetative growth (Wolabu and Tadege, 2016). This can lead to changes in tillering patterns as the plant redirects its resources towards reproductive growth (Sanon *et al*., 2014). Sorghum typically initiates tiller development in response to shorter day lengths, which signal to the plant that the growing season is advancing towards the end of the growing period. This cue causes the plant to begin developing tillers in order to improve its reproductive capacity prior to the beginning of unfavourable conditions (Lafarge *et al*., 2002). Sorghum tiller initiation is frequently linked to the balance between day length and temperature. There are complicated correlations between day length and the length of the vegetative phase, which ends with the onset of flowers (Clerget *et al*., 2004). When the day length is too long or the temperatures are too high, it might cause premature blooming and limit tiller development (Hellmers and Warrington, 2018; Suzuki, 2019). Lengthy day lengths decrease tiller development in sorghum because sorghum is sensitive to short days and when it experiences long day lengths, it tends to suppress tiller development (Yang *et al*., 2014). Sorghum plants are most sensitive to photoperiod during flower initiation. They prioritize vertical elongation and the development of the main stem and leaves over the production of tillers in regions with extended day-light hours or when grown under continuous artificial lighting (Wolabu and Tadege, 2016).

Primitive effects of photoperiod on tillering could be mainly attributed to the prolongation of the tillering stage rather than the enhancement of bud outgrowth. Photoperiod duration is known to alter cytokinin levels (Wang *et al*. 2004). Cytokinin is required for the defence against high light stress and to protect plants from any type of abiotic stress caused by an altered photoperiod (Mandal *et al*., 2022; Frank *et al*., 2022). There are differences in photoperiod sensitivity among sorghum cultivars, with some being more responsive to changes in day length than others. This variation in

sensitivity can have implications for the adaptation of sorghum cultivars to different environments and growing conditions where tropical cultivars are more photoperiod sensitive than short-season sorghum cultivars (Wolabu and Tadege, 2016). Furthermore, variations in photoperiod sensitivity among different sorghum cultivars highlight the importance of selecting appropriate cultivars for specific environmental conditions, particularly in tropical regions where photoperiod sensitivity is more prominent.

2.7 Planting density manipulation

Sorghum exhibits plasticity, which means it can adjust its growth and development in response to environmental conditions. Sorghum plants can exhibit plasticity in their tillering response to plant population (Kim *et al*., 2010). This plasticity is influenced by environmental factors, including light availability (R:FR ratio), nutrient availability, and competition for resources (Alam *et al*., 2014). Under high planting density crops receives low R:FR light and in response to a low R:FR ratio, sorghum plants may allocate more resources to height growth and fewer resources to tillering. This is an adaptive strategy to increase the chances of reaching sunlight and avoiding shading from nearby plants. Consequently, the development of tillers may be reduced under conditions of high plant population and low R:FR ratio. This low R:FR ratio decreases as light filters through green leaves, leading to inhibited tillering in dense canopies with taller plants (Lafarge and Hammer, 2002; Alam *et al*., 2014).

Reducing plant population in sorghum may result in an increased number of tillers that utilise the available resources and may result less or in no yield contribution (Guo *et al*., 2021). Management practices can affect tillering by modifying plant density (Lafarge and Hammer, 2002). This adjustment is associated with changes in light quality, which can influence hormonal regulators or the availability of assimilates thus influencing yield (Timlin *et al*., 2014; Zhang *et al*., 2019; Guo *et al*., 2021). Plant density significantly impacts tillering in sorghum, affecting the number and fertility of tillers and overall grain yield through competition of resources (Lafarge *et al*., 2002). A study on sorghum over a wide range of population densities found that as plant density increased, the number of tillers per plant decreased, but the fertility rate of the remaining tillers increased, leading to higher grain yield per plant (Lafarge *et al*., 2002). The emergence of tillers was probably associated with the supply of assimilates and

light quality, whereas their development, fertility, and contribution to yield were significantly influenced by the growing conditions present at the time of tiller emergence (Lafarge *et al*., 2002). Tiller appearance was highly synchronized with the emergence of leaves on the main shoot, demonstrating a consistent hierarchy across different environments (Kim *et al*., 2010).

Plant density affects tiller outgrowth and survival (Yang *et al*., 2019). High plant density enhance shading, which can limit the amount of sunlight that reaches lower leaves and inhibit photosynthesis. Additionally, this configuration reduces evapotranspiration, potentially conserving soil moisture. However, it also intensifies competition among plants for both water and light within the crop canopy, which can affect overall growth and yield (Baumhardt, 2004) thus reducing assimilate availability for tillering. This is because they allocate more resources to the main stem and leaves (Lafarge *et al*., 2002). On the other hand, sorghum plants at lower population densities may produce more tillers due to less competition for resources. With less competition, individual plants can invest more in tiller development, potentially leading to larger and more productive tillers (Kim *et al*., 2010; Bean, 2018). In such situations, plants may allocate resources differently, affecting cytokinin distribution. Consequently, conditions where tillering is crowded with limited resources may result in reduced cytokinin levels which leads to decrease in tillering. Conversely, lower plant density with ample resources might favour higher cytokinin levels and more tiller development (Kebrom and Mullet, 2015). Therefore, maintaining a low plant density is an effective management strategy for promoting tiller production, which can significantly contribute to overall yield. Reducing the number of plants per unit area can lead to each individual plant having a greater access to essential resources such as light, water, and nutrients.

2.8 Conclusion

Effective management practices for tillering can improve grain yield by regulating resource allocation and minimizing competition among tillers. The selection for cultivar should be guided by their adaptability to varying environmental conditions and their known propensity to tiller under varying environmental conditions. In water limited environments, stay-green and low tillering cultivars are recommended as they help conserve moisture and enhance grain production. Conversely, high tillering cultivars are preferred in favorable environments due to their efficient resource utilization.

Nitrogen fertilization strategies should balance nitrogen supply and plant demand, especially during early vegetative stages, to promote tiller initiation and yield without compromising the main stem's growth. Sorghum's sensitivity to photoperiod plays a crucial role in its growth and development, with optimal flowering occurring under shorter day lengths of 10 to 11 hours. Longer photoperiods tend to favour vegetative growth at the expense of tillering, as the plant redirects its resources towards reproductive development. Variations in photoperiod sensitivity among different sorghum cultivars highlight the importance of selecting appropriate cultivars for specific environmental conditions. Planting density manipulation is important where under high planting densities, tillering is normally reduced due to increased competition for resources, while lower densities encourage tillering since it provides more access to resources. Furthermore, implementing low plant density as a management practice not only maximizes tiller production but also creates a favorable environment for plant growth and development, ultimately leading to increased crop yields and improved productivity. Therefore, understanding these dynamics allows for better management of sorghum cultivation, optimizing tillering and yield potential in diverse environments.

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CHAPTER 3: TILLERING PROPENSITY AND TILLER CONTRIBUTION TO CROP PERFORMANCE AND YIELD PARAMETERS AS A FUNCTION OF CULTIVAR SELECTION AND VARYING IRRIGATION REGIMES

ABSTRACT

Tillering is one of sorghum's adaptive traits to water availability, which can 'make or break' crop yields depending on cultivar genetics. The complex interaction between water availability and genetic expression makes tiller contribution to yield difficult to be predicted and quantified. Therefore, this study was aimed at quantifying sorghum tillering propensity and tiller contribution to growth and yield traits under different irrigation regimes and cultivars. The study was carried out as a 3 x 4 factorial, laid out as a split-plot and arranged in a randomized complete block design (RCBD). The plots comprised of two irrigation regimes assigned as the main (full, deficit) which were compared to rainfed (unirrigated control) and four sorghum cultivars as subplots (Mr Buster, PAN606, Macia, Local landrace) replicated three times. The collected data included phenological development, canopy cover, plant height, stem width, biomass accumulation, number of tillers and fertile tiller percentage, harvest index, grain yield, and the contribution of tillers to yield. The interaction of varying irrigation regimes and cultivar selection significantly influenced shoot dry biomass and grain yield. Significantly higher shoot dry biomass (5.70 ton/ha) and grain yield (7.10 ton/ha) were obtained by landrace under deficit irrigation. This was attributed to plant height, tillering propensity, maturity length and the adaptability of landrace to local environment. The phenological development, plant height, stem width, harvest index, shoot dry biomass, and grain yield differed significantly within the sorghum cultivars, with Landrace outperforming the other cultivars in plant height, stem width, harvest index, biomass and yield. However, it flowered and matured later than all the cultivars. Deficit irrigation significantly influenced yield and prolonged maturity for the crops. Deficit irrigation plot (4,5 ton/ha) outperformed the rainfed plot (3,4 ton/ha) due to controlled water stress and enhanced water use efficiency during critical growth stages while low yield in the rainfed plot was due to early maturity due to drought escape. The tiller grain yield had an influence on the overall yield where the results quantified 57 % of tillers contribution, which is higher than the main stem contribution of 43 %. The early emerging tillers (T1 (27 %), T2 (15 %) and T3 (9%)) are the most productive due to their better access to

assimilates whereas later emerged tillers (T4 (4 %) and T5 (2 %)) are less competitive and contribute minimally to yield. This suggests that tillers up to tiller 3 are worth harvesting, while tiller 4 and tiller 5 have a minimal impact on the total yield. Therefore, the cut-off for harvesting tillers could be set at tiller 3, as tillers beyond this do not significantly contribute to the overall yield. Therefore, farmers can cultivate landrace under deficit irrigation for sustainable yields and target the tiller harvest up to tiller 3 for higher tiller contributions.

Keywords: tillering, irrigation regimes, growth, tiller contribution, sorghum cultivars, yield.

3.1 Introduction

Sorghum is primarily grown in regions where water is scarce, and it tends to contribute to food security for smallholder farmers due to its resilience to dry soil moisture conditions (Rockstrom *et al*., 2009; Mupangwa *et al*., 2012). However, the sorghum yields are below potential (Aishah *et al*., 2011) and in semi-arid regions they have remained steady around 1.0 t/ha compared to the global average of 2.5 t/ha (USDA, 2019). This could be attributed to poor water management strategies (Rockstrom *et al*., 2010) and poor cultivar choice selection. Sorghum has a plastic, adaptive trait known as tillering, which serves as a backup for plants under stressful conditions (Lafarge and Hammer, 2002). Its propensity and intensity can be influenced by various environmental and genetic factors which when they interact can sometimes reduce the predictability and success of tillering in the crop (Lafarge *et al*., 2002). Tillering can assist in lessening the water scarcity crisis by enhancing the overall water-use efficiency of plants particularly in Sub-Saharan Africa (Passioura, 2006; Chimonyo, 2015). However, water availability can limit crop yields by reducing the number of tillers produced, which in turn impacts tiller fertility and lowers grain production per plant. This decline in productivity can negatively affect both food availability and quality (Lafarge *et al*., 2002; Kim *et al*., 2010; Hossain *et al*., 2022).

Sorghum tiller fertility can range widely from 7 to 91%, with tillers contributing between 5 and 78% to the overall yield (Lafarge *et al*., 2002; Wang *et al*., 2020). This variability highlights the pivotal role of tillering ability in sorghum where low tiller contribution can

lead to reduced yields and potential crop failure, whereas a high contribution can enhance yields, particularly in marginal environments. In water scarce environments, high number of tillers occurring during the early crop growth stages can increase soil water demand (Cerrudo *et al*., 2013). Consequently, increasing water consumption, overall leaf surface area resulting into greater transpiration rate (Elhani *et al*., 2007; Cerrudo *et al*., 2013; Rotili *et al*., 2021) leading to high competition of resources among the main stem and tillers. Moreover, in water-scarce conditions when the main stem fail due to a lack of water, the tillers compensate by producing more panicles and adding to overall production (Elhani *et al*., 2007).

Tillers can have both positive and negative effects on grain yield and excessive tillering can lead to high tiller abortion and small panicle size, which cause reduced grain yield (Alam *et al*., 2009). Different irrigation levels can affect the morphology and growth of sorghum, with some varieties performing better than others under water stress conditions (Fazel *et al*., 2023). Beyond that, cultivar genetics play a role in the performance of sorghum under irrigation, with improved cultivars generally outperforming local ones in terms of yield and other growth parameters (Menezes *et al*., 2015). In contrast, the sorghum hybrids had less number of fertile tillers under adequate irrigation while they had more tiller production under water stress (Wang *et al*., 2020). This could be subjected to the response of ABA that help the plant to combat stress by producing the additional tillers that contribute to yield (Müller and Leyser, 2011; Reddy *et al*., 2013; Rameau *et al*., 2015). Sorghum landraces are likely to tiller extensively under water stress conditions and this explains why smallholder farmers are persistently cultivating it due to adaptability to local conditions (Andiku *et al*., 2021). Moreover, it is viewed favourably by subsistence farmers who link tillering to yield compensation in stressful circumstances (Walters, 2018; Marone *et al*., 2021).

Sorghum yield potential is largely dependent on tillering; however, its production can also be hampered by water deficit, and this is due to varying varieties that respond to the availability of resources differently which is influenced by their genetic make-up (Assefa *et al*.,2010; Bhadha *et al*., 2016; Rockstrom, 2003). Water availability is one of the constraints to crop production as it threatens food security for the vulnerable group of smallholder farmers (De Klerk *et al*., 2004). The complex regulation of the interaction between water availability and genetic expression makes it difficult to predict the occurrence, onset, and success of tillering in sorghum (Wang *et al*., 2020).

Although sorghum tillering has been the subject of numerous research (Kim *et al*., 2010; Boyles, 2016; Wang *et al*., 2020), but none have precisely examined the interaction between tillering of different sorghum varieties and irrigation levels. However, the impact of different irrigation regimes on tillering propensity, performance, and ultimately yield parameters of various sorghum genotypes is still unclear. Moreover, there has been limited focus on the tillering adaptation of varietal selection, especially under varying water conditions. Therefore, this study is aimed at providing empirical, quantified field-based evidence to showcase tiller contribution to sorghum yields under complex tiller-regulating practices of water availability and cultivar selection.

3.2 Material and methods

3.2.1 Experimental site description

The field trials were planted on the 1st of December 2023 at the University of Limpopo experimental farm, Syferkuil (23°50’ 2.98 S; 29°41’31.11 E) located in Mankweng within Capricorn district of Limpopo province, South Africa. The site is characterised by a semi-arid climate with an uneven annual rainfall of about ±450 mm per annum (Moshia *et al*., 2008). The study area experiences winter temperatures that range from 5 and 28°C and summer temperatures ranging from 10 to 36 °C (Tyasi *et al.,* 2022). The data for rainfall, minimum and maximum temperatures received during the growing cycle was sourced from the weather station situated at a 100 m radius in the University of Limpopo Experimental farm (Moeletsi *et al*., 2022).

