Influence of cultivar, nitrogen and plant density on production of sorghum planted under different environmental conditions

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Dissertation submitted in fulfilment of the requirements for the degree *Master of Crop Science* at the North-West University

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DECLARATION

I, the undersigned, declare that this Master's dissertation herewith submitted to North West University Mafikeng, South Africa has not been submitted by me for a degree at any other university or institution or institution of higher education and that all the sources cited are acknowledged by comprehensive referencing.

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DEDICATION

This dissertation is dedicated to the Almighty God who granted me the opportunity to complete this study against all odds. To my wonderful parents, Rev. Oludare Ajidahun and Pastor Titilayo Ajidahun, who gave all they had for me to embark on this journey, and to my siblings. I love you all.

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ABSTRACT

Sorghum is an important cereal crop in the semi-arid regions of sub-Saharan Africa. This study was conducted in the 2016/17 and 2017/18 planting seasons at Mafikeng and Taung, North West Province, South Africa. The main objective of the study was to evaluate the yield and quality of sorghum cultivars as influenced by different nitrogen rates and plant density under different environmental conditions. The experimental design was a split-split plot arrangement fitted into a randomized complete block design with four replicates. The main plot factor comprised of high (33 333 plants/ha) and low (22 222 plants/ha) plant densities. The nitrogen fertiliser rates were 0, 100 and 150 kg N/ha as the sub plot factor. The sub-sub plot factor consisted of two sorghum cultivars, PAN 8625 and PAN 8816. Parameters measured for the study included, plant height, stem diameter, number of leaves per plant, chlorophyll content index, leaf area index, days to 50 and 100 percent flowering, panicle length, panicle mass per plant, panicle mass/ha, 1000 seed mass, biomass yield, grain yield, protein, sugar, starch, oil, fibre, and ash content.

In both planting seasons, the cultivar had a significant effect ($P < 0.05$) on the plant height and stem diameter of the sorghum plant. Sorghum cultivar PAN 8625 had a significantly taller plant and larger stem diameter than PAN 8816. The cultivar also had a significant effect on sorghum panicle mass per plant and sorghum biomass yield in both seasons. Sorghum cultivar PAN 8625 had a significantly higher panicle mass per plant and higher biomass yield than PAN 8816. Significant effects were also obtained on the cultivars for protein and starch content. Sorghum cultivar PAN 8816 had a significantly higher protein and starch content than PAN 8625.

Plant density had a significant effect ($P < 0.05$) on the sorghum leaf area index (LAI), panicle mass per plant and sorghum biomass yield in both seasons. Sorghum planted under high density had a significantly higher value of LAI than those planted under low density. Sorghum planted under high plant density had a significantly higher panicle mass per plant and a higher biomass yield than sorghum under low density.

Location had a significant effect ($P < 0.05$) on the sorghum chlorophyll content index and days to the 50 and 100% flowering in both seasons. Sorghum planted at Mafikeng had a significantly higher chlorophyll content index value than those recorded at Taung during the 2016/17 planting season while in 2017/18 planting season reverse was the case. During the 2016/17 planting season, sorghum planted at Mafikeng flowered significantly earlier than sorghum planted at Taung and contrary in the following season.

Location had a significant effect ($P < 0.05$) on the sorghum 1000 seed mass and grain yield in both seasons. Sorghum planted at Mafikeng had a significantly higher 1000 seed mass than sorghum planted at Taung in both seasons. Grain yield obtained in Mafikeng was significantly higher than value from Taung in 2016/17 planting season. With regards to the oil and starch content of sorghum, location had a significant effect in 2017/18 season; where Sorghum planted at Mafikeng had a significantly higher oil and starch content than sorghum planted at Taung. Mafikeng offers a better nutritive value for the sorghum produced than the one planted in Taung due to favourable weather conditions especially the rainfall. It is therefore recommended that sorghum is cultivated in Mafikeng.

Keywords: Cultivar, location, nitrogen fertiliser rate, plant density, planting season.

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ABBREVIATIONS

AAS = atomic absorption spectrophotometer

CCI = chlorophyll content index

cm = centimetre

DAFF = Department of Agriculture, Fisheries, and Forestry.

DAP = days after planting

E = East

EM = early-maturing

FAO = Food and Agricultural Organization

g = gram

ha = hectare

Kg = kilogram

Km = kilometre

LAI = leaf area index

LM = late-maturing

LSD = least significant difference

m = metres

m^2 = square metres

Max T = maximum temperature

mg = milligram

Min T = minimum temperature

mm = millimetres

N = nitrogen

NIR = near infrared reflectance

^oC = degrees Celsius

P = probability

RCBD = randomised complete block design

S = south

SADC = South African Development Community

SAWS = South African Weather Service

SSP = single superphosphate

UNESCO = United Nations Educational, Scientific and Cultural Organization

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CHAPTER 1

GENERAL INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) remains one of the most important cereal crops, ranking fifth worldwide behind maize, wheat, rice and barley in terms of its production and the extent of the areas where it is sown (FAO, 2013). It is also an important component in the diet of over 500 million people in about 30 countries of the world (FAO, 2013). Sorghum is processed into a range of salutary and conservative foods such as semi-leavened bread, dumplings, and fermented and non-fermented porridges (Taylor, 2004). It is a high priority crop to food security in Africa owing to its drought resistance and its natural capacity to tolerate periods of high temperature (Dicko *et al.,* 2006). Sorghum is a warm-weather crop which depends on high temperatures for excellent germination and growth. The minimum temperature for germination ranges between 7 and 10°C. Temperature plays a fundamental role in its growth and development after germination (Du Plessis, 2008).

The perfect time to plant sorghum is when there is sufficient water in the soil, particularly when soil temperature is about 15°C or more and at a soil depth of 10 cm. A temperature of 27 to 30°C is required for optimum growth and development. Exceptionally high temperatures cause a decrease in yield (DAFF, 2010). Maximum sorghum yield requires about 450 to 650 mm of rainfall that is uniformly distributed all through the planting season and this is normally adequate for cultivars which mature in three to four months (Assefa *et al.,* 2010). In relatively dry areas with low and irregular precipitation, such as South Africa, sorghum responds positively to supplementary irrigation. However, there are significant differences among cultivars in their response to irrigation (Steduto *et al.,* 2012).

Sorghum is predominantly cultivated on low capacity, shallow soils with high clay content, which ordinarily are not suitable for maize production. It grows poorly on sandy soils, except where heavy textured subsoil is present (Kimber, 2000). Although sorghum performs well in soils with low fertility, soils with clay content ranging from 10 to 30% are ideal for producing sorghum (Vanya, 2012). Nitrogen (N) is essential for excellent growth and the development of sorghum, but over-fertilisation is often detrimental as it results in a low-quality yield (Tamang, 2010). Previous research indicated that the application of nitrogen up to 150 kg/ha increases sorghum grain number and yield (Mousavi *et al.,* 2013).