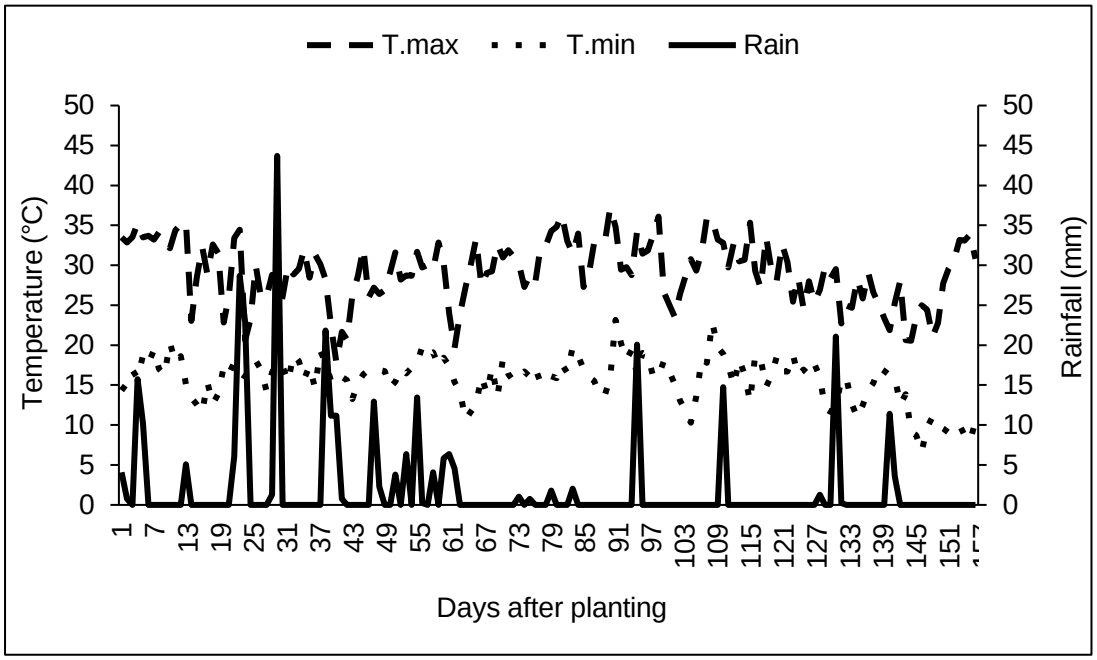

Figure 3.1: The daily rainfall, minimum and maximum temperatures at University of Limpopo experimental farm, Sykerfuil for sorghum throughout its growing season.

3.2.2 Soil classification, sample collection and soil analysis prior to the experiment

Prior to establishment of the trial, a 1.2 m deep soil pit was dug adjacent the experimental plot for soil classification. The dominant soil form in the area was classified as Westleigh characterized by an orthic A-horizon underlain by a soft plinthic B-horizon and a gleyic layer (Soil Classification Working Group, 2018). After classification, three faces of the soil profile were demarcated at 30 cm intervals (0-30, 30-70, 70-100) to collect soil samples for bulk density and other samples for analysis of chemical and physical properties. Three samples for each physicochemical variables were collected on each horizon utilizing the spade and hammer. The bulk density samples were collected utilizing the large core rings, the plunk, and the hammer. The collected samples were bagged and labelled individually according to their distinguished horizons, their physical and chemical properties. The soil physicochemical properties (structure, texture, bulk density, gravel content, and organic matter) were used as inputs in the SPAW model to give the results of soil hydraulic properties (permanent wilting point, field capacity, saturation point, and plant available water) that aid in determination of irrigation amount and duration (Saxton *et*

al., 2006). The SPAW (Soil-Plant-Air-Water) is a computer model used to simulate the dynamics of soil water under various field conditions and soil types. The bulk density was determined using the cylinder method (FAO, 2023). The samples were oven dried at 105°C until constant weight was reached. After the drying period, the dried samples were weighed with an electronic weighing balance, and the volume of the core ring was calculated to determine the bulk density of the soil, along with the dried soil. Soil texture was determined using the hydrometer method (Bouyoucos, 1962). Soil organic carbon was determined using the Walkley-Black Method (Walkley and Black, 1934).

Table 3.1: Soil physicochemical properties before planting

Soil physicochemical properties	**Soil horizon**		
	Orthic A	**Soft plinthic B**	**Gleyic**
Depth (m)	0.3	0.4	0.3 m
Texture	Sandy clay loam	Sandy clay	-
Bulk density (g cm^{-3})	1.26	1.17	-
Organic matter	0.7	0.5	-
Soil form		Westleigh	

Table 3.2: Soil hydraulic properties prior planting

Soil horizons	Depth (m)	80% FC (%)	PWP (%)	SAT (%)	KSAT (m d^{-1})
Orthic A	0,3	7,8	5,1	12,3	0,069
Soft plinthic B	0,4	14	10	16,8	0,124
Gleyic	0,3	-	-	-	-

Note: FC = field capacity, PWP = permanent wilting point, SAT = saturation point, and KSAT = saturated hydraulic conductivity

3.2.3 Plant material

Three sorghum genotypes used in the study were a low tillering (PAN606) obtained from Pannar Seeds®, and a high tillering (Mr Buster) hybrid, an open pollinated variety (Macia) from International Crop Research Institute for the Semi–Arid Tropics (ICRISAT), and a landrace from local farmers.

PAN606 is a bronze grained hybrid with low-tannin, semi-dwarf variety with a height of 1.2 m. It is a medium-late maturing cultivar that takes about 120-150 days to reach maturity. It is a low tillering cultivar with 0-1 tillers expected and is preferred by commercial farmers who do not link tillering to yield due to its low tillering propensity.

Mr Buster is a red grained, non-tannin hybrid that produces about 4-8 tillers, and it is considered as a high tillering cultivar mostly preferred by commercial farmers (Elhassan *et al*., 2015). It is a medium maturing type (120-130 days to maturity) that has broad adaptation to a wide range of environments. It is suitable for dryland and irrigated fields and has a yield potential of 5.5 -10 t/ha (Smith, 2006), as it delivers on both narrow and wider row configurations, and this makes it persistently popular in the sorghum seed market since its release in the early 1990s (Clarke *et al*., 2019). In most of the tillering research, Mr Buster has been used as a standard commercial check hybrid (Kulathunga *et al*., 2021).

Macia is a white grained, low tannin variety developed by ICRISAT and CGIAR. It offers nutritional benefits, biotic stress tolerance, and market-related needs but is prone to tillering (Upadhyaya and Vetriventhan, 2018; Nagesh Kumar *et al*., 2021). It is widely grown in semi-arid regions across Sub-Saharan Africa and thrives well under harsh conditions (Takele and Farrant, 2013; Charyulu *et al*., 2014). The variety is high yielding with a potential of 3–6 t/ha and it matures early (115 -120 days to maturity) (Setimela *et al*., 1997; Kubiku *et al*., 2022). It is a semi-dwarf variety with the height of 1.3 -1.5 m and has a thick stem and it is drought and bird tolerant, causing it to be widely favoured by farmers (Kugedera *et al*., 2022). Macia is a medium tillering variety producing about 1-3 tillers per plant or does not tiller and has a stay green trait which extend beyond harvest.

The local landrace sourced from smallholder farmers in Mankweng (23°53′1.2″ S and 29°42′28.36″ E) Limpopo province, South Africa; is a dark-browned grained with high tannin, and it is a late maturing (140-180 days) and a tall cultivar with a height ranging from 3 – 4.5 m (Buah *et al*., 2010). It is a high tillering cultivar mostly preferred by smallholder farmers due to its adaptability to local conditions and produces about 4-8 tillers per plant. The information on landrace yield potential, morphology and phenology were lacking due to minimal contribution to sorghum formal and commercial markets.

3.2.4 Experimental design and layout

The experiment was laid out as split-plot with water regimes as main blocking factor and the sorghum varieties as the sub-factor laid out in randomised complete block and replicated three times. The study comprised of 4x3 factorial combination of sorghum varieties and irrigation regimes which were achieved using sprinkler. The irrigation levels were full irrigation, deficit irrigation, and rainfed which were separated by 10 m pathways to limit water lateral flow between the blocks. The trial had 144 experimental rows of 3 m long and a 1 m spacing between the replications. The plot had inter and intra row spacing of 0.75 and 0.20 respectively which then accounted for 66 667 plants/ha. Each subplot had 3 x 2.25 (6.75 m^2) with four rows, where the two inner most rows were for experimental plants, and the 2 remaining border rows were for destructive sampling for biomass assessment.

The six moisture access tubes were inserted into the soil where each experimental plot had two access tubes between the replications. The rainfed trial had 2 access tubes which were situated between the replicates 1 and 2 and the other between replicates 2 and 3. Subsequently, the full and deficit irrigation plots also had the same setup of inserting the access tubes. The soil water content was recorded weekly at the depth of 1 m using a moisture probe PR2/6 HH2 (Delta-T, UK) that was connected to a PR2/6 HH2 meter and inserted into the access tube to give soil water readings in percentages. The moisture probe measures soil moisture at 6 different depths at intervals of 0.1, 0.2, 0.3, 0.4, 0.6 and 1.0 m within the soil profile (Delta-T, UK). The irrigation amount and duration were applied based on the readings in soil water content which were used to check the difference to 80% field capacity in a spreadsheet containing data from the SPAW model.

The plots were subjected to irrigation at 80% field capacity as to accommodate future rainfall, minimize drainage and subject crops to stress (Ayars *et al*., 2006; Mondaca-Duarte *et al.*, 2020). This field capacity method involves accounting for all incoming and outgoing water from the soil root zone. The major inputs for the sorghum trial were rainfall (P) and irrigation (I), while output that was considered was change in soil water contents (ΔSWC). Initially after planting, the plots had received water from rainfall which then facilitated their emergence. The method of applying irrigation as the difference to 80% FC from soil water content was launched/used soon after rainfall had stopped on full and deficit irrigation plots.

The full irrigation plot was supplemented with water weekly throughout its life cycle starting from the time irrigation was launched. The rainfed plot had solely received water from rain throughout its life cycle. For plots subjected to deficit irrigation, water was applied from flag leaf stage till physiological maturity. The withdrawal of irrigation at vegetative stage was to allow the tiller appearance and assess their performance and recovery. Furthermore, irrigation could not be withdrawn during the reproductive stage because water stress can cause yield reduction of more than 55% which is more compared to 36% reduction in vegetative growth stage (Assefa *et al*., 2010). The flag leaf stage was observed when 50 % of the plants in the experimental rows had the leaf that was shorter than the preceding leaves positioned upright, emerged prior flowering and located close to the panicle (Roozeboom and Prasad, 2019). Physiological maturity was then observed when formation of the black layer, a dark spot at the base of the grain was visible and the plants had reached their maximum dry matter accumulation (Djanaguiraman *et al*., 2018; Roozeboom and Prasad, 2019).

3.2.5 Land preparation and crop management

The land was prepared mechanically using a tractor with a mouldboard plough and rotovated to loosen the soil. The plots were demarcated manually using the strings, 100 m measuring tape, markers, and the hoes. The seeds were hand sown manually and at crop establishment they were thinned to the selected crop density of 0.2 m. NPK calculations were done based on the recommended rates of 90:45:45 in kg/ha. Round-up® was applied to control weeds four weeks before planting, thereafter, weeding was done manually using hand hoes regularly after planting to eliminate resource competition. The scarecrows were established to control the bird damage at emergence. The panicles were covered by the nets at flowering to protect the grains from bird attacks.

3.2.6 Data collection

3.2.6.1 Phenological development

The 10 plants were randomly selected after crop establishment for tagging procedure which required the rope, white plastic tags, and the permanent marker. The main stem was identified and attached with a tag at the base and labelled as main stem. Tiller emergence and ranking were observed weekly on 10 tagged plants until there was a stagnation of 14 days in the number of tillers from the two experimental rows, with emergence defined as when tillers first became visible as a side branching shoot from

the base of the main stem. The ranking of tillers was based on identifying the first tiller that appeared at the base of the main stem and its growth was following that of the main stem which was then tagged as tiller 1. The second to appear was labelled tiller 2 and others that appeared after were also labelled accordingly. The rank of each emerged tillers was defined by timing of appearance.

Flag leaf formation stage was determined when half of the experimental plants exhibited the leaf tip in the whorl prior to heading. Time to flowering was recorded when yellow anthers appeared at the tip of the panicle and 50 % of the plants were showing anthers that were midway down the panicle. Physiological maturity was then recorded when 90 % of the grains had uniform colour corresponding to the variety's maturity stage, also by the appearance of the black spot on the base of the seed. During this stage the grains had reached their maximum dry weight, and their moisture content decreased to optimal level (≤12.5%).

3.2.6.2 Growth and development

The number of tillers per plant were calculated weekly as the sum of all tillers counted on the 10 tagged plants, divided by the number of plants. Number of fertile tillers per plant were calculated at physiological maturity as a percentage of the sum of all tillers that produced panicles on the tagged plants, divided by the number of plants. Fractional green canopy cover (FGCC) was used to estimate crop canopy development (Patrignani and Ochsner, 2015). The Canopeo app was used where downward-facing images were taken weekly from crop establishment until physiological maturity in the middle of experimental rows using a smartphone camera. The camera was adjusted at 0.5 m distance from the top of the canopy to minimize overestimation of FGCC.

Plant height and stem width were measured upon physiological maturity using the measuring tape and calibrated ruler to validate the performance and contributions to biomass of the cultivars and the stem ranks.

Biomass and dry biomass accumulation were determined by destructively sampling plants harvested from the plot every two weeks. The samples were collected at the two border rows. Scissors were used to cut the plants and put them in the brown paper bags and labelled as whether it is a main stem or tiller. The main stem and tillers were put in separate bags and later weighed using a weighing scale. The fresh shoot

biomass was weighed to assess the growth, development and productivity of plants over time and the samples were then oven dried at 80°C for 72 hours. The shoot dry biomass was weighed after 72 hours and the data on biomass and dry biomass accumulation were used to assess how tillers contribute to biomass accumulation under various irrigation regimes mainly reporting on their performance and their vigour. The panicle mass and shoot biomass were weighed separately upon the start of grain filling whereby panicles from tillers and main stem were separated in destructively sampled plants to enable determination of harvest index (HI) which was calculated as follows:

$$HI = Y/B \qquad \text{Equation 2}$$

Where: Y= panicle mass of tillers and main stem

B = above ground biomass

3.2.6.3 Yield and yield parameters

Three panicles per experimental plot were selected randomly after harvest and were used as the representatives which were then used to calculate the yield average. The panicles of main stem and that of tillers were then weighed separately and then threshed. Grain yield was measured by weighing the grains of the three selected panicles per plot separately. The panicles were weighed using a weighing scale and then later threshed and selected 1000 seeds. The 1000 seeds weight were selected from the three representative grain weight and the selection was based on assessing the quality of the seeds by selecting only the healthy and viable.

The tiller contribution to yield was calculated using the following formula:

$$Tiller\ contribution = \frac{yield\ of\ the\ tiller}{total\ \ yield} \times 100 \qquad \text{Equation 3}$$

3.2.7 Data analysis

Data collected were subjected to statistical analysis of variance (ANOVA) using GenStat® Version 20 (VSN, International, United Kingdom). The unbalanced ANOVA was done to account for unequal number of tillers due to differences in tillering propensity of the cultivars. Means were separated using least significant difference

(LSD) at a probability of 5% level of significance. The Bonferroni test was then conducted for multiple mean comparison.

3.3 Results and discussion

The number of tillers significantly differed within the cultivars due to genetical differences of the varieties. Additionally, the number of fertile tillers, height and stem width were significantly influenced by main interaction (C x IR), cultivar, (C) and the irrigation regimes (IR). The integration (C x IR) significantly influenced the shoot dry biomass (SDB) and the grain yield (GY). The significant differences could be attributed to the highly significance differences of cultivars.

Table 3.3: Summary analysis of variance indicating the effect of integrating irrigation regimes, stem ranks, and different sorghum cultivars on sorghum growth and development and yield parameters.