Singh and Balyan (2000) reported that plant height increases significantly with increasing nitrogen levels from 0 to 120 kg N/ha, whereas 120 kg N/ha recorded higher grain weight per panicle when compared with 80, 160 and 200 kg N/ha (Wani *et al.*, 2003). Sorghum cultivars with a wide adaptability would be a good choice for a farmer wanting to start sorghum production. The careful selection and planting of cultivars that are best adapted to a combination of environmental conditions are important for best performance (Dlamini and Liebenberg, 2015). In order to select suitable cultivars, knowledge of their main characteristics is essential (Dlamini and Liebenberg, 2015).

Plant density is considered to be one of the most essential management practices for crops and is accorded a high research priority (Sangoi *et al*., 2002). The interrelationship between plant density and cereal grain yield has been investigated widely, but there are inconsistent reports which generates new interest in plant density and cereal crops. Increasing plant densities up to 166 000 and 333 000 plants/ha for tall and short types of sorghum have been reported to lead to reduction in morphological parameters; plant height, stem diameter, number of green leaves and leaf area of plants, while grain yield was found to be higher with increased plant density in both types (Ma *et al*., 2003; Alderfasi *et al*., 2016).

1.1 Problem statement

The continuous reduction in soil fertility, low usage of mineral fertilisers and several other advanced technologies in agriculture are some of the fundamental reasons for the decline in per capita food production (Henao and Baanante, 2006), which results in hunger and food insecurity. Poor environmental conditions limit sorghum yields in South Africa. One of the reasons for the low yields generally in sorghum production is insufficient nitrogen fertilisation. The inability of farmers to attain high yields during harvesting can also be as a result of the poor plant density and the use of inappropriate varieties. Optimizing planting density is vital in environments where crop growth is constrained by limited precipitation: as increased plant densities may deplete most of the available moisture before the crop matures, while reduced densities may leave moisture unutilized.

Consequently, low soil fertility, limited use of improved cultivars, and poor stand establishment are major constraints in sorghum production. The aforementioned conditions have negative implications on food security in South Africa. There is need to increase sorghum yield in smallholder farming enterprises which are prevalent in the North West province of South

Africa. However, there is limited knowledge about the nitrogen requirement, optimum plant density for various cultivars of sorghum in the North West province. Therefore, it is important to study the effects of plant density, nitrogen fertiliser rates on the yields of selected sorghum cultivars with the aim of developing appropriate agronomic package for the province.

1.2 Rationale

This study targets small-scale farmers to ensure that they manage to increase food production at the household level and subsequently expand their farming enterprises to commercial scale. Data collected from the field will explain the relationship between nitrogen fertiliser, plant density, and sorghum cultivars planted under different environmental conditions. Furthermore, the results of the research will equip farmers with the relevant information for selecting the appropriate cultivars, optimum nitrogen rate as well as appropriate plant density that will result in huge net returns on sorghum field. This is necessary since several African agricultural practices have generally focused on the use of long-duration cultivars, inappropriate plant densities and inadequate fertiliser use. Ashiono *et al*. (2005) reported that sufficient applications of nitrogen improve the sorghum yield in terms of quality and quantity. Therefore, this study will provide appropriate agronomic package in terms of optimum amount of nitrogen fertiliser to apply to increase the sorghum yield which will eventually translate into higher income to the farmers.

Study on short, medium and late-season cultivars will serve as a guide for farmers in choosing appropriate variety and assist in timing planting operations for effective utilisation of resources. Short-season cultivars will make use of less water and in turn less nitrogen fertiliser because of the short period that they take to mature and their short stature (Cothren *et al.,* 2000). Meanwhile, the yields of the late-maturity hybrids tend to be higher than those of the shorter-season sorghum cultivars, owing to the longer grain-filling period and increased vegetative growth (Baumahardt *et al.,* 2005). The importance of plant density cannot be overemphasized as it will have a direct impact on the total grain yield during the respective seasons. Environmental conditions during the planting season can also have variable effects on grain quality and yield. Hence, there is a need to maximize the plant density in relation to the resources available so as to ensure an optimum grain yield at harvest. Therefore, it is important to evaluate the cultivars available on the market, while seeking a balance between the plant components combined with high biomass, grain productivity and nutritional value. Owing to climate variability, farmers could benefit from the latest knowledge, especially concerning the appropriate management practices for late and early-maturing sorghum hybrids in the North West region of South Africa. This might assist them in exploiting strategies to lessen the risk in instances of climate variability or reduce the considerable yield losses experienced in periods of drought.

1.3 Aim and Objectives

The aim of this study was to evaluate the yield and quality of sorghum cultivars as influenced by varying nitrogen fertiliser regimes and plant density under different environmental conditions in North West Province.

Objectives of the study

- To determine the performance of sorghum as influenced by different environmental conditions.
- To determine the effect of different rates of nitrogen fertiliser on the growth, yield and grain quality of sorghum;
- To determine the effect of plant density on the growth and yield and grain quality of sorghum;

1.4 Hypotheses

- The different environmental conditions have no effect on performance of sorghum
- Nitrogen fertiliser rates do not influence the growth and yield of sorghum
- Plant density does not have an impact on the growth and yield of sorghum

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CHAPTER 2

LITERATURE REVIEW

Sorghum (*Sorghum bicolor* L. Moench) is an indigenous African cereal which has an extraordinary tolerance to environmental stresses; such as heat and drought. It thrives moderately in adverse conditions (Teetor *et al.,* 2011). Sorghum originated from Africa but its cultivation has increased over the world with current production in many countries including Africa, China, Central and South America, India, and the USA (Dicko *et al.,* 2006). Some 55% of the world's sorghum farming areas are in Africa; and this grain represents a chief source of dietary energy and protein for nearly 1 billion people in the semi-arid tropics (Belton and Taylor, 2004).

World annual production of sorghum is above 60 million tonnes, out of which Africa produces about 20 million tonnes (FAO, 2004). This makes sorghum the second most important cereal grain in Africa after maize. In South Africa, sorghum production increased by 92 960 tonnes (114.7%) while maize production increased by 8.2 million tonnes (99.7%) from the previous season and this can mainly be attributed to the favourable production conditions that prevailed at the beginning of 2017 (Trends in the Agricultural Sector, 2018).

Sorghum and millets are genetically adapted to drylands. The water requirements for sorghum over the growing period is an average of 400 mm and about 300 - 350 mm for millet compared to 500 mm for maize (Orr *et al.,* 2016). It can be destroyed by frost and is preferably cultivated where relative humidities are less than 60%. Sorghum grows in a range of temperatures with an optimum around 25°C and a January mean greater than 21°C. Sorghum grows on a range of soils, but ideally the crop prefers a deep and well drained light to medium textures. (Schulze and Maharaj, 2007)

2.1. Economic importance of sorghum

As opposed to other cereal crops grown under different environmental conditions, sorghum generally adapts better and is more economical in terms of its productivity (Diallo, 2012). Sorghum plays a dual role, particularly in Africa, as a means of generating income and reducing the problem of food shortage (Thornton and Herrero, 2014). Hence, it plays a critical role for food security in some semi-arid regions of Africa, Asia and Latin America (Dicko *et al.,* 2006; Ngmengu, 2014). The low cost of inputs and the ability to adapt to different environments makes sorghum important for numerous food and non-food products.

2.1.1. Food and other uses

Sorghum is consumed in several forms and this largely depends on the part of the world concerned. It is grown in the United States, Australia, and other developed nations, essentially for animal feed (Awika, 2011). However, in Africa and Asia, the grain serves as food for human nutrition and animal feed. Sorghum has always been important as feed for poultry birds, pigs and ruminant animals. According to Liu *et al.* (2013), various strategies have been suggested to improve the value of feeds by increasing the digestibility of their protein and starch content. An estimated 300 million people from developing countries ultimately rely on sorghum as their basic energy source (Godwin and Gray, 2000).

In Southern Africa, sorghum grain is mainly used in traditional foods such as fermented and unfermented, thin and thick porridges (Taylor and Anyango, 2011). The fermented porridges are common in South Africa, while the unfermented ones are popular in Botswana, Zambia, Malawi, and Zimbabwe. Taylor and Emmanbux (2010) reported dumplings as another product made from sorghum meal and flour.

Although sorghum is a subsistent food crop, but it is steadily becoming the foundation for successful food and beverage industries (Taylor and Taylor, 2009). Over 35% of sorghum is grown directly for human consumption (Awika and Rooney, 2004), while the remainder is used in animal feeds, alcohol and industrial products (Kleih *et al.*, 2000; Awika and Rooney, 2004). Although its pecuniary requirements and usage may shift over the years, it will remain as a basic primary food for many rural communities (Taylor, 2003). Also, in Southern Africa, sorghum is useful as malt in the processing of alcoholic and non-alcoholic beverages (Sernia-Saldivar, 2016). Mahewu, produced in Zimbabwe, is an example of a non-alcoholic beverage made from sorghum (Taylor and Emmambux, 2008).

Sorghum grain is highly nutritious, with carbohydrate (70-80%), protein (11-13%), fat 2-5%, fibre (1-3%), and ash (1-2%) content. The protein in sorghum is gluten-free, therefore making it a choice food for diabetic patients and sufferers of celiac disease (Taylor *et al.*, 2006). This is due to its relatively low protein and starch digestibility which prove to be favourable factors in the management of body weight and obesity. The dietary properties of sorghum are exclusive and vary according to the cultivars (Prasad and Staggenborg, 2009). Several other cultivars have abundant polyphenols, especially condensed tannins, which are valuable as natural antioxidants (Dykes and Rooney, 2006). Other vital nutrients of sorghum include dietary fibre, fat-soluble B-vitamins, and minerals (Waniska *et al.*, 2004). All these nutritional attributes attract attention to sorghum as a primary component in various forms in the human diet and as such an incentive for improved production and application as human food in various forms.

2.1.2. Biofuel and industrial uses

Sorghum is gradually becoming an important element in the industrial sphere. Besides being and important food, sorghum could equally play a significant role in the production of ethanol and other bio-industrial products such as bioplastics, especially in semi-arid to dry regions such as those in South Africa where other crops are not easily produced (McLaren *et al.,* 2003). For instance, the focus in recent years has been on applying sorghum in the manufacture of biofuel and ethanol (Cai *et al.,* 2013). The production of biofuel from plant structural carbohydrates (cellulose, hemicellulose, and lignin) is projected to boost the amount of energy per unit of land area by five percent (5%) as compared to the biofuels that are generated from starch and sugar (Farrell *et al.,* 2006; Somerville, 2007). A good number of the bioenergy-linked attributes such as biomass, carbohydrates, and stem juiciness, are present in sorghum, and as indicated by their continuous modification within a population, they can be described as multifaceted, thus suggesting that there are several genes responsible for the perceived variability. However, there are inadequate studies regarding the genetics of sorghum carbohydrates and biomass production (Shiringani *et al.,* 2010; Cai *et al.,* 2013).

2.1.3. Market and Economy

Sorghum is cultivated in 105 countries, 37 of which have areas of more than 0.1 million hectares where sorghum is harvested (Rakshit *et al.,* 2014). Another eight of the countries namely; Sudan, India, Nigeria, Niger, the United States, Ethiopia, Burkina Faso, and Mexico, in decreasing order, have more than one million hectares of land area used for sorghum cultivation. Together, the over-all contribution of these countries is 71% of the total area in the world where sorghum is harvested.

In western and central Africa, sorghum is produced between the Sahara Desert in the north and the equatorial forests in the south, while in the southern and East Africa it is cultivated largely in arid areas (Dinar *et al.,* 2012). The commercial market for sorghum traded in the world is generally connected to the demand for livestock product, which is ultimately influenced by the feed requirements and prices in the developed countries. Approximately six percent (6%) of the sorghum traded in the world ends up as a food product, and is usually in form of imports by African countries (Orr *et al.,* 2016).

2.2 Effect of cultivar evaluation on sorghum production

There are five basic races of sorghum namely; *bicolor, guinea, caudatum, kafir, durra*; and ten intermediate races under *S. bicolor*. Sorghum is a cereal of remarkable genetic variability; with more than 30 000 selections present in the world's genetic collections (Assefa and Staggenborg, 2010). According to Dayakar Rao *et al*. (2016), sorghum varieties and cultivars can be grouped into four categories on the basis of their utilization. They include grain sorghum, forage sorghum, grass or Sudan sorghum, and broomcorn. The grain sorghum can be broken down into sub-classes based on kernel characteristics which include grain size, shape, pericarp colour, testa and endosperm texture (Serna-Saldivar, 2012). Another characteristic of sorghum is the grain colour and presence of condensed tannin; it could be white tan, red/yellow, or brown tannin sorghum (Serna-Saldivar, 2012).

In Southern Africa, only Botswana, South Africa and Zimbabwe have in place standard grading systems for sorghum (Taylor and Duodu, 2009). The South African Sorghum Section 7 Committee (2007) has recommended the use of improved cultivars as a means of boosting profitability and competitiveness. Over 27 improved varieties have been released in eight Southern African Development Community (SADC) Countries and nine (33%) are being cultivated in six countries of the region (Mgonja *et al.*, 2008).