Source of variance	P values									
	No. T	No. FT	Height	SW	SDB	SBDC	HI	HIC	GY	GYC
Stem ranks (S)					**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
Cultivar (C)	**<.001**	**0.013**	**<.001**	**<.001**	**<.001**	0.979	**0.016**	0.976	**<.001**	0.991
Irrigation regimes (IR)	0.109	**0.001**	**0.004**	**0.020**	0.891	0.880	0.170	0.946	**0.031**	0.975
C x IR	0.175	**0.014**	**<.001**	**0.030**	**0.018**	0.997	0.604	1.000	**<.001**	1.000

Note: No. T= number of tillers, No. FT= number of fertile tillers, SW= stem width, SDB= shoot dry biomass, SDBC= contribution to shoot dry biomass, HI= harvest index, HIC= harvest index contribution, GY= grain yield, GYC= grain yield.

3.3.1 Crop growth and development

3.3.1.1 Shoot dry biomass

The interaction of cultivar selection and irrigation regimes had a significant impact on sorghum shoot dry biomass ($p<0.05$). Shoot dry biomass was comparable and statistically similar in different irrigation regimes (figure 3.2A), indicating that cultivar selection was the main contributor to observed statistical differences within the main interaction.

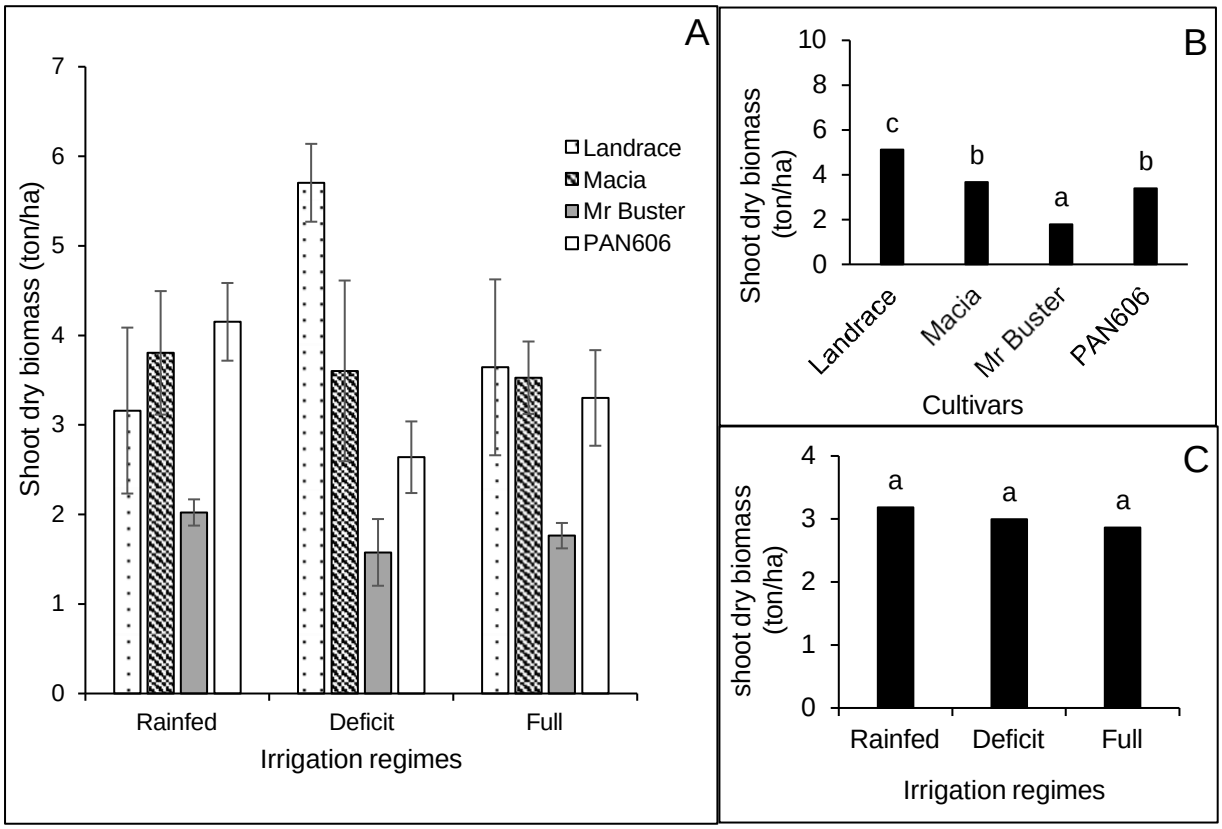

Figure 3.2: Shoot dry biomass response under the integration of different cultivars and irrigation regimes (A), the different sorghum cultivars (B), irrigation regimes (C). Bar values displaying the same letter are not significantly different at p≤0.05.

The irrigation regimes did not have a significant effect on the shoot dry biomass production (Figure 3.2C). This is because the amount of rainfall received from planting until towards flowering (1- 62 DAP) was sufficient for biomass production (Figure 3.1), and as such the crops were not subjected to water stress. Thus, the amount of water received during these days did not differ within the plots. The amount of rainfall received in rainfed was 321, 32 mm while deficit and full irrigation had 408, 54-mm and 443,68-mm water use throughout the sorghum growing season. Since sorghum requires 450 – 650 mm of water for optimal growth during a growing season (Jewitt *et al*., 2009; Hadebe *et al*., 2016), this means that the plots had experienced similar stress but in later growth stages where rainfall was inefficient. This is because rapid biomass accumulation in the shoot is at vegetative stage and in flowering (Malhi *et al*.,

2006). Moreover, the plants tend to shift more energy to dry matter partition in the grains particularly after flowering (Youssefian *et al.,* 1992).

Landrace had indicated to have significantly higher shoot dry biomass compared to other cultivars (Figure 3.2B). These differences can be attributed to genetics such as maturity length, the height and stem width of the cultivars and their tillering propensity which contribute to biomass accumulation (Alam, 2013). Landrace as the late maturing cultivar tend to have longer growing season which increase the duration of photosynthesizing and allocation of resources to aboveground growth over a prolonged period leading to high biomass (Jiang *et al*., 2022). Mr Buster as a commercial dwarf hybrid with a very thin stem (Van Oosterom *et al*., 2021) had very low shoot dry biomass due to height and stem width which were the major contributors to biomass as indicated in Figure 3.3 B and C. Landrace have a very thick stem and it is a tall cultivar which had an advantage on light interception which translated to high biomass. Height affects the plant's ability to capture light efficiently, which directly impacts the plants overall growth and biomass production (Bebre *et al*. 2021). Taller plants tend to have a larger leaf surface area, which allows them to intercept light and support higher rates of photosynthesis leading to an increase in above ground biomass (Khurana and Singh, 2001; Anten, 2005).

This study's results are in contrary to the expected outcomes where the high tillering cultivars such as Mr Buster are expected to contribute to biomass particularly under sufficient water availability. This is because tillers play a role in biomass accumulation, and it directly affect plant architecture (Hammer, 2006; Kim *et al*., 2010). Biomass accumulation decreases with the decrease in irrigation whereby under full irrigation the biomass is expected to be higher than in water deficit conditions (Dahmardeh *et al*., 2015; Chai *et al*., 2016). The results of this study indicate that Mr Buster did not perform well in all the irrigation regimes due to intraspecific competition between the stem ranks which might have led to root growth being prioritised over the aboveground growth. This is because plants adjust to water availability through shift of resource allocation between the shoots and roots resulting into less shoot growth (Chaves *et al*., 2003; Bektas *et al*., 2023).

Contributions to shoot dry biomass

The contribution of stem ranks to shoot dry biomass differed significantly within the stem ranks ($p<0.05$). The main stem had higher contributions relative to tillers which also dominated within the cultivar selection and irrigation regimes. This could be attributed to main stem developing earlier than the tillers, giving it a head start in terms of growth and resource accumulation. Furthermore, the main stem receives more carbon allocation compared to tillers which then impact biomass partitioning (Fumey *et al*., 2016). Additionally, the resource allocation or availability are firstly accumulated by the main stem and then be partitioned to the tillers. This is because the availability of assimilates for tiller demand decreases with either increasing demand of the main stem or reduced supply (Lafarge and Hammer, 2002). There is a positive trend within the stem ranks, which decreases within the stem ranking hierarchy.

3.3.1.2 Harvest index

The primary interaction of cultivar selection and irrigation regimes did not have a significant difference on the harvest index. However, the cultivars exhibited a significant difference (figure 3.5A) whereas the irrigation regimes did not show any differences (figure 3.5B). This could be attributed to differences in phenological developments of cultivars (figure 3.5 C and D). Landrace had high harvest index compared to Mr Buster. This could be due to it being a late maturing cultivar which tend to have a longer vegetative and reproductive phase whereas short season cultivars tend to have low harvest index (Calvino *et al*., 2003). This then allows more time to capture resources, which can lead to increased biomass accumulation, both in vegetative and reproductive parts (Prasad *et al*., 2006). The low harvest index of Mr Buster could be attributed to intraspecific competition between the stem ranks which then resulted to very few numbers of fertile tillers. More tillers competing for the same resources under unfavourable conditions lead to tiller growth being compromised, leading to lower biomass accumulation and grain filling (Rotili *et al*., 2021).

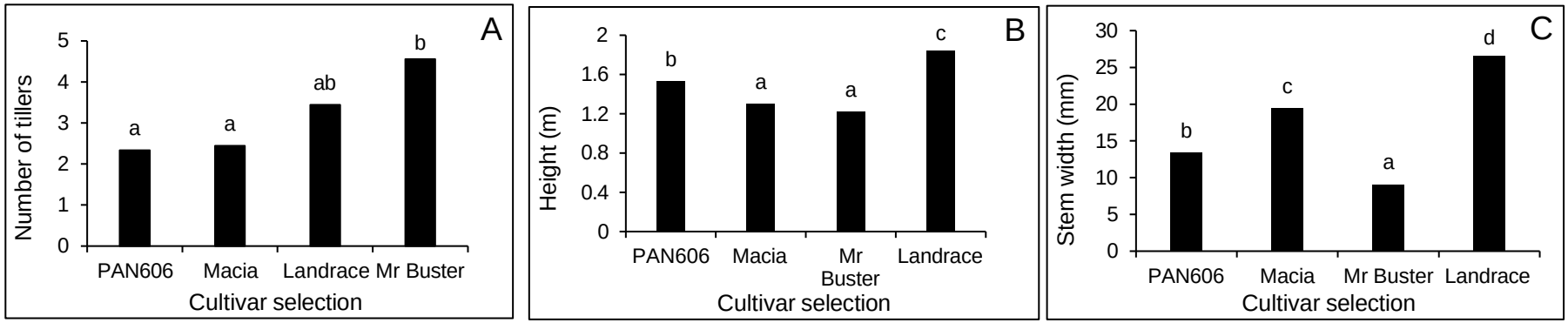

Figure 3.3: The response of total number of tillers under the integration of different cultivars and irrigation regimes (A), the total tiller number produced by different sorghum cultivars (B), and the height of the cultivars. Bar values displaying the same letter are not significantly different at p≤0.05.

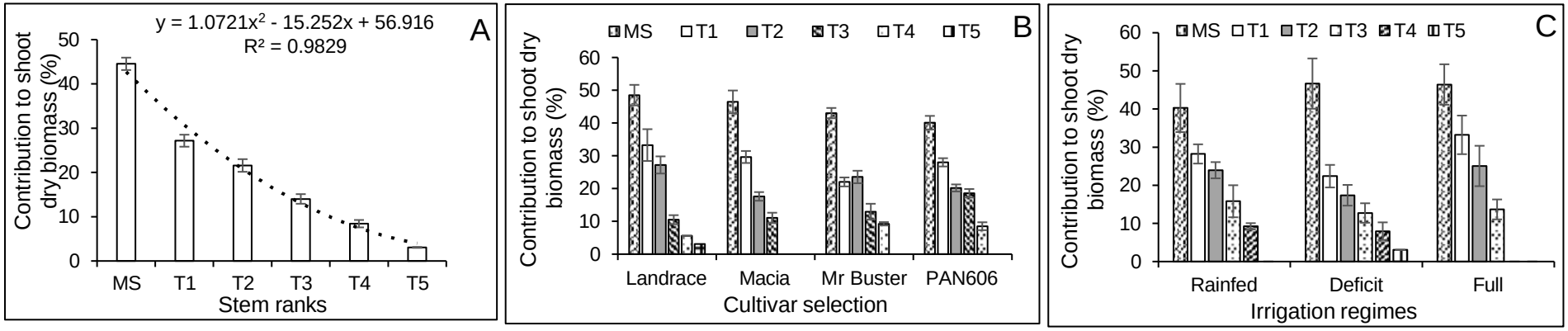

Figure 3.4: The contribution of the stem ranks to shoot dry biomass (A) within the cultivar selection (B) and different irrigation regimes (C).

These results are in contrary with the expected outcomes where early flowering hybrids tend to have high harvest index due to shorter vegetative growth and channelling the biomass partitioning to grains (Hammer and Broad, 2003; Diawara, 2012). Landrace as the traditional variety possess adaptive traits that optimize their growth under local conditions leading to high yield production (Lopes *et al*., 2015; Kumar *et al*., 2022; Mohammed *et al*., 2023). However, hybrids are bred to optimize grain yield and tend to allocate more biomass to grains, resulting in a higher harvest index and are mostly bred to have higher grain yield potential than landraces (Belay and Meresa, 2017; da Silva *et al*., 2018). Landrace and Mr Buster have statistically indicated to have similar number of tillers (Figure 3.6 A), however differed in the percentage of fertile tillers (figure 3.6 B). The study findings then indicate that more yield is anticipated on landrace while less from Mr Buster. This is because both cultivars have produced more tillers as high tillering varieties, however, due to competition of resources within the stem ranks of Mr Buster led to very few fertile heads.