Some of the sorghum hybrid cultivars released are BSH 1 (SDSH) 48), MMSH-375, 413, 1257, and 625, ZWSH-1, BANJO, MR BUSTER (also identified as Mafia), OVERFLOW, NS-5511, 5655, and 5751, PAN-8625, 8609, 8564, 8247, 8706W, 8648W, 8407. 8017, 8474, 8657, 8816, 8677, 8507, and 8488 (Adetunji, 2011). These hybrid cultivars constantly produce higher grain yields when compared with their parent varieties. The grain yield potential of the hybrids is superior to the traditional landraces, which typically have a very low yield potential, less than 0.8 tons/ha (FAO, 2004). The following hybrid cultivars show the highest potential grain yield; PAN 8564, 8738, 8816, 8677 and 8507 (2-10 tons/ha). The data corresponds with the detail as indicated by House *et al.* (1995), that hybrid sorghum cultivars continually produce higher grain yield than their parent varieties.

A knowledge of the existing landraces and of the selection criteria of farmers are the prerequisites to designing a concrete breeding programme and to fostering the hope that the improved varieties will be adopted (Haussmann *et al.*, 2012). Considering the changes in climate, the development of modern and well-adapted cultivars of sorghum that could meet the demands of both farmers and consumers is also becoming a challenge (Haussmann *et al.*, 2012).

Certain agronomic tactics that can be employed to cut or minimize sorghum yield losses under drought conditions include a reduction in the planting density and the choice of a hybrid which presents limited initial growth in the leaf area to avoid extreme transpiration rates as a way of conserving water early in the season (Kholová *et al*., 2013). Other ways in which farmers can become accustomed to drought would be by making use of hybrids that are drought-tolerant and others that are tolerant to the cold in the germination stage and planning early planting dates and minimum tillage (Wade *et al.,* 1993; Tiryaki and Andrews, 2001).

O'Shaughnessy *et al.* (2014) suggested planting early-maturing (EM) hybrids to ease the pressure of pests and avert risk. Consequently, to enhance grain sorghum production, farmers could combine the use of early-maturing hybrids, later planting dates, and lower seeding rates as an approach. Nonetheless, DeBaeke *et al.* (2006), who focused on the application of simulation techniques, pointed out that planting semi to early, or late-maturing (LM) hybrids instead of early-maturing hybrids would be supported 87 percent of the time in rain-fed situations or where there is limited irrigation.

Candido *et al*. (2002) reported that the large demand for better-quality materials favours the emergence of numerous genotypes of sorghum, with specific mention of the size (high, medium or low), cycle (early or late), aptitude (forage, dual purpose or grain) and traits which have a strong effect on the nutritional value of the crop. According to Neuman *et al*. (2002a), comparative studies of genotypes are important as they contribute to the breeding programme and recommend cultivars for producers whose silage has the best production: nutrition ratio.

2.3 Effect of climatic conditions on sorghum production: water requirements for sorghum

Grain sorghum productivity is significantly influenced by the availability of water to plants, the soil water content at planting, crop management practices, the distribution and amount of rainfall during the planting season, and other climatic conditions (Stone and Schlegel, 2006). Reports by Gibson *et al.* (1992) found that retaining sorghum stubble on the soil increased the sorghum yield by 393 kg/ha due to increased water use efficiency because of a greater amount of water stored in and extracted from the soil profile.

Amongst the factors affecting grain sorghum yields, water stress and temperature are particularly significant. Environmental conditions such as the amount of rain, temperature, the relative humidity, solar radiation, and wind, influence the water requirements of sorghum (Vanya, 2012). Sorghum is an essential cereal crop in semi-arid regions of the world. It requires a mean optimum temperature which ranges from 21 to 35°C for seed germination, 26 to 34°C for vegetative growth and development, and 25 to 28°C for reproductive growth (Prasad *et al.*, 2008).

Water usage by sorghum is a function of the crop factor and prevailing weather or climatic conditions. Less water is available to sorghum in climates with high evapotranspiration rates than under mild climatic conditions (Tolk and Howell, 2003). The water-use efficiency of sorghum is an important factor to be considered when striving for improved yields in water-scarce environments (Passioura and Angus, 2010). Soils vary in their water and nutrient holding properties and in their resistance to root penetration. A study has shown that sorghum performs better in well-irrigated clay soils (Assefa *et al.*, 2010). In situations where the supply of water through irrigation or precipitation is inadequate, loam soil has proved to be ideal for grain sorghum production owing to its high water-holding capacity. On the other hand, soils which have a high bulk density could limit root growth, and the water available to plants will in turn be affected negatively (Tolk and Howell, 2003; Assefa and Staggenborg, 2010).

Sorghum is capable of producing yields in semi-arid regions where other grain crops often fail. However, grain sorghum yields are maximized when all environmental conditions are optimum. The highest recorded sorghum yield is 20 mg/ha (Assefa *et al.*, 2010). Many other studies in the United States have reported an above 8 mg/ha yield for fully-irrigated sorghum field (Assefa and Staggenborg, 2010). Sorghum can survive considerable strain arising from extreme weather conditions such as drought, hail, and low temperatures, subsequent to the growing point differentiation (Assefa and Staggenborg, 2010), which follows 30 to 35 days after emergence, and this normally corresponds with the seventh or eighth leaf stage. Even though sorghum is believed to be more drought-tolerant than maize, it is sensitive to an inadequate water supply at its key growth stages, mainly from panicle initiation subsequent to the early dough stage (Prasad *et al.*, 2008). Water stress at some stage in panicle initiation lowers the panicle size and likely the grain number, while critical stress experienced during the flowering stage hinders pollination. Stress at initial grain filling triggers the abortion of maturing grains, which in turn reduces the mass of each grain (Steduto *et al.*, 2012). The results are reductions in the number of seeds per panicle, grain yield at harvest, and the final biomass (Assefa, 2010).

2.4 Effect of soil types on sorghum production

For sorghum to take advantage of its inherent yield potential, the prime growth requirements of sorghum include; a deep soil that is well-drained and has a good fertility status (Assefa *et al.,* 2010). Sorghum is widely cultivated in drier areas, usually on shallow and heavy clay soils. The crop will equally need a medium to good, and moderately constant rainfall pattern throughout the growing season. It also requires a frost free period of approximately 120 to 140 days (DAFF, 2010). The average yield for drylands, however, is about half or less than the reported irrigated yields. The crop grows well on most soils but it does better in light to medium textured soils. Therefore, the soil should preferably be well-aerated and well-drained with pH values ranging from 5 to 8.5 (Folliard *et al.,* 2004), as sorghum is moderately tolerant to short periods of waterlogging and salinity (Almodares *et al.,* 2008a, b; Promkhambut *et al.,* 2010).

2.5 Effect of nitrogen fertiliser on sorghum production

Nitrogen deficiencies restrict the production of sorghum more than a deficit of any of the other elements (Arisnabarreta and Miralles, 2010). Nitrogen improves the sorghum yield by increasing the number of panicles, the grain number per panicle and the 1000 grain weight (Mousavi *et al.,* 2012). Consequently, a deficiency in the supply of nitrogen has a significant influence on crop growth and can in extreme cases lead to a complete loss of grain yield (Mengel and Kirkby, 2001).