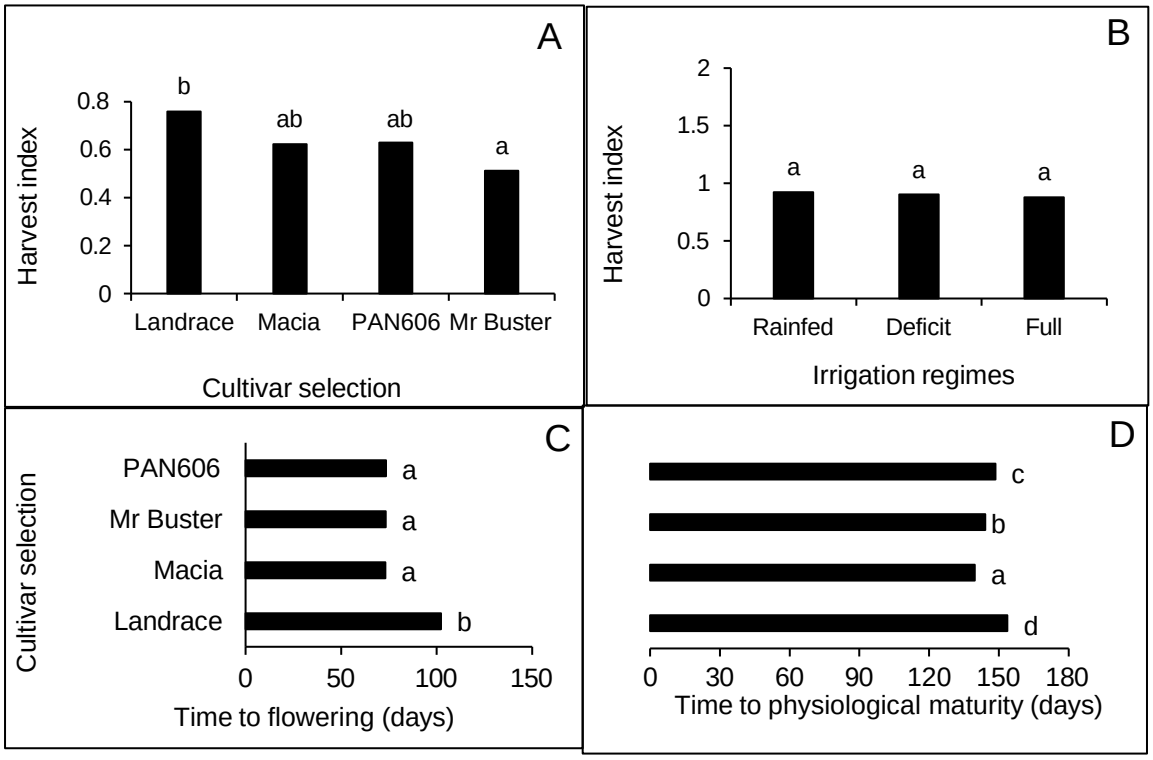

Figure 3.5: Sorghum harvest index between the cultivars (A) and within varying irrigation regimes (B) as influenced by time to flowering (C) and physiological maturity (D). Bar values displaying the same letters are not significantly different at p≤0.05

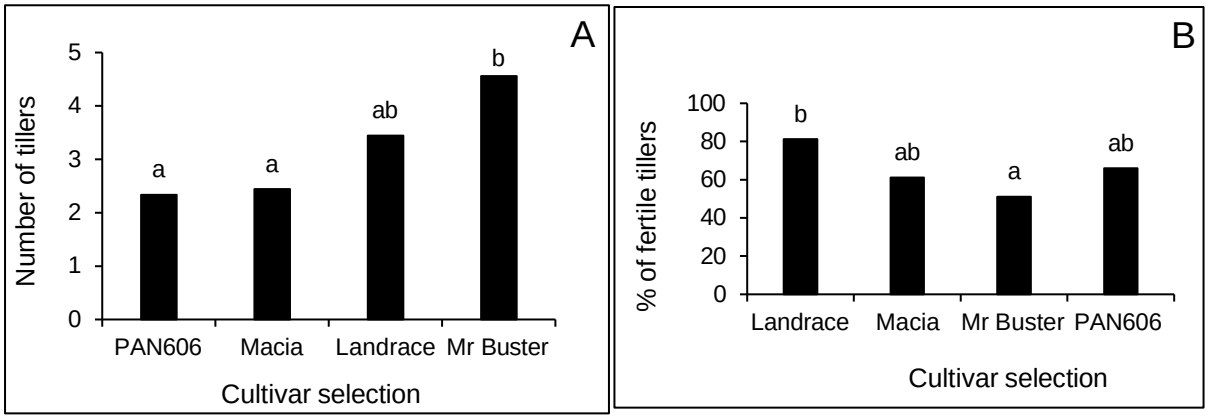

Figure 3.6: Sorghum number of tillers (A) and the percentage of fertile tillers (B) within the cultivar selection. Bar values displaying the same letters are not significantly different at p≤0.05.

Harvest index within the stem ranks

The stem ranks indicated a highly significant difference in harvest index (Figure 3.7A) and this could be attributed to differences in phenological development (Figure 3.7 B and C). Main stem and tiller 1 had indicated to have high harvest index compared to tiller 5. This is because tiller 1 follows an early developmental path that is synchronized with the main stem as compared to other tillers. Moreover, tiller 5 underwent all the developmental stages later than other tillers and it was the last to reach maturity. These findings indicate that more yield is expected from main stem and tiller 1 while average from tiller 2 till tiller 4 but very less from tiller 5. These results were anticipated because the duration of sorghum developmental differ among the main stem and tillers due to consistent hierarchy that tillering follow (Lafarge *et al*., 2002).

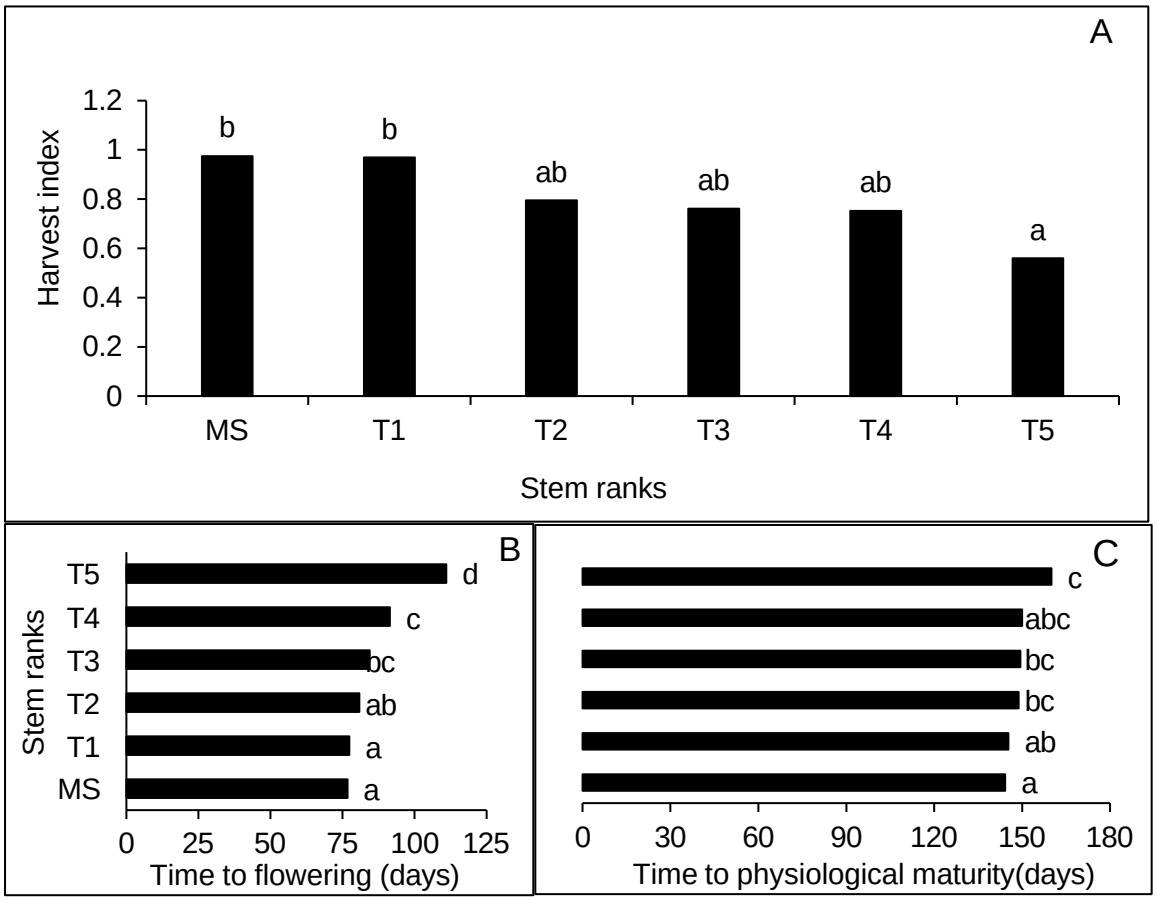

Figure 3.7: Harvest index between the stem ranks (A) as influenced by time to reach flowering (B) and physiological maturity (C). Bar values displaying the same letters are not significantly different at p≤0.05.

Contributions to harvest index

The contribution of stem ranks to harvest index differed significantly. These differences can be attributed to the variability in maturity timing between the main stem, first tiller, and subsequent tillers which then lead to varying contributions in harvest index (Destro *et al*., 2001). The main stem had indicated to have a high harvest index within the stem ranks (Figure 3.8 A); however, it was not the case within the irrigation regimes and the cultivar selection (figure 3.8 B and C). The mean averages of harvest index within the stem ranks indicated that more yield was sourced from the main stem, tiller 1, tiller 2, and average from tiller 3 and tiller 4 while less was anticipated from tiller 5. Since the fertility of tillers that have a significant contribution to yield range from 7 – 91% (Lafarge *et al*., 2002; Wang *et al*., 2020), the results indicate that the tiller cut-off for significant contribution could be from tiller 1 to tiller 3. This is because competition for resources

tend to grow stronger as more tillers appear at the base of the stem. Moreover, as the order of tillers increases, the later emerged face challenges in resources accumulation which then makes it difficult for them to significantly contribute to overall yield (Kariali *et al*., 2008).

The main stem in deficit and full irrigation had comparable contributions with the tillers (figure 3.8 B). However, rainfed main stem had indicated to have high yield potential compared to tillers. This could be attributed to the phenology of the stem ranks indicating that main stem took less time in vegetative stage hence focusing the energy into grain production. The stem ranks were comparable within the cultivar selection (figure 3.8 C). The cultivars had indicated to have a tiller cut off threshold of 7 % for significant contribution which is based on the tiller fertility range. These results indicate that tillers contributing below the cut off threshold do not have a meaningful impact on yield and are not worth harvesting. Tillers up to tiller 3 demonstrate significant contributions, while tiller 4 and tiller 5 lack the capacity to contribute significantly to the overall yield.

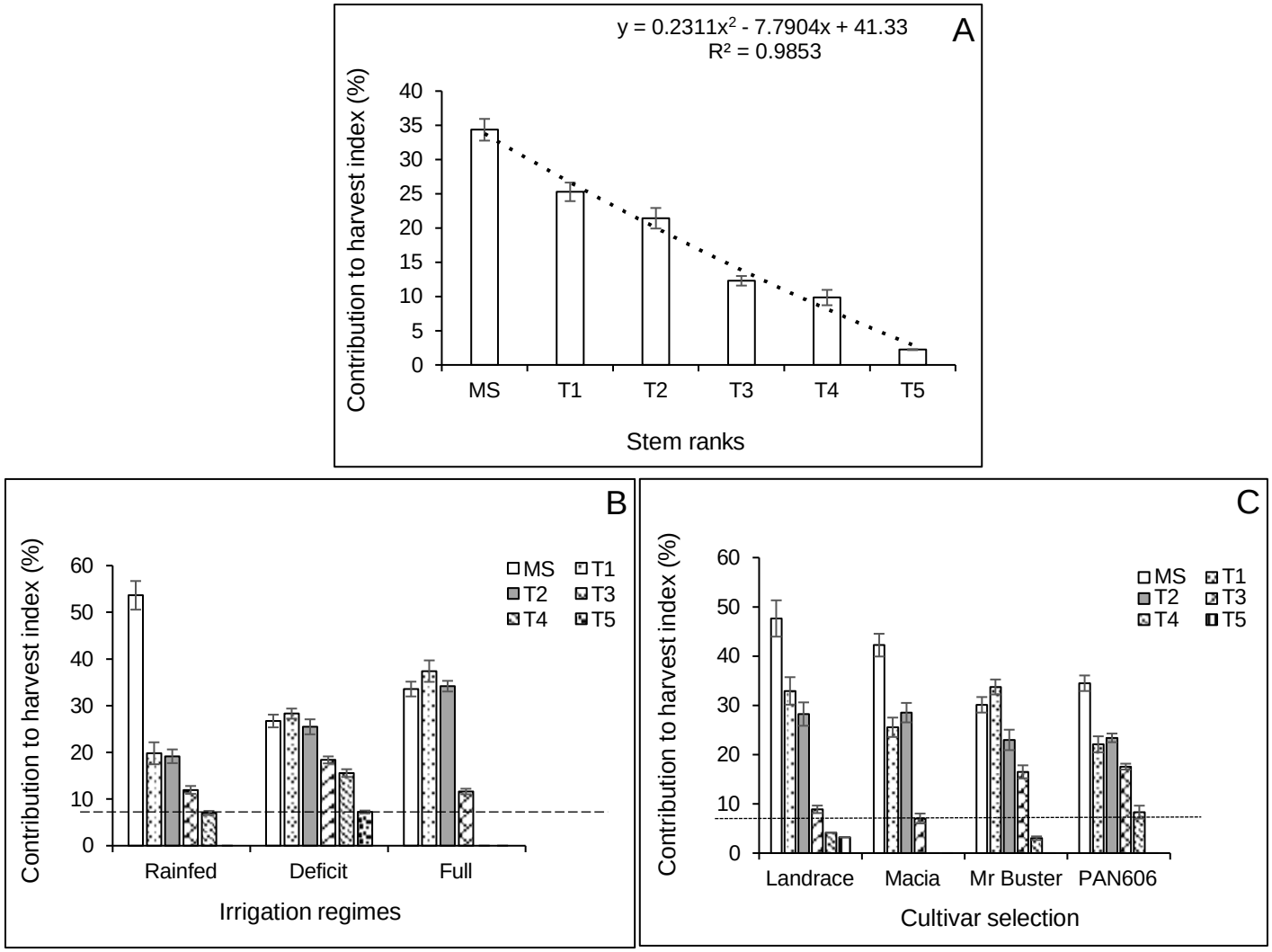

Figure 3.8: Contributions of stem rank to harvest index (A), within the irrigation regimes (B) and cultivar selection. The bar values having the same letters are not statistically different at p≤0.05

3.3.2 Grain yield

The interaction of irrigation regimes and the cultivar selection significantly influenced sorghum grain yield ($p<0.05$) indicating that both cultivar selection and irrigation regimes contributed to yield. The yield was statistically comparable within the interaction and high yield was sourced from deficit plot.

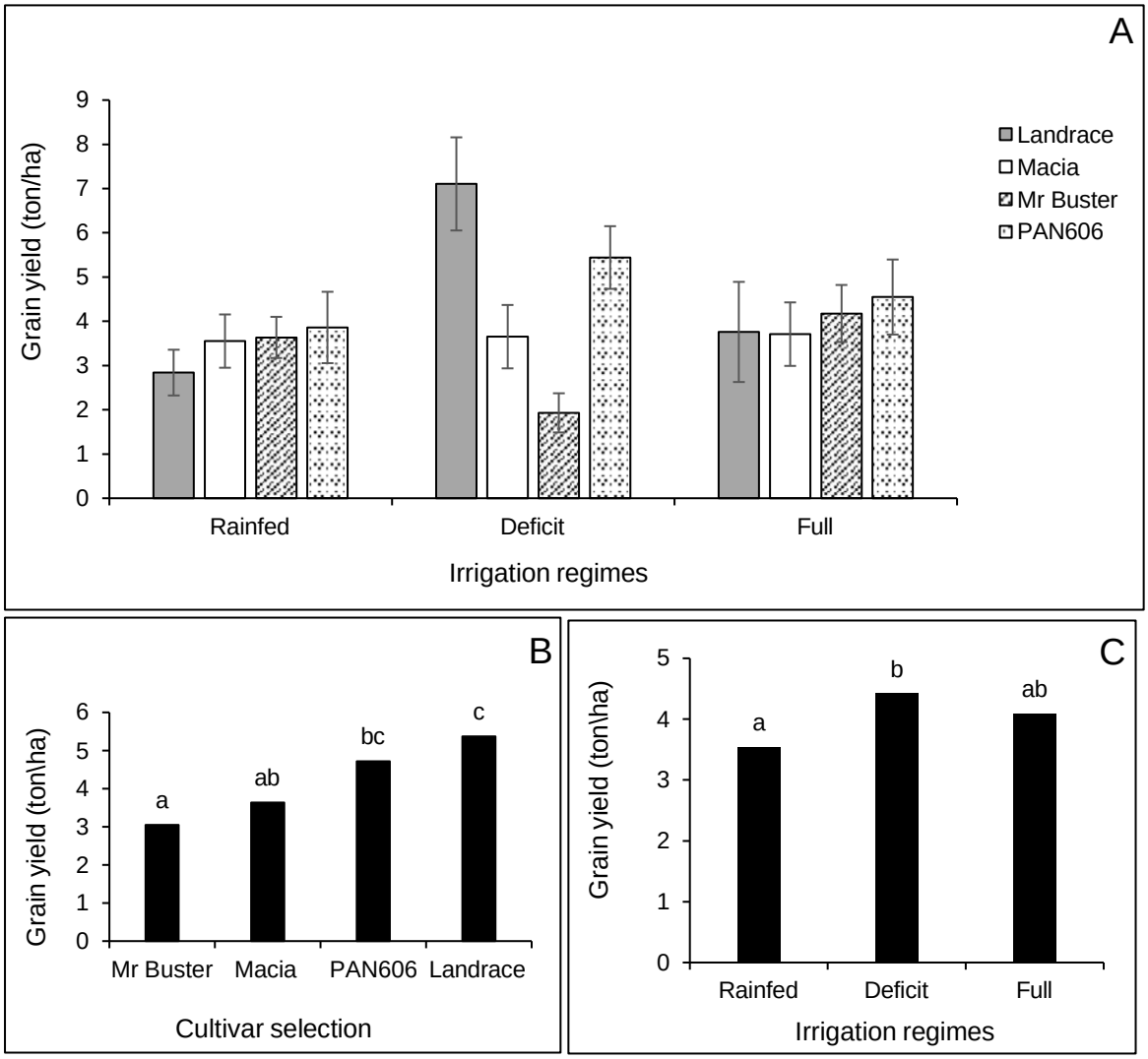

Figure 3.9: Grain yield response under the interaction of different cultivars and irrigation regimes (A), the different sorghum cultivars (B) and varying irrigation regimes (C). Bar values displaying the same letter are not significantly different at $p\leq0.05$.