Asghari *et al*. (2006) studied the effect of different nitrogen fertilisation rates on various cultivars of grain sorghum, and reported that an increase from 0 to 150 kg/ha enhances grain and biological yield significantly. These researchers obtained 4.35 kg/ha (lowest) and 8.56 kg/ha (highest) grain yields from nitrogen fertilisation rates of 0 kg/ha and 150 kg/ha respectively. According to Jaynes *et al.* (2001), an increase in the nitrogen fertilisation rate results in a correspondingly effective increase in the grain yield of sorghum, but overly high rates of nitrogen tend to reduce the yield. Nitrogen is essential for plant growth but is also among the chief elements to limit sorghum yield (Zhao *et al.,* 2005; Mosier and Syers, 2013). To secure sustainable returns, the economical use of resources, such as nitrogen is crucial for boosting yields in every season. It is necessary to use the minimum amount of nitrogen for the maximum growth of sorghum every planting season (Jaynes *et al.,* 2001). The nitrogen requirement for cereal crop production has been determined from experiments in the field that involve different application rates for nitrogen fertilisers (Lak *et al.,* 2006).

As a result of disparities in climatic, soil and genotypic components around the respective seasons and different locations, inconsistent responses have been observed in experiments involving the application of nitrogen fertiliser to maize and sorghum (Abunyewa *et al.*, 2017). The ideal application of the nitrogen fertiliser rates (kg/ha) depends on the expected yield in a given environment as influenced by the climate, management practices and type of cultivar (Khosla *et al*., 2002). Depending on the nitrogen fertility of the soil, farmers apply somewhere around 45 and 225 kg N/ha in grain sorghum production (Zhao *et al.*, 2005) which is considered to be sufficient to raise the sorghum yield.

2.6 Effect of plant population and plant density on sorghum production

The quantitative and qualitative properties of sorghum grains are primarily affected by the nitrogen in the soils and plant density (Mousavi *et al.,* 2012). Plant density alters the microclimate and essentially has an influence on sorghum yield. It might equally have an effect on the growth, yield and quality parameters of sorghum (Sangoi *et al.*, 2002). The number of seeds planted should be increased to compensate for poor stand establishment (Du Plessis, 2008). However, Berenguer and Faci (2001) indicated that a greater number of grains per panicle and a considerably heavier grain weights compensated for lower plant densities.

Another important factor, namely the optimum density of plants per unit area, significantly affects grain yield. Thus, the optimal density to achieve the most cost-effective yield depends on the crop genotype, the purpose of production, the availability of nutrients in the soil, water content and particularly the nitrogen levels (Chatzistathis and Therios, 2013). Ma *et al.* (2003) and Selim (1995) reported that increasing plant density up to 166 000 and 333 000 plants/ha for tall and short varieties of sorghum respectively resulted to a decrease in plant height, stem diameter, the number of green leaves and leaf area per plant, however grain yield for both varieties increased when plant density was increased. The South African Department of Agriculture and Forestry (DAFF, 2010) recorded recommendations which vary from 3.0 to 7.0 kilograms of seed per hectare of land. The plant population and seed required per rows (0.91, 1.5 and 2.3m) and in-row spacing (10 to 150 mm) vary; and the densities ranges from a low density of 28 985 plants/ha to the highest obtainable density of 444 444 plants/ha.

The correlation between plant density and cereal yields has been widely researched, but inconsistent reports have steered new interest into the effects of high plant densities on cereal yields (Workayehu, 2000; Ma *et al.*, 2003). Previous experiments have revealed that the relationship between plant row spacing and grain sorghum yield is unpredictable and that the latter is more dependent on environmental conditions. According to LaFarge and Hammer (2002), alongside Conley *et al.* (2005), high plant densities increase sorghum grain yields. However, it should be noted that lower plant populations may turn out significant yields under dry conditions, especially when moisture stress prevails (Buah and Mwinkaara, 2009). The combination of fertiliser application together with an ideal plant density could improve the crop production levels and thus food production, and ultimately preserve the environment for coming generations (Fernandez *et al.*, 2012).

Considering the long-term rainfall, soil type (potential), the soil's water-holding capacity and some other factors, sorghum is planted in 0.91, 1.5 or 2.3 m rows in South Africa (DAFF, 2010). However, it has been proven that plant population performs a major role in the final crop yield under varying conditions (Rubaihayo *et al.*, 2002). Having an appropriate plant density is the safest method to improve sorghum production under arid conditions (Zand and Shakiba, 2013).

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CHAPTER 3

Effects of cultivar, nitrogen fertiliser rate and plant density on the growth performance of sorghum

3.1 Introduction

Sorghum is a warm-weather crop, which requires high temperatures between 26º and 30ºC for successful germination and good growth (Patane *et al.,* 2009). Nitrogen (N) is a crucial nutrient for crop development and productivity (Hao *et al.,* 2014) and performs a significant role in cell division during the various stages of plant growth (Stals and Inzé, 2001). Several investigations have been carried out to corroborate the relationship between applications of nitrogen at various levels and sorghum growth (Nour, 2010).

Applications of nitrogen fertiliser generally result in positive linear responses in plant height (Amsal *et al.,* 2000). Several studies have discovered marked improvement in plant height in response to each increment in the nitrogen fertiliser doses (Abdulkadir *et al.,* 2016; Abebe and Manchore, 2016; Harfe, 2017). An appropriate nitrogen supply has the tendency to promote leaf and stem development, whereas a lack of nitrogen ultimately results in poor plant growth and further leads to the yellowing of leaves (Nour, 2010). Recommendations for the application of nitrogen are affected by plant genotype, the ability of the soil to supply water and nutrients, besides the intended use of the crop (Barbanti *et al.,* 2006; Tamang *et al.,* 2011; Erickson *et al.,* 2012; Holou and Stevens, 2012). Nitrogen deficiencies affect the partitioning of assimilates between the vegetative and reproductive organs and can influence the growth and development of the crop (Sangoi, 2001). Asghari *et al.* (2006) reported that an increase in the rate of fertilisation from 0 to 150 kg N/ha increases the growth parameters of sorghum significantly.

The optimum plant density level for sorghum varies, depending on the cultivar and environmental factors such as soil fertility, moisture supply, and date of planting (Jahanzad *et al.,* 2013). In regions where crop growth is limited by an inadequate rainfall, it is critical to adapt the plant density because high plant densities may exhaust most of the available moisture whilst low densities may leave the moisture unexploited (Bayu *et al.,* 2005). Plant density significantly alters the leaf area index (LAI), and subsequently light capture and canopy photosynthesis (Borrás *et al.,* 2003). Meanwhile Bayu *et al.* (2005) reported that higher leaf area index values for leaf area are obtained by increasing the planting density, which results in higher crop growth rates during the grain-filling phase.

With other conditions being equal and favourable for sorghum growth, a good full-season (late-maturing) cultivar will out-grow similar early or medium-season cultivars every time (McMaster *et al.,* 2016). The general practice is to plant the latest-maturing cultivar available within the limitations of the projected moisture availability, the average length of the growing season, and the crop sequence. Cultivar selection can then be narrowed down to that group of cultivars that meet the maturity criteria. (Sauer *et al.,* 2014).

There are few studies that have compared the effects of plant density and the nitrogen fertiliser rate on sorghum growth performance (Guler *et al.,* 2008; Zand and Shakiba, 2013). A low nitrogen content in the soil substantially reduces the growth of various cultivars of sorghum (Abunyewa *et al.,* 2017). Furthermore, over population also tends to reduce sorghum growth. Therefore, the objective of this study was to determine the effects of cultivar, nitrogen fertiliser rate and plant density on growth performance of sorghum planted under different environmental conditions.

3.2 MATERIALS AND METHODS

3.2.1 Description of experimental sites

This study was conducted during the 2016/17 and 2017/18 planting seasons at two locations in North-West province, South Africa, the first being the Department of Agriculture Experimental Station at Taung and the second being the North West University Research Farm at Mafikeng, South Africa. The North West University Research Farm is situated at 25^o 48′S and 45^o 38′E and at an altitude of 1 012 m above sea level. It is located about eight kilometers from the city of Mafikeng towards the Botswana-South Africa border. The region is classified as semi-arid tropical savanna and receives a mean annual rainfall of 571 mm in summer (Kasirivu *et al*., 2011). Approximately 68% of the annual precipitation in this area falls between November and January in a few heavy downpours, with the pronounced dry season being from April to September. The mean maximum temperature is 37^{o}C while the mean minimum temperature is 7 – 11^{o}C. The annual average pan evaporation of North West is 1 023 mm (Kasirivu *et al.,* 2011). According to South Africa’s soil classification, the soil at the site has a sandy loam texture and belongs to the Hutton series (Molope, 1987, Kasirivu *et al.,* 2011). According to the FAO-UNESCO system, the soil of North West University Research Farm is classified as Ferric luvisol (FAO-UNESCO, 2006).

The Department of Agriculture’s experimental station at Taung, about 293 km from the North West University Mafikeng campus, is situated at 27^o 30′S and 24^o 30′E and at an altitude of 1

111 m above sea level. The Taung experimental site is situated in a grassland savannah region with a mean annual rainfall of 1 061 mm, the rainfall season usually starts in October (Pule-Meulenberg *et al.,* 2010). According to South Africa's soil classification system, the soils of this site belongs to the Hutton series (Molope, 1987 and Kasirivu *et al.*, 2011). Taung has deep but, fine sandy soils dominated by red, freely-drained, eutrophic soils with parent material that originated from aeolian deposits (Staff, 1999).

3.2.2 Experimental design

The experimental design is a split-split plot arrangement fitted into a randomized complete block design (RCBD) with four (4) replicates. The experiment considers high (33 333 plants/ha) and low (22 222 plants/ha) plant densities as the main plot factors. The nitrogen fertiliser rates, 0, 100 and 150 kg N/ha were considered to be the sub-plot factors, while the two sorghum cultivars, PAN 8625 and PAN 8816, were the sub-sub plot factors. The experiment involved a total of 48 plots and a total field area measuring 60 m x 36 m (2160 m^2) at each location.

3.2.3 Pre planting soil sampling

The soil samples at both locations were collected using a soil auger at depths of 0-15 and 15-30 cm before land preparation during each planting season. All samples were air-dried and sieved using a 2-mm sieve, while physical and chemical analyses were conducted using standard laboratory procedures. Soil samples were analyzed for $N\text{-}N0_3$, NH_4, Bray 1-P, exchangeable K and soil pH (KCl). The soil texture was determined by Bouyoucos' hydrometer method (Moodie *et al.,* 1959). The presence of $N\text{-}N0_3$ and NH_4 was determined according to the Kjeldahl digestion procedure and the available phosphorus (P) was determined using the Bray-1 procedure described by Bray and Kurtz (1945). Exchangeable potassium (K) was extracted using a neutral normal ammonium acetate solution and the potassium (K) concentration in the solution was read off an atomic absorption spectrophotometer (AAS), while the soil pH was determined in potassium chloride (KCl) with the aid of a glass electrode pH meter.

Table 3.1. The results of soil chemical (mg kg^{-1}) and the physical properties of samples collected before planting at two locations during the 2016/17 and 2017/18 planting seasons

Location	Chemical/physical properties	2016		2017	
		0-15(cm)	15-30(cm)	0-15(cm)	15-30(cm)
Mafikeng	$N\text{-}N0_3$	4.24	8.66	8.50	10.00
	$N\text{-}N0_4$	0.75	1.40	1.75	1.95
	P (Bray-1)	54	54	19	33
	K	268	268	198	195
	% Sand	82	80	81	82
	% Silt	4	6	4	4
	% Clay	14	14	15	14
	pH (KCl)	6.26	6.07	5.28	5.24
Taung	$N\text{-}N0_3$	11.06	5.39	28.50	26.75
	$N\text{-}N0_4$	0.50	0.80	1.35	1.55
	P (Bray-1)	9	6	9	8
	K	235	203	188	198
	% Sand	84	82	85	86
	% Silt	3	4	3	3
	% Clay	13	14	12	11
	pH (KCl)	5.79	5.39	5.65	5.74