The irrigation regimes indicated significant difference where deficit plot had high yield compared to rainfed (figure 3.9 C). This could be attributed to deficit irrigation strategy that conserves water while optimizing the grain yield by allowing plants to experience controlled water stress hence promoting deeper root development and improving water use efficiency during critical growth periods like flowering and grain filling (Costa *et al*., 2007). These differences could also be attributed to time taken in phenological development between the irrigation plots (figure 3.10). The low yield in rainfed plot could be attributed to crops experiencing water stress which then forced the plants to enter reproductive and maturation stages earlier leading to shorter growth cycle as a means of drought escape (Mabhaudhi and Modi, 2013). The deficit plot reached flowering at the same time as full irrigation plot but matured later than all the plots. This could have led to longer duration for grain filling and extended period for resources utilization.

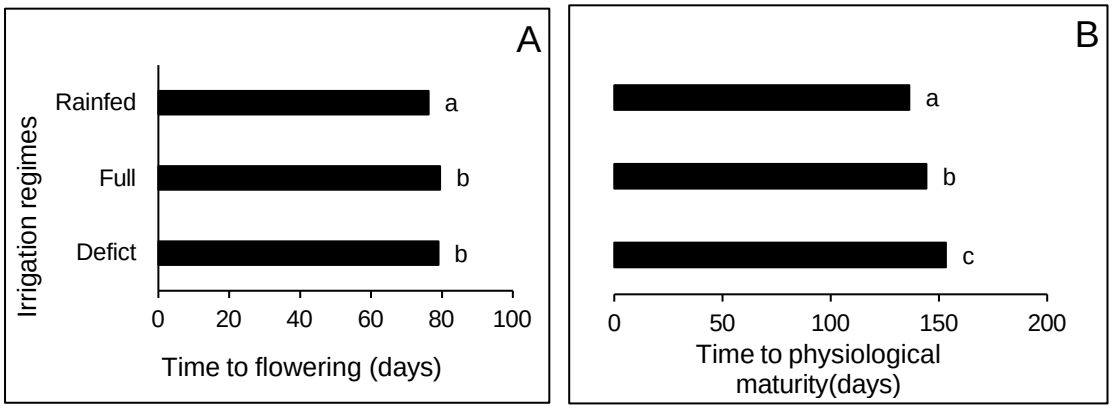

Figure 3.10: The difference in time to flowering (A) and time to physiological maturity (B) between the irrigation regimes. Bar values displaying the same letters are not significantly different at p≤0.05.

Landrace indicated significantly higher yields compared to Mr Buster and Macia (figure 3.9 B). This could be attributed to maturity length where it took the longest time to mature, hence accumulating more resources. Late maturing cultivars tend to have longer growth period which enables them to accumulate more biomass over time,

leading to higher overall yields (Jatoi *et al*., 2012; Jiang *et al*., 2022). Since the landrace was sourced from a local farmer in Mankweng, its yield was anticipated to be high due to its adaptability to local environmental conditions. Conversely, sorghum landraces are known to produce low grain yields which are less than 1 ton/ha on average despite their diverse adaptive traits (Adam *et al*., 2018).

Although Landrace and Mr Buster are genetically high tillering cultivars and indicated to have produced statistically similar average number of tillers (figure 3.6 A), their yield differed significantly due to the differences in percentage of fertile tillers (figure 3.6 B) that contributed to yield. Landrace indicated to have 81% of fertile tillers while Mr Buster had 51%. This is because Mr Buster produces up to 8 tillers and as a modern hybrid it produces from zero to four fertile tillers that contribute around 70 – 80 % to overall yield (Lafarge *et al*., 2002; Lafarge and Hammer, 2002). This then explains that only half of the produced tillers were fertile and this could be due to intraspecific competition and resource capture between the stem ranks. The study results are in contrary with the expected outcomes for Mr Buster as it is known to have a yield potential of 5.5-10 ton/ha, has a broad adaptation to a wide range of environments and suitable for dryland and irrigated fields (Smith, 2006; Clarke *et al*., 2019). However, on average it yielded 3.04 ton/ha which was the lowest compared to other cultivars.

Contributions to grain yield

The stem ranks significantly differed in their contributions to yield where the main stem had indicated to be the major contributor in varying irrigation regimes and some of the cultivars excluding Mr Buster where it indicated tiller 1 contributing higher than main stem. This could be attributed to tillers playing an important role in grain yield particularly in water limited conditions, such as rainfed and deficit where it can compensate for main stem failure or poor growth (Lafarge and Hammer, 2002; Assuero and Tognetti, 2010). The tiller yield contributions can vary widely, ranging from 5 - 78% (Lafarge *et al*., 2002). The results indicated that the overall tiller contribution was 57 % having tiller 1 and tiller 2 as the major contributors while main stem contributed 43 %. This is because tillers that emerge earlier have a high advantage of resources accumulation. In contrast, later emerging tillers are less

competitive, contributing less to yield due to their reduced access to assimilates and weaker sink strength.

Tillers are known to contribute significantly to overall yield within the threshold of 5 and 78 %. This then demonstrate that any yield contribution that is less than 5 % is considered a non-significant contribution. The stem ranks within the irrigation regimes indicated a significant difference in contributions where the main stem was the dominating contributor. Three tillers T1 (27 %), T2 (15 %) and T3 (9%) had indicated to have contributed significantly to total yield in irrigation regimes as they contributed within the threshold whereas later emerged tillers T4 (4 %) and T5 (2 %) had minimal contributions (Figure 3.8 B). The stem ranks indicated a decreasing trend with an increase in number of tillers. The cultivar selection highlighted differences in the contribution of stem ranks, with the main stem being the dominant contributor, similar to the pattern observed across irrigation regimes. On average, the significant contributors across cultivars were the first three tillers (tiller 1 – tiller 3), as they consistently contributed within the threshold. This suggests that the cut-off for harvestable tillers could be up to tiller 3, as the later-emerging tillers (tiller 4 and 5) did not make a significant contribution to the total yield.

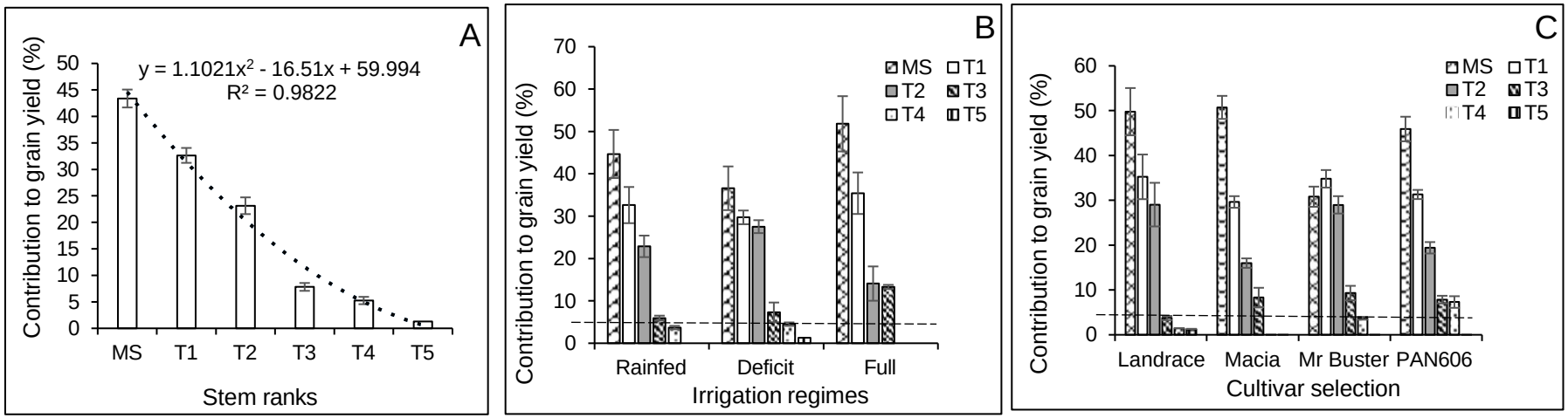

Figure 3.11: Contributions of stem rank to harvest index (A), within the irrigation regimes (B) and cultivar selection. The bar values having the same letters are not statistically different at p≤0.05

3.4 Conclusions and recommendations

The study findings indicated that the interaction of varying irrigation regimes and cultivar selection significantly influenced the sorghum yield. The significantly higher yields were obtained by landrace under deficit irrigation and this was attributed to maturity length and the adaptability to local environment. The results revealed significant differences in yield across irrigation regimes and cultivars, with the deficit irrigation plot (4.5 ton/ha) outperforming the rainfed plot (3.4 ton/ha). This was attributed to the controlled water stress in deficit irrigation, which promoted deeper root development and enhanced water use efficiency during critical growth stages. The low yield in the rainfed plot was due to early maturity driven by drought escape, while the deficit plot benefited from a longer grain-filling period. Among the cultivars, Landrace had the highest yield (5.37 ton/ha) than Mr Buster (3.04 ton/ha) due to its longer maturity period which allowed it to accumulate more biomass. Although both Landrace and Mr Buster are high tillering cultivars, their yields differed significantly due to the higher percentage of fertile tillers in Landrace (81%) compared to Mr Buster (51%). This suggests that farmers in water-limited environments can adopt deficit irrigation to optimize grain yield with limited water input. Additionally, selecting cultivars like Landrace that are well-adapted to local conditions and have higher percentages of fertile tillers may improve yield outcomes. The tiller grain yield had an influence on the overall grain yield where the study results quantified 57 % of tillers contribution, which is higher than the main stem contribution of 43 %. This then shows that the high tiller contribution can enhance total yield. The results show that the main stem was statistically the dominant contributor to yield across different irrigation regimes and cultivars. The early emerging tillers T1 (27 %), T2 (15 %) and T3 (9%) are the most productive due to their better access to assimilates whereas later emerged tillers T4 (4 %) and T5 (2 %) are less competitive and contribute minimally to yield due to reduced access to assimilate. The results indicate that tillers contributing less than 5% are considered non-significant, while tiller 1 to tiller 3 consistently contributed within the 5-78% threshold across irrigation regimes and cultivars. This suggests that tillers up to tiller 3 are worth harvesting, while tiller 4 and tiller 5 have a minimal impact on the total yield. Therefore, the cut-off for harvesting tillers could reasonably be set at tiller 3, as tillers beyond this point do not significantly contribute to the overall yield.

Therefore, farmers can cultivate landrace under deficit irrigation for sustainable yields and target the tiller harvest up to tiller 3 for greater tiller contributions.

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CHAPTER 4: EFFECT OF VARYING IRRIGATION REGIMES ON CROP WATER USE AND WATER PRODUCTIVITY FROM TILLERS AND MAIN STEM OF SELECTED SORGHUM VARIETIES

ABSTRACT

The contributions of sorghum tillers and main stem to 'yield per drop' and water use under different water availability and sorghum cultivars have not been extensively quantified both locally and globally. Therefore, the study investigated the impact of varying irrigation regimes on water use and water productivity of the main stem and tillers of different sorghum varieties, hence assessing their contributions to water productivity. The study was carried out as a 3 x 4 factorial, laid out as a split-plot and arranged in a randomized complete block design (RCBD). The plots comprised of two irrigation regimes assigned as the main (full, deficit) which were compared to rainfed (unirrigated control) and four sorghum cultivars as subplots (Mr Buster, PAN606, Macia, Local landrace) replicated three times. The data collected included soil water content, maximum canopy cover, water use (ET), and water productivity. The interaction of irrigation regimes and cultivar selection significantly influenced water use and water productivity. The longer maturity of deficit plot extended the water consumption which led to significantly high ET than other plots. High maximum canopy of rainfed was due to tillering propensity as a means of stress response. Mr Buster significantly had high water use (239.9 mm) compared to landrace (215.9 mm). The main stem significantly had low water use compared to tiller 5 due to early maturity. The water use contribution of tillers was higher (70 %) compared to the main stem (30 %). The rainfed plot exhibited high water productivity due to low water use and moderate yield. The high yield of landrace and its low water use translated to high water productivity. The water productivity of main stem and tiller 1 was higher than other tillers. The contribution of water productivity from tillers was 53 % while main stem contributed 47 %. The high-water productivity of rainfed plots reinforces that sorghum yield can be productive under water scarce conditions. Therefore, farmers can cultivate landrace under rainfed to maximize 'food per drop'. It is recommended to account for local environmental conditions while choosing cultivars that uses less water to give reasonable yield.

Keywords: evapotranspiration, tillering, sorghum cultivars, water productivity.

4.1 Introduction

South Africa is one of the most water-scarce countries (Blignaut and Heerden, 2009; Moeletsi and Walker, 2012) receiving an average annual rainfall of just 450 mm, which is nearly half the global rainfall average of 860 mm (Botai *et al*., 2018; Schneider *et al*., 2017). This then subjects the rainfed crops to a wide range of water supply trends during their growing season with distinct timing of water stress and its intensity (Chapman *et al*., 2012). Water scarcity is increasing, so there is a need to increase crop production with low water input (Marston *et al*., 2020). Currently, 20% of the cultivated area is used for irrigated agriculture, which produces 40% of the world's food supply and is essential to maintaining global food security (Molden *et al*., 2007; Dowgert, 2010). However, only 12% of arable land in South Africa is suitable for rainfed farming despite many farmers utilizing this type of farming for cultivating their crops (Du Plesis, 2008). The majority of people living in dry lands, especially in food insecure areas, rely on rainfed agriculture, and drought under that production is the major constraint to crop production (ICRISAT, 2007). This then result to challenges of food and water security intrinsically linked, therefore requiring integrated solutions to address (Hadebe *et al*., 2021). Growing drought-tolerant crops to produce higher yields under water-limited conditions is one possible comprehensive way to solving the linked problem of water and food security. Sorghum due to its drought-tolerant niche is then deemed suitable for growing under water-limited situations whereas alternative crops like maize may fail (Belton and Taylor, 2002; Hadebe *et al*., 2016).