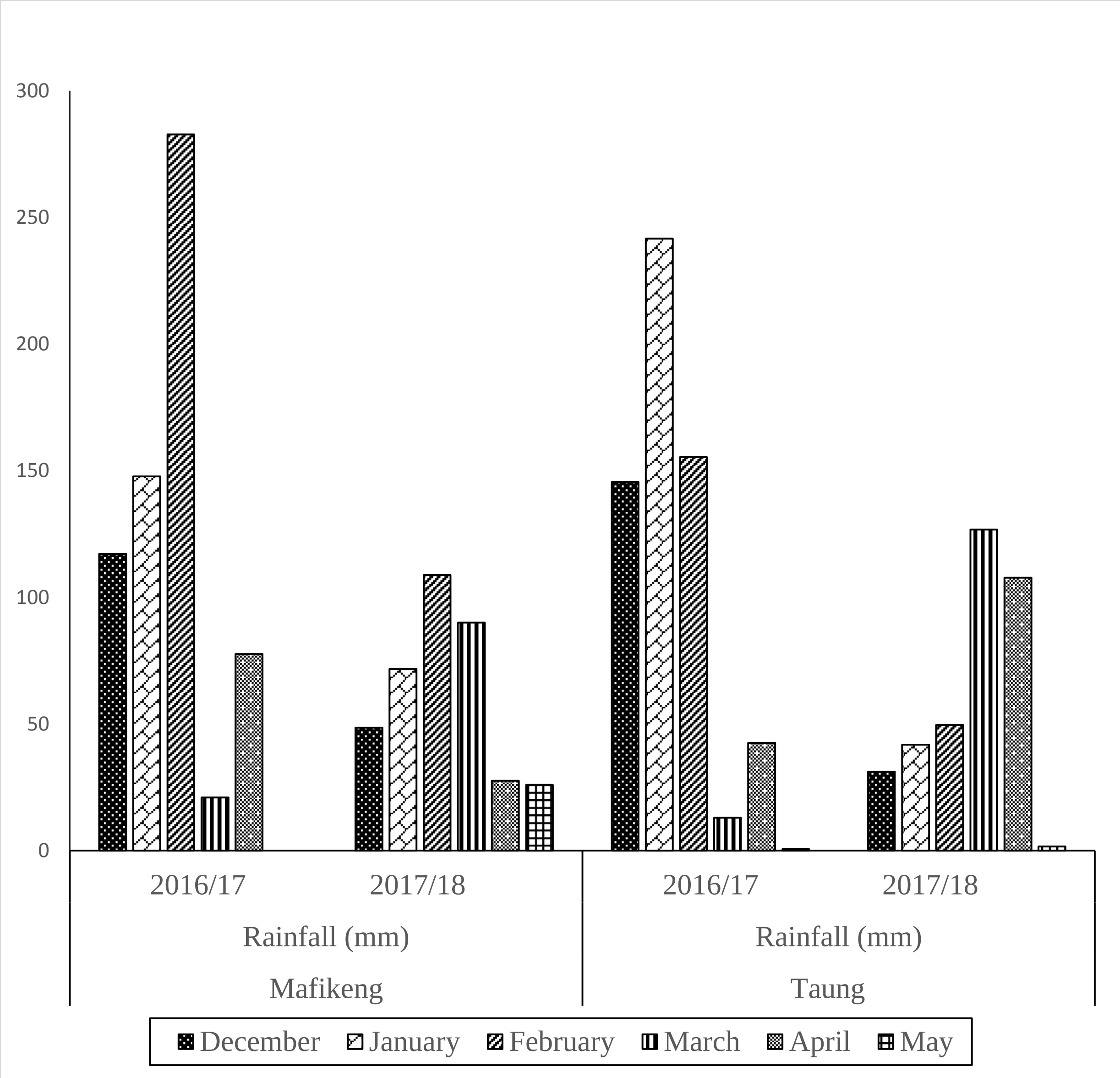

Figure 3.1. Mean rainfall (mm) at Mafikeng and Taung during the 2016/17 and 2017/18 planting seasons

mm = millimeters

Source: ***South African Weather Service (SAWS), 2018***

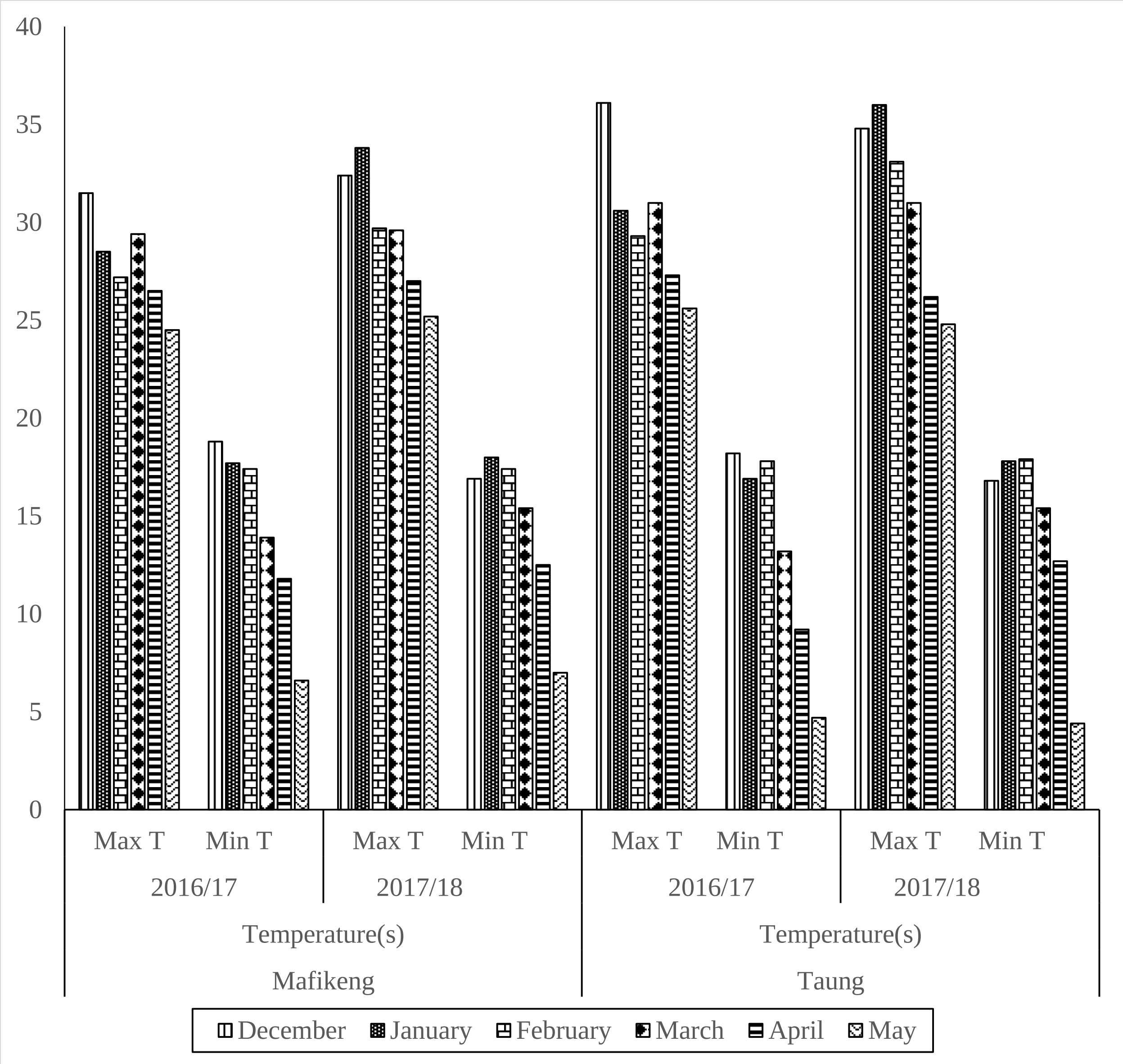

Figure 3.2. Mean maximum and minimum temperatures (°C) at Mafikeng and Taung during the 2016/17 and 2017/18 planting seasons

Max = maximum temperature in degrees Celsius (°C), Min = minimum temperature in degrees Celsius (°C)

Source: ***South African Weather Service (SAWS), 2018***

3.2.4 Land preparation, planting trial and source of planting material

The seedbeds were prepared through disc ploughing and harrowing. Planting on different experimental plots commenced on the field in December, 2016/17 and was repeated in the 2017/18 planting season. Sorghum seeds were purchased from PANNAR Seed Company and two cultivars, namely PAN 8816 and PAN 8625, were planted. PAN 8816 is a medium to late maturing cultivar while PAN 8625 is a late maturing-cultivar.