Sorghum is a major summer crop in rainfed farming systems worldwide (Hammer *et al*., 2014; Geetika *et al*., 2019) and is primarily grown under rainfed conditions in South Africa, with some commercial farmers cultivating it under irrigation in drier regions of the country (Hadebe *et al*., 2017). It requires 450 – 650 mm of water for optimal growth during a growing season, which frequently subjects it to water stress when grown under semi-arid rainfed conditions (Hadebe *et al*., 2016). However, as a drought tolerant crop it has a stress adaptive trait known as tillering which has the ability to contribute significantly to grain yield, with studies indicating that fertile tillers can contribute between 5% and 78% to the total yield (Lafarge *et al*., 2002; Wang *et al*., 2020).

Tillers can directly and indirectly influence water demand as it contributes to the plant structure through an increased leaf area which then result into high transpiration rates (Cerrudo *et al*., 2013). As a result, this then leaves the water use and productivity of tillers under varying water availability unquantified. The studies on water use and water productivity of varying sorghum varieties were done locally (Hadebe, 2015; Kunz *et al*., 2015; Kunz *et al*., 2020) and globally (Ibrahim *et al*., 2023). The authors focused on comparing sorghum water use efficiency with other crops like soybean under irrigation (Kunz *et al*., 2015; Kunz *et al*., 2020). The other study investigated the water use and water productivity among the sorghum cultivars under rainfed conditions (Hadebe, 2015). These studies have emphasized the ability of sorghum to perform better under water scarce conditions and when compared to other crops. Ibrahim *et al*. (2023) conducted a study on water productivity under different irrigation levels where the study focused on assessing the response of sorghum water productivity and yield. However, none of these studies have quantified the influence of varying irrigation regimes and different sorghum cultivars on tiller contribution to water use and water productivity and how they use given amount of water to maximize yield. Although, the importance of water has been quantified for many crops (Karunaratne *et al*., 2011), there is still limited information in terms of the response of sorghum tillers to water use and water productivity under varying irrigation regimes.

Water productivity is a useful indicator for quantifying the impact of irrigation scheduling decisions with regard to water management (Steduto *et al*., 2009). The water productivity concept is vital for food security in a world where water resources are rapidly being exhausted (Zwart, 2010). It is affected by various factors, such as crop cultivar type, applied water, soil factors and management practices (Ali and Talukder, 2008). The integrated strategies that can increase water productivity should focus on optimizing cultivar selection and the management practices which in this case is water availability (Azizian and Sepaskhah, 2014). The study investigated the impact of different irrigation regimes on water use and water productivity of various sorghum varieties, assessing and quantifying contribution of tillers and main stem to crop water use and water productivity.

4.2 Materials and methods

4.2.1 Experimental design and layout

The experiment was laid out as split-plot with irrigation regimes as main blocking factor and the sorghum varieties as the sub-factor laid out in randomized complete block and replicated three times. The study comprised of 4x3 factorial combination of sorghum varieties and irrigation regimes which were achieved using sprinkler irrigation. The irrigation levels were full irrigation and deficit irrigation compared to rainfed (unirrigated control) which were separated by 10 m pathways to limit water lateral flow between the blocks. The study design and layout are as outlined in chapter 3 (section 3.2)

4.2.2 Data collection

4.2.2.1 Crop water use

The data for amount of annual rainfall received during the growing cycle was sourced from the weather station situated at a 100 m radius in the University of Limpopo Experimental farm. The six moisture access tubes were inserted into the soil where each experimental plot had two access tubes between the replications. The moisture probe measures soil moisture at different depths at intervals of 0.1, 0.2, 0.3, 0.4, 0.6 and 1.0 m within the soil profile (Delta-T, UK). Therefore, soil water content was measured weekly from experimental plots using a soil moisture probe PR2/6 HH2 meter (Delta-T, UK) up to 1m depth. The soil moisture readings were then plugged into the water data spreadsheet containing data from the SPAW model to read irrigation required to 80% FC and the duration required to accomplish that. The SPAW (Soil-Plant-Air-Water) is a computer model used to simulate the dynamics of soil water under various field conditions and soil types (Saxton *et al*., 2006). The SPAW model uses variables such as soil texture, organic matter, and bulk density to give results of soil hydrological properties such as wilting point, field capacity, saturation point, and plant available water (Saxton and Rawls, 2006). The plots were subjected to irrigation at 80% field capacity as to accommodate future rainfall, minimize drainage and subject crops to stress (Ayars *et al*., 2006; Mondaca-Duarte *et al*., 2020). The irrigation was applied based on the readings in soil water content which were used to check the difference to 80% field capacity. Therefore, the water balance equation was utilized for calculating crop water use (ET) for various experimental parameters and combinations using rainfall, irrigation, capillary rise, run-on and off lateral flow-in and

out, drainage, and soil water content (Zhao *et al*., 2004; Steduto *et al*., 2009) from sowing until physiological maturity as follows:

ET = water input – water output

$$= I + P + C + L_{in} + R_{on} – D - L_{out} - R_{off} \pm \Delta SWC \quad \text{Equation 1}$$

Where: ET = evapotranspiration or crop water use, I = irrigation (mm), P = rainfall (mm), C = capillary rise (mm), D = drainage (mm), R_{off} = run-off, R_{on} = run-on, L_{in} = lateral flow-in, L_{out} = lateral flow-out, and ΔSWC = change in soil water content (mm)

However, lateral flows, run-on and off were considered negligible in the soil water balance equation, due to sorghum plots being separated by 10 m pathways which then limits the lateral flows and the run-on and off. Capillary rise and drainage were also considered negligible since the plot had the gleyic impeding layer which prevent the upward and downward movement of water to the water table (Gregory and Northcliff, 2012). Therefore, the water balance equation utilized for calculating crop water use (ET) was then simplified to:

$$ET = I + P \pm \Delta SWC \quad \text{Equation 2}$$

4.2.2.2 Water productivity

Water use obtained from equation 2 was then utilized to calculate water productivity which is a measure of agricultural output per unit of water consumed (Sadras *et al*. 2013). Following that, water productivity was determined by dividing grain production by crop water use (Steduto *et al*., 2009) using the following formula:

$$WP = Y/ ET \quad \text{Equation 3}$$

Where:

WP = water productivity (kg/m^3), Y = grain yield of main stem and the tillers (kg/ha), and ET = evapotranspiration (mm)

The tiller contribution to water use and water productivity was calculated using the following formula:

$$Tiller\ contribution = \frac{WP\ of\ the\ tiller}{total\ \ WP} \times 100 \quad \text{Equation 4}$$

4.2.6 Data analysis

The data collected were subjected to analysis of variance (ANOVA) using GenStat® version 20 (VSN, International, United Kingdom). An unbalanced analysis of variance was conducted to account for inequality of number of tillers due to differences in tillering propensity of the cultivars. Means were separated using the least significant differences (LSD) at a probability level of 5% and multiple mean comparisons were done using the Bonferroni test.

4.3 Results and discussion

The primary integration (C x IR) significantly influenced the water productivity (WP) and the water use (ET). This is attributed to both parameters (ET and WP) indicating highly significant differences in the cultivars (C) and the irrigation regimes (IR).

Table 4.1: Summary analysis of variance indicating the effect of integrating irrigation regimes, stem ranks, and different sorghum cultivars on their response to water use and water productivity.

Source of variance	P values			
	ET (mm)	ETC (%)	WP (kg/m^3)	WPC (%)
Cultivars (C)	**<.001**	0.061	**0.002**	0.083
Irrigation regimes (IR)	**<.001**	**0.50**	**0.010**	0.121
Stem ranks (S)	0.134	**<.001**	**<.001**	**<.001**
C x IR	**<.001**	0.359	**<.001**	0.262

Note: ET= evapotranspiration, ETC = contributions to evapotranspiration, WP = water productivity, and WPC = contributions to water productivity.

4.3.1 Sorghum response to annual rainfall and temperatures

The minimum and maximum temperatures experienced at Syferkuil during the sorghum growing season did not fall below or above the sorghum temperature thresholds of 7 and 37 °C as reported by Du Plesis (2008). The recorded minimum and maximum temperatures were within the thresholds (37, 21°C and 6,67 °C). This then implies that the crops did not encounter any temperature stress be it cold nor

heat. The annual rainfall received during the season was 321.32 mm and sorghum crop requires about 450 to 650 mm of water distributed evenly over the growing season (Jewitt *et al*. 2009; Assefa *et al*., 2010; Hadebe *et al*., 2017). The full irrigation plot received the total amount of 443.68 mm while deficit received 408.54 mm which is inclusive of the rainfall. This means that the plots had experienced similar stress due to not meeting the plant water requirements. However, the stress occurred in later growth stages because there was high to moderate rainfall particularly from day 1 until day 67 as indicated in Figure 3.1.

4.3.2 Crop water use (ET)

The interaction of cultivar selection and irrigation regimes significantly influenced water use ($p < 0.05$). Evapotranspiration within the cultivars were comparable and statistically similar in different irrigation regimes (Figure 4.1), indicating irrigation regimes as the main contributor to observed statistical differences within the primary interaction. The interaction indicated that the rainfed and full irrigation had comparable evapotranspiration whereas deficit plot statistically differed from them.

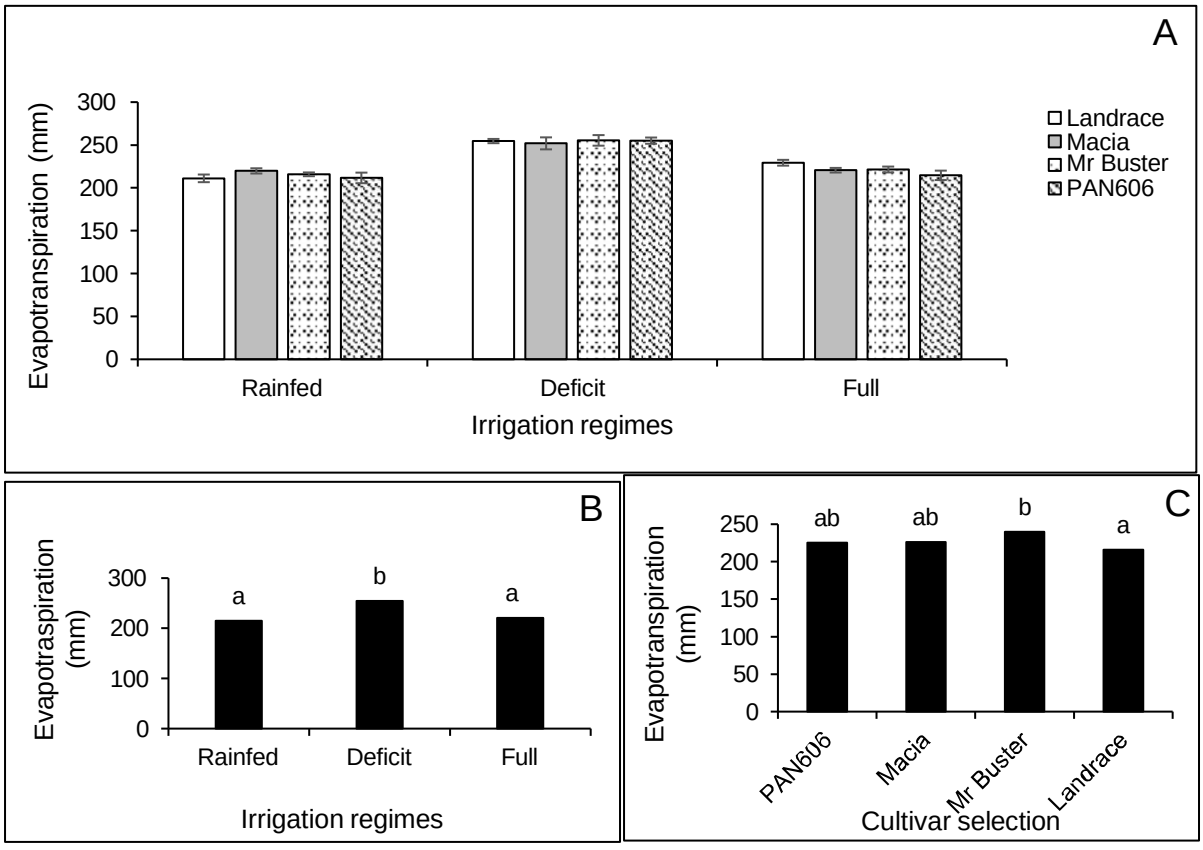

Figure 4.1: Water use response under the interaction of different cultivars and irrigation regimes (A), irrigation regimes (B) and cultivar selection (C). Bar values displaying the same letter are not significantly different at $p \leq 0.05$.

Deficit irrigation had high water use compared to other irrigation regimes. This could be attributed to maturity time that the plot used which then led to extended periods of crops accumulating water (Figure 4.2 A). The rainfed cultivars had less water use and this could be attributed to the crops primarily relying on the precipitation patterns for water availability which is often scarce and unpredictable in semi-arid regions (Golla, 2021). However, the inconsistency in rainfall patterns can lead to a decrease in soil moisture content, which in turn affect plant's ability to absorb water. This subsequently drives crops to activate their drought-resistant responses such as reducing leaf area and stomatal closure, resulting in lower evapotranspiration (Marcinska *et al*., 2013; Fahad *et al*., 2017; Buckley, 2019).

Maximum canopy improves water use through an increase in transpiration than in soil evaporation. The maximum canopy results indicate that rainfed plot had significantly higher maximum canopy compared to full irrigation (Figure 4.2C). This could be attributed to tillering propensity of the sorghum crop as a means of water stress response. The results indicated that the rainfed and deficit plots had high number of tillers produced compared to full irrigated plot (Figure 4.2 D). This is because under water stress, tillering is triggered, and more tillers appear as an adaptive feature to water stress (Wenzel *et al*., 1999; Kim *et al*., 2010; Alam *et al*., 2014) whereas under optimal water availability the main stem growth is encouraged and less tillers are expected. More tillers of rainfed then encouraged the larger canopy which led to insignificant differences in shoot dry biomass as shown in chapter 3 (Figure 3.2 C). Large canopy cover is known to lower soil evaporation hence increasing the transpiration leading to high water use by the plants (Wang and Liu, 2007). The low maximum canopy of full irrigation indicates low water use by the crops which could be due to high soil evaporation hence low transpiration.

Mr Buster significantly had high water use (ET) than landrace (Figure 4.2 B). This is because as a hybrid that is mostly preferred by commercial farmers, it is mostly cultivated under irrigation which then accustomed it to be grown under sufficient water availability leading to high water use (Clarke *et al*., 2019; Serafin *et al*., 2022). The low

water use of landrace is due to its traditional traits of well adaptation to local conditions since the study was conducted under semi-arid conditions. The landrace is accustomed to growing under water scarce conditions which then leads to low water use and this then supports the notion of sorghum being a drought tolerant crop that can produce reasonable yield under low water availability. These results are in contrary with the expected outcomes where longer maturing cultivars are generally anticipated to have high evapotranspiration because of their extended water usage periods (Saadi *et al*., 2015). However, the study revealed that the landrace cultivar, despite being longer maturing, exhibited low water use. This unexpected outcome could be attributed to the landrace's superior drought adaptive trait, such as efficient water conservation even under limited water environments.

High number of tillers in Mr Buster which is statistically similar to landrace could have led to high water consumption (Figure 4.2 B). This is because higher number of tillers and main stem can lead to increased water use, as each stem requires water for growth and development (Ma *et al*., 2018; Farooq *et al*., 2019). The tillers can influence water demand through an increase in leaf surface area which results in greater transpiration rates leading to higher water demand (Cerrudo *et al*., 2013), and this could result in higher evapotranspiration rates. However, landrace with similar number of tillers exhibited low water use due to its superior qualities that help it to survive in harsh environmental conditions.

Contributions to evapotranspiration

Stem ranks significantly differed in their water use where the early emerged stem ranks had low evapotranspiration compared to the latter tiller to emerge (Figure 4.3 A). This could be attributed to the maturity timing where main stem and tiller 1 had physiologically matured at the same time. This translates to that their early growth had led to lower water use which then led to higher yield as reported in chapter 3. Tiller 5 had high evapotranspiration because of its late maturing time which led to extended periods of water consumption. The contributions of stem ranks differed with respect to evapotranspiration (Figure 4.3 B). The contributions displayed a decreasing trend with an increase in the stem ranks. The results indicate that the later tillers to mature do not contribute much to water use of the crop. The main stem contributions to

evapotranspiration are 30% while the tillers contribute 70 %. This then supports the notion that tillers do increase water use of the sorghum crop.

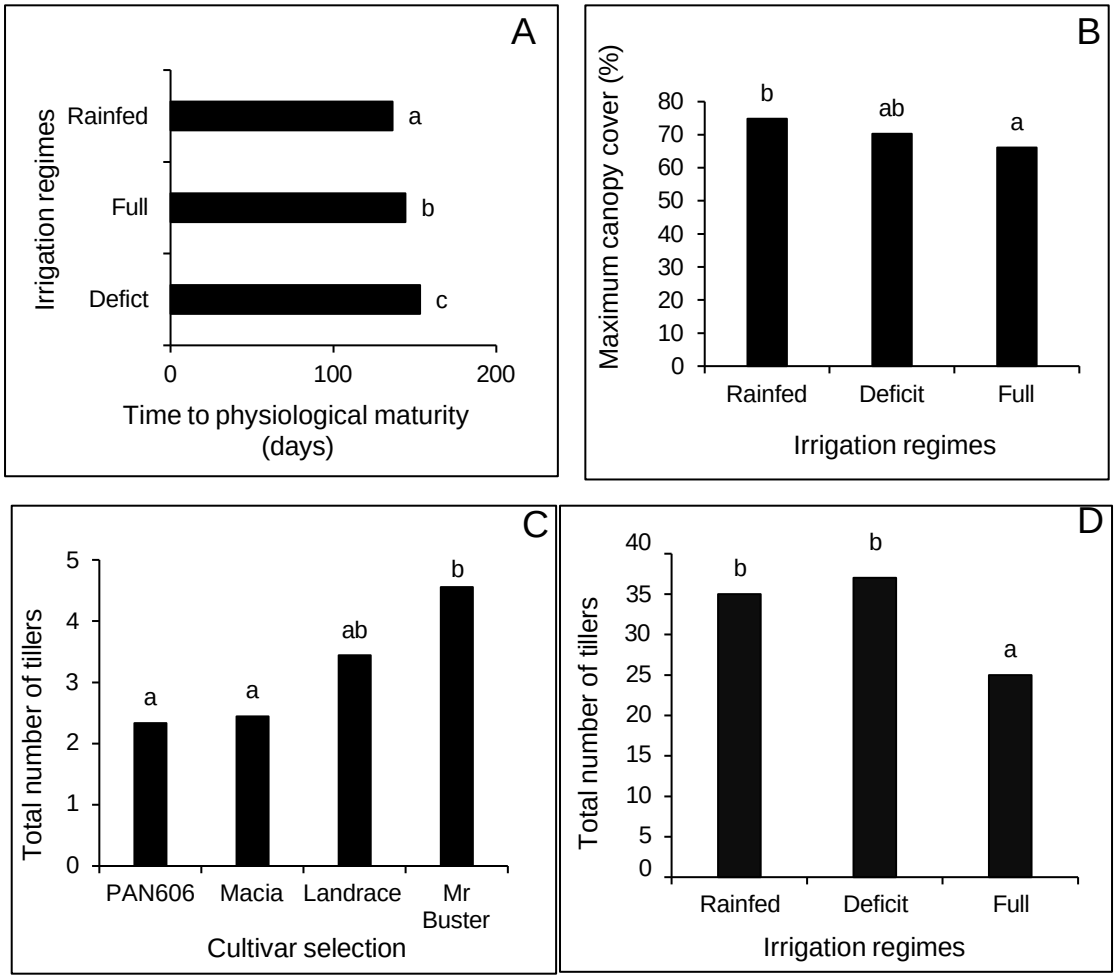

Figure 4.2: Time to physiological maturity within the irrigation regimes (A), the maximum canopy cover of different irrigation regimes (B), total number of tillers within the different cultivars (C) and irrigation regimes (D). Bar values displaying the same letter are not significantly different at $p \leq .05$.

The stem ranks within the irrigation regimes indicated a significant difference in contributions (Figure 4.4 A) where the main stem was the dominating contributor only in rainfed and full irrigation plots. There is a greater number of tillers produced under deficit irrigated plot which is statistically similar to that produced in rainfed plot (Figure 4.2 D). This then suggests that the water was shared among the stem ranks where tiller 1 and tiller 2 had contributed similarly to the main stem. Since deficit plot matured late and it had periods of water stress, this could elucidate that the stems might have activated the quiescence stage which led to similar contributions to water use. There

is an increase in contribution to water use with the increase in stem ranks hierarchy in rainfed plot. The landrace with its many tillers indicated to have a decreasing water use trend with an increase in stem rank. It has a superior main stem that contributed significantly to water use. Contrastingly, PAN606, Macia and Mr Buster indicated to have comparable contributions from main stem and the early emerged tillers.

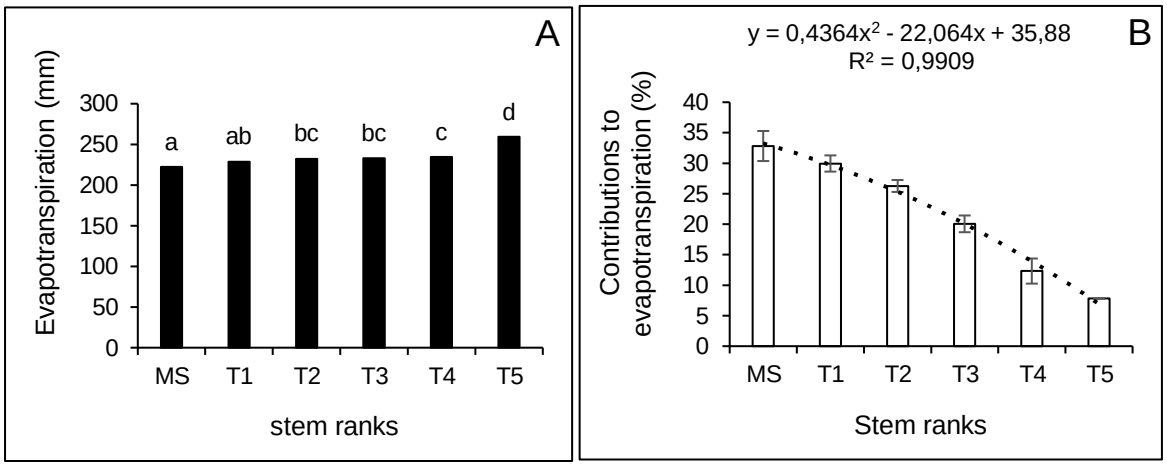

Figure 4.3: The response of stem ranks to water use (A) and their contributions to evapotranspiration (B). Bar values displaying the same letter are not significantly different at $p \leq 0.05$.

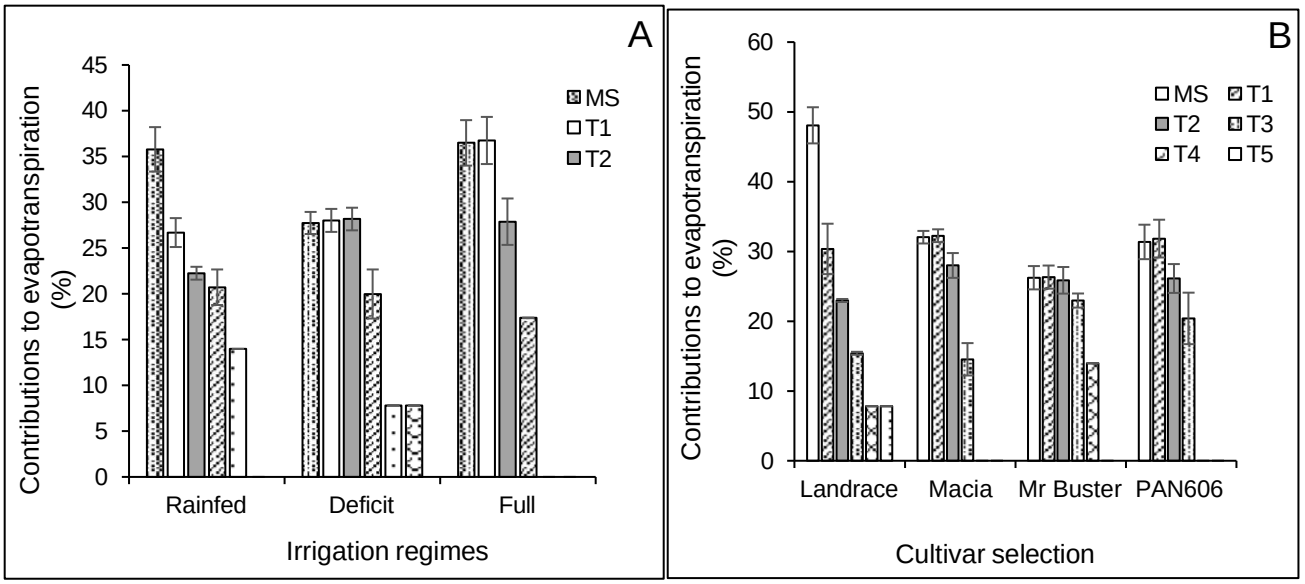

Figure 4.4: The contribution of stem ranks to evapotranspiration under different irrigation regimes (A) and cultivar selection (B).

4.3.2 Water productivity

The interactive effects of varying irrigation regimes and cultivar selection had significantly influenced water productivity (Figure 4.5A). The water productivity across the irrigation regimes was comparable which then indicated that both cultivar selection and the irrigation regimes (Figure 4.5C) contributed to this significant interaction.

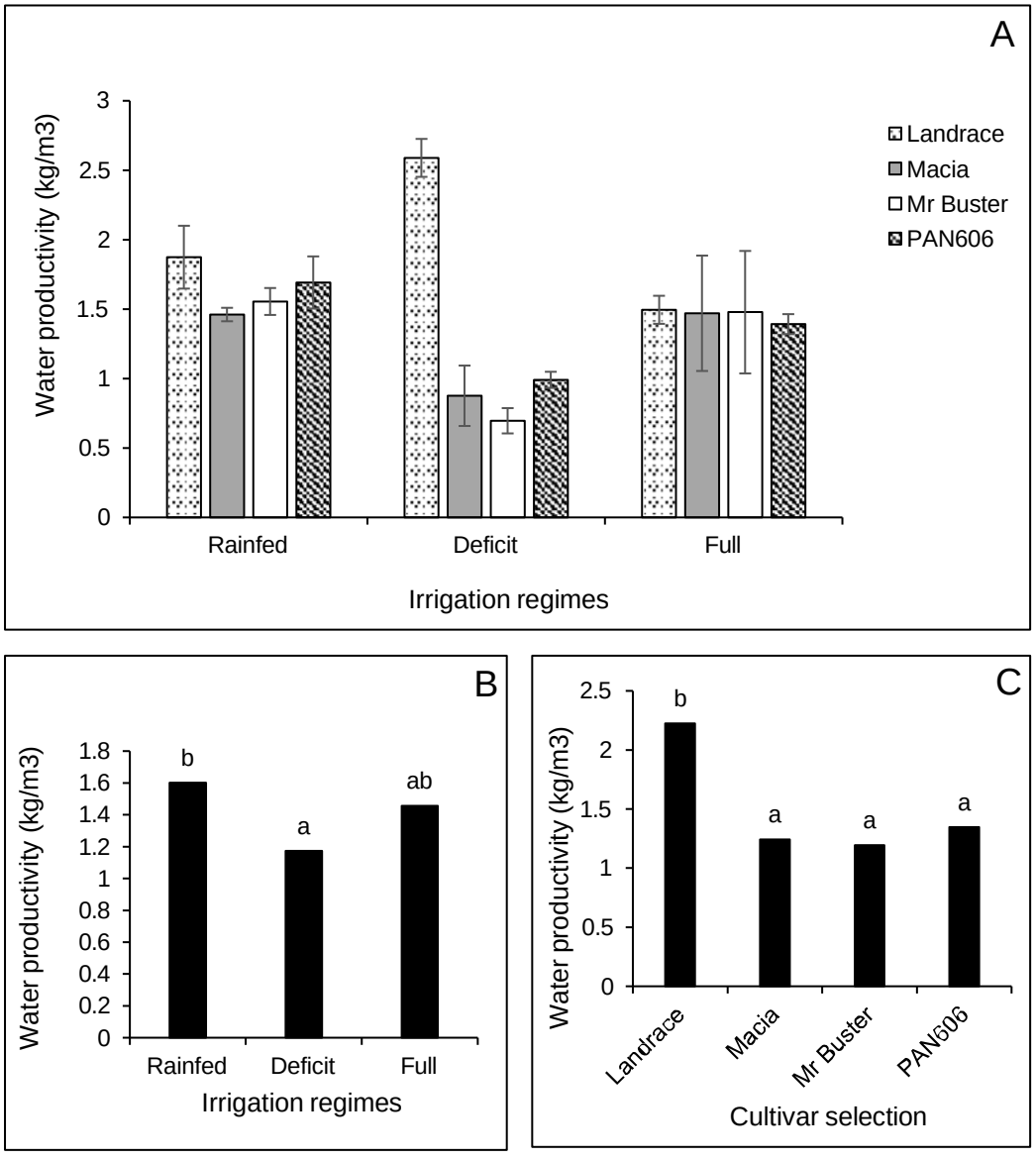

Figure 4.5: Water productivity response under the interaction of different cultivars and irrigation regimes (A), irrigation regimes (B) and cultivar selection (C). Bar values displaying the same letter are not significantly different at $p \leq 0.05$.

The irrigation regimes displayed highly significant differences with water productivity (Figure 4.5 B). The trend observed for water productivity was rainfed (1, 60 kg/m^3)> full (1,45 kg/m^3)>deficit (1,17 kg/m^3). These finding suggest that under rainfed conditions, sorghum may be able to use water more efficiently compared to when it is under deficit or even full irrigation. This could be explained by plants optimizing water use more effectively under limited water availability by reducing water loss through transpiration, leading to higher water productivity (Passioura, 2006). The high-water productivity of rainfed plot than deficit plot could be due to low evapotranspiration that the plot had which translated to reasonable yield as reported in chapter 3 section 3.3.1.3. This is because water productivity can be improved by low evapotranspiration with a fixed yield because it is directly proportional to yield and inversely proportional to ET. High water productivity is associated with reduced ET (Rodrigues and Pereira, 2009; Molden *et al*., 2010). Moreover, water stress improves water productivity, and this reinforces that sorghum yield can be productive under water scarce conditions (Deng *et al*., 2006; Mabhaudhi *et al*., 2013; Belete, 2018). This is because under rainfed agriculture, water productivity of major cereal crops becomes a key factor in increasing yield under water scarcity (Blum, 2005). The low water productivity of deficit irrigated plot was due to high water use that the plot took due to long maturity. However, the deficit plots yield reported in chapter 3 section 3.3.1.3 was higher than the other irrigation plots even so, high water use obtained then translated to low yield productivity. Contrastingly, deficit irrigation is known as a success in increasing water productivity for crops without causing severe yield reductions (Geerts and Raes, 2009). The statistically comparable water productivity between rainfed and full irrigation might indicate that beyond a certain threshold, additional water does not translate into proportional gains in productivity, possibly due to luxury consumption of water or inefficient use at higher availability.

Landrace significantly had high water productivity than other cultivars. Since water productivity is a function of grain yield divided by evapotranspiration, this suggests that Landrace is more efficient in converting water into grain due to its high yield obtained with relatively low ET. The higher water productivity of Landrace can be due to its late maturity which extended growing period, and this allowed the plant to accumulate more biomass and assimilates, contributing to higher yield potential without a significant increase in water usage. The higher water productivity of Landrace

compared to Mr Buster, PAN606 and Macia could be attributed to its greater phenotypic plasticity, and more effective drought avoidance strategies (Newton *et al*., 2011; Ficiciyan *et al*., 2018), as well as its strong adaptation to the Syferkuil climatic and soil conditions. Although hybrids are often bred for high water-use efficiency, especially under optimal conditions, they may not always outperform traditional landraces in environments where water is scarce (Zhao *et al*., 2018; Hatfield and Dold, 2019). The complex trade-offs between yield and water efficiency, particularly under stress conditions, suggest that Landrace long-term adaptation to its environment gives it an advantage in water productivity, especially in semi-arid and arid conditions. The study findings then highlight that landrace is highly suitable for production under water limited conditions, because more 'food per drop' is produced with less water use. This then reinforces reports that landraces are well-adapted to harsh environmental conditions (Mabhaudhi and Modi, 2013). This then highlights the importance of considering local environmental conditions when selecting cultivars for water limited regions.

The water productivity differed within the stem ranks where the main stem significantly contributed higher to water productivity relative to tillers. This could be attributed to main stem being the first shoot to appear after emergence. The main stem as the primary emerged shoot has the advantage of accumulating the resources such as light, water, and nutrients. better than the tillers (Fumey *et al*., 2016). However, its greater contribution to water productivity could be elucidated by more yield contribution which does not differ from that of tiller 1 and tiller 2 which is higher than tiller 3 - tiller 5. The contribution of stem ranks to water productivity differed significantly among the stems of the sorghum cultivars. The main stem was the primary contributor to overall water productivity which is consistent with the plant's growth dynamics. This can be explained by the main stem's dominance of forming before the tillers and its ability to compete in high plant densities and have high grain output (Mahmood and Al hassan, 2017). The main stem contributed 47 % while tillers contributed 53 % to water productivity. The early emerged tillers T1 (25 %), T2 (15 %), and T3 (7 %) had significant contributions while the later emerged tillers T4 (4 %) and T5 (2 %) had less contribution.

The stem ranks differed within the irrigation regimes and the cultivars (Figure 4.6). The main stem dominated as the major individual stem rank contributor to water

productivity within the irrigation regimes (Figure 4.7 A) indicating a decreasing trend with an increase in stem ranks. The deficit plot had more tillers but only few of them contributed significantly to water productivity. Contrastingly, there was no trend in stem ranks within the cultivar selection where tiller 1 indicated to have surpassed the main stem contribution in Mr Buster. This could be attributed to intraspecific competition within the stem ranks.

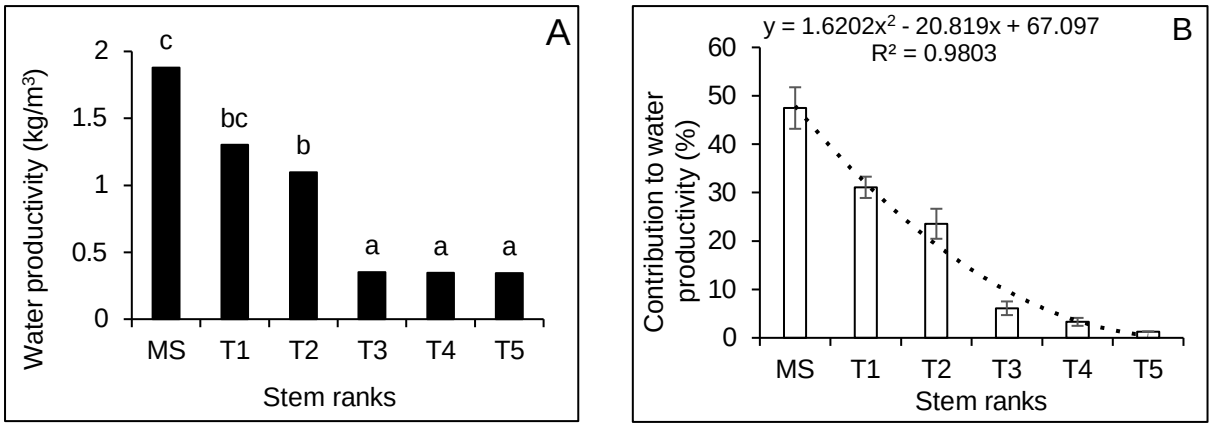

Figure 4.6: The response of stem ranks to water productivity (A) and their contributions to water productivity (B).

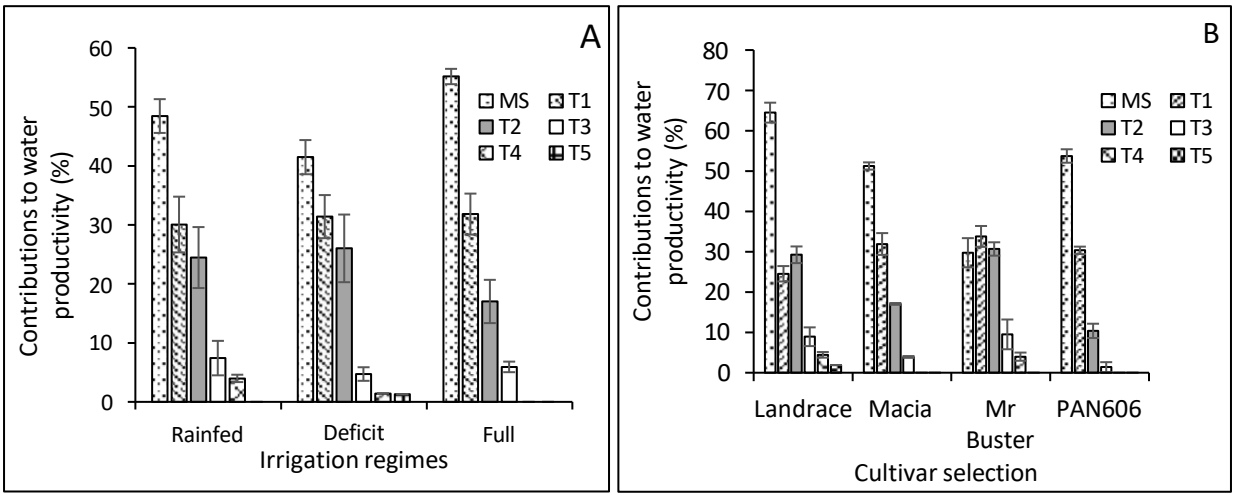

Figure 4.7: The contribution of stem ranks to water productivity under different irrigation regimes (A) and cultivar selection (B).

4.4 Conclusions and recommendations

The study was conducted to investigate the effect of varying irrigation regimes on water use and water productivity of tillers and main stem of different sorghum cultivars. The interactive effects of varying irrigation regimes and cultivar selection significantly influenced the crop water use and water productivity of sorghum cultivars. The findings of the study reveals that deficit irrigation resulted in higher evapotranspiration than rainfed due to the extended maturity period. Moreover, rainfed plot had higher maximum canopy cover which was attributed to increased tillering as an adaptive water stress response. Mr Buster significantly had higher water use compared to the landrace and this was due to its bred traits that are suitable for commercial farmers that cultivate under irrigated conditions. However, despite similar number of tillers, the landrace used less water due to its superior adaptation to semi-arid conditions, reinforcing its suitability for water limited environments. The contributions of tillers to water use were higher (70 %) than the main stem contributions (30 %), due to early maturity of main stem which then led to low water use. Significantly higher water productivity was obtained in rainfed plot indicating that sorghum can optimize water use under limited water availability leading to higher yield production efficiency. Despite higher yields under deficit irrigation reported in chapter 3, its higher water use resulted in lower water productivity, indicating that efficient water use is not solely linked to maximizing yield but also minimizing evapotranspiration. Among the cultivars, landrace exhibited higher water productivity due to low water used, high yield, adaptability to local conditions, and longer maturity periods outperforming other cultivars. The main stem contribution to water productivity was 47 % which is lower than the tiller contributions of 53 % to water productivity. Farmers can then cultivate landrace under rainfed conditions for high water productivity. It is then recommended that to maximize "food per drop" for sustainable production, local environmental conditions must be taken into account while choosing cultivars that use less water to give reasonable yield. The findings suggest the importance of understanding cultivar specific water use patterns and adaptive traits to optimize water productivity in sorghum under varying irrigation regimes**.**

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CHAPTER 5: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 General discussion

This study aimed to evaluate tillering propensity and water use of sorghum cultivars under complex tiller regulating practices, hence showcasing tiller contribution to sorghum yields and their water productivity under different water availability and cultivar selection.

The literature review findings indicated that managing the tiller regulating practices can improve the tiller yield contribution. Highlighting that the cultivar selection influences tillering propensity and it should be based on their adaptability to environmental conditions. The field experiment validated these findings where the landrace had higher yield compared to other varieties. This was attributed to its adaptability to the environmental conditions since it was sourced locally. Moreover, tillering is viewed favourably by subsistence farmers who link it to yield in marginal environments (Walters, 2018; Marone *et al*., 2021). Literature indicated that high tillering cultivars are at a great advantage of high biomass and yield accumulation due to increased leaf area and the number of panicles which influences biomass accumulation and yield (Hammer, 2006; Kuraparthy *et al*., 2008; Kim *et al*., 2010). The landrace had significantly high biomass accumulation than Mr Buster, however they all have the high tillering propensity. The high biomass accumulation of Landrace was attributed to its longer maturity and its height. The longer maturing cultivars tend to extended their photosynthesising period, grain filling and resource accumulation (Costa *et al*., 2007). Moreover, the tall cultivars have larger leaf surface area, which allows them to intercept light and support higher rates of photosynthesis leading to an increase in above ground biomass (Anten, 2005).

Mr Buster significantly had low shoot dry biomass due to intraspecific competition among the stem ranks. The competition of resources translated to low biomass partitioning to harvestable products indicating low harvest index leading to low yield. Its lower yield was due to intraspecific competition among its tillers, with only 51% of them being fertile. However, it significantly exhibited high water use compared to other cultivars and this is due to its bred effects where it is mostly cultivated under sufficient water conditions. The high evapotranspiration and low yield of Mr Buster led to low

water productivity. The yield average of Mr Buster was 3,04 ton/ha which was below its known yield potential of 5,5–10 ton/ha, indicating underperformance due to competitive resource capture between stem ranks. Contrastingly, landrace significantly had higher yield (5,37 ton/ha) with low water use which translated to higher water productivity (2,22 kg/m^3) than other cultivars. This then reinforces reports that landraces are well-adapted to harsh environmental conditions (Mabhaudhi and Modi, 2013). The high yield could be attributed to the 81% of fertile tillers produced which was higher than other cultivars.

The fertility of tillers directly contributes to yield through the production of fertile panicles. The literature indicated that the tillers that significantly contribute to yield falls within the fertility range of 7 – 91 %, indicating their significant yield contribution of 5 – 78 % (Lafarge *et al*., 2002; Wang *et al*., 2020). This was confirmed by the yield contributions of 57 % of tillers which falls within the given thresholds. The results indicate that only tillers contributing at least 5% to yield are considered significant. On average, the first three tillers (tiller 1 to tiller 3) consistently contributed meaningfully to yield, suggesting that the threshold for harvestable tillers should be set at tiller 3. Tillers beyond tiller 3 (tiller 4 and tiller 5) did not make significant contributions, demonstrating the diminishing impact of later-emerging tillers on yield due to competition and resource limitations. Furthermore, the study revealed significant differences in biomass contributions among stem ranks, with the main stem contributing the most in all cultivars and irrigation regimes. This dominance was due to the early development of the main stem, which receives more carbon allocation than later-emerging tillers. The main stem’s early growth advantage and priority in resource allocation impacted overall biomass distribution, with contributions decreasing as stem rank increased. However, the early physiological maturity of the main stem and tiller 1 led to low water use, which resulted in higher yield. Conversely, late-emerged tillers (tiller 5) exhibited higher water use due to extended growth periods, which led to low yield contributions that translated to low water productivity. Moreover, main stem significantly outperformed tillers in water productivity contributions. This was attributed to the main stem's early emergence and superior resource accumulation compared to tillers. While the main stem accounted for 47% of overall water productivity, the tillers collectively contributed 53%. Variations in contributions were noted across different irrigation regimes and cultivars. In particular, the main stem consistently dominated

water productivity in various irrigation settings, exhibiting a decreasing trend with increasing stem ranks

The cultivars differ in their tillering propensity which is influenced by the management practices including water availability (Kebrom *et al*., 2013; Shang *et al*., 2021). The rainfall received and crop water use was below sorghum water requirements of 450 – 650 mm (Jewitt *et al*., 2009; Hadebe *et al*., 2017). The findings indicate that deficit irrigation plots showed higher water use compared to other irrigation regimes. This increased water consumption is attributed to the extended growth periods, which allow crops to accumulate water over a longer duration. In contrast, rainfed plots relied on unpredictable precipitation, leading to lower water use. The rainfed crops, facing fluctuating rainfall levels, activated drought-resistant responses such as reducing leaf area and closing stomata, thereby lowering evapotranspiration. Literature findings indicated that high number of tillers lead to increased water demand and competition of resources with the main stem. For instance, Mr Buster with a high number of tillers could have led to its high water use and the competition affected the yield and led to low water productivity.

5.2 General conclusion

The study was set to assess tiller propensity, performance and their contribution to yield and yield parameters hence evaluating the tillers and main stem water use and water productivity under the interaction of cultivar selection and varying irrigation regimes. The interactive effect of different cultivars and irrigation regimes significantly influenced shoot dry biomass, grain yield, water use, and water productivity. The study findings suggest a cut-off threshold of 5% for tiller contributions, with tillers beyond tiller 3 having low contributions due to resource accumulation challenges and competition from earlier-emerging stems and tillers. The results suggest that cultivating landrace under deficit conditions could lead to high yield with less water used, leading to high productivity.

5.3 Recommendations

The limitation of this study results is that it was done on one planting site and one season planting. However, a further study is recommended that will assess the tiller contributions under varying tiller management practices which will include multi-

location trials and multiple growing seasons to account for spatial and temporal variability in environmental conditions. This study findings suggest that the early emerging tillers should be given priority (tiller 1 to tiller 3), as they play a crucial role in yield contribution. The later emerging must be thinned out reduce resource competition and enhance overall plant productivity as they also delay harvest due to later maturing. Additionally, further studies should investigate targeted agronomic practices aimed at enhancing the productivity of tillers while minimizing the occurrence of unproductive tillers. This could involve assessing strategies such as planting population, nutrient management, and efficient water application techniques to improve tiller fertility and minimize competition among plants.

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