3.2.5 Fertiliser application and cultural practices

Some of the management practices carried out in this two-year study included fertiliser application, thinning, weed control and pest control. According to the Fertiliser Society of South Africa (FSSA); 120 kg N/ha should be applied for sorghum cultivation. However, after soil analysis the fertiliser requirements was determined and the rates above and below the recommended rates were selected for this study. The nitrogen fertiliser used was urea (46% nitrogen) while phosphorus fertiliser used was single superphosphate (SSP). Fertiliser application was done by banding; the nitrogen application rates were 0, 100 and 150 kg/ha of urea and the phosphorus (SSP) application rate was 60 kg/ha at planting. Thinning was carried out three weeks after emergence, leaving one plant per stand. Weeds were first removed three (3) weeks after planting and subsequently at the vegetative and flowering stages and during grain filling to prevent pest infestation, and crop-weed competition for nutrients. Cypermethrin (pyrethroid) 200 EC was applied intermittently to control aphids and flies, while sorghum panicles were protected from birds by using monofilament bags.

3.2.6 Data collection

The vegetative and reproductive growth data were collected 51 and 74 days after planting (DAP) respectively from a sampling area measuring 9.6 m^2 per plot. Six plants were randomly selected from the inner rows and tagged for data collection. Plant height was measured in centimeters (cm) from the base to the tip of the main stem with a measuring tape. Stem diameter was measured in centimeters (cm) using a Vernier caliper. The number of leaves on the tagged plant was counted and an average was determined. The chlorophyll content was determined by placing a chlorophyll meter in the middle of a fully developed leaf (away from the midrib/leaf vein) exposed to direct sunlight, and the value displayed by the meter was recorded. The leaf area was determined using the formula:

$$\text{Maximum leaf length x the maximum leaf width x 0.75,}$$

as suggested by Stickler *et al.* (1961), while the leaf area index was calculated using the formula; $\frac{Leaf\ area}{Plant\ spacing}$. The number of days to the 50 and 100% flowering was also recorded.

3.2.7 Data analysis

An analysis of variance was performed using GenStat: 11th edition (2008). The least significant difference (LSD) was used to separate the means, and a probability level of less than 0.05 was considered to be statistically significant (Gomez and Gomez, 1984). The high factor interactions were considered under the measured parameters.

3.3 RESULTS AND DISCUSSION

3.3.1 The effects of treatment factors on the sorghum plant height (cm) at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect ($P \leq 0.05$) on the sorghum plant height at 51 and 74 DAP during the 2016/17 planting season as indicated in Table 3.2. Sorghum cultivar PAN 8625 had a significantly taller plant of 101.79 cm than PAN 8816 which had 99.07 cm at 51 DAP. Sorghum cultivar PAN 8625 also had a significantly taller plant of 124.88 cm than PAN 8816 which had 117.43 cm at 74 DAP. During the 2017/18 planting season, the cultivar had a significant effect ($P < 0.001$) on the sorghum plant height at 74 DAP. Sorghum cultivar PAN 8625 had a significantly taller plant t of 136.13 cm than PAN 8816 which had 120.13 cm at 74 DAP. The differences in plant height could be attributed to variations in genetic composition among the cultivars used. This corroborates the findings by Ayub *et al.* (2002), who reported that differences in plant height among cultivars can be attributed to differentiations in genetic characteristics.

During the 2016/17 planting season, location had a significant effect ($P < 0.001$) on the sorghum plant height at 51 and 74 DAP. Sorghum planted at Taung had a significantly taller plant of 104.59 cm than sorghum planted at Mafikeng which had 96.28 cm during 51 DAP. Sorghum planted at Mafikeng also had a significantly taller plant of 123.72 cm than sorghum planted at Taung which had 118.60 cm at 74 DAP. During the 2017/18 planting season, location also had a significant effect ($P = 0.031$) on the sorghum plant height at 51 DAP. Sorghum planted at Taung had a significantly taller plant of 92.82 cm than sorghum planted at Mafikeng which had 89.88 cm. This could be attributed to the improvement of the soil structure at the both locations (Table 3.1). This corroborates the findings by Boomsma *et al.* (2010), who reported that in the case of maize, the structure of the surface soil and aggregation impacts upon growth and thus plant height.

During the 2017/18 planting season, the nitrogen fertiliser rate had a significant effect ($P \leq 0.05$) on the sorghum plant height at 51 and 74 DAP. Sorghum fertilised with 100 kg N/ha had a significantly taller plant of 94.07 cm than sorghum fertilised with 0 (88.94 cm) and 150 kg N/ha (91.06 cm) at 51 DAP. The observed increase in plant height could be attributed to the positive response of sorghum to increased applications of nitrogen fertiliser which causes an increase in the number of nodes, as well as in the inter-nodal distance. This corroborates the findings by Eltelib (2004) and Stales and Inze (2001), who reported that nitrogen could have an effect on plant growth through cell division and cell enlargement, which in their turn lead to an increase in plant height. Sorghum fertilised with zero nitrogen fertiliser had a significantly taller plant of 131.06 cm than sorghum fertilised with 100 (127.65 cm) and 150 kg N/ha (125.66 cm) at 74 DAP. This positive result associated with zero nitrogen fertiliser rate was unexpected. It contradicts the findings by Bilal *et al*. (2000), who reported that in association with increased applications of nitrogen fertiliser, plant height increases progressively up to harvest-time.

During the 2017/18 planting season, plant density had a significant effect ($P = 0.028$) on the sorghum plant height at 74 DAP. Sorghum planted under high density had a significantly taller plant of 129.26 cm than sorghum planted under low density which had height of 126.99 cm. This observation could be attributed to the fact that plants which are grown under higher plant density are usually prone to compete, especially for sunlight, hence, the height of such plants is likely to be taller than those growing lower density conditions where competition is minimal.

This corroborates the findings of Maurya *et al*. (2013), who reported that the taller plants were produced under the most densely populated conditions and this could be attributed to the competition for light and other growth resources among the plants that are crowded as a result of closer plant spacing.

During the 2016/17 planting season, plant density and the nitrogen fertiliser rate did not have a significant effect on the sorghum plant height at 51 and 74 DAP. During the 2017/18 planting season, cultivar and plant density did not have a significant effect on the sorghum plant height at 51 DAP. Location also had no significant effect on the sorghum plant height at 74 DAP.

Table 3.2. The main effects of treatment factors on the sorghum plant height (cm) at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Treatment factors	2016/17		2017/18	
	51 DAP	74 DAP	51 DAP	74 DAP
Cultivar	Means	Means	Means	Means
PAN 8625	101.79	124.88	90.46	136.13
PAN 8816	99.07	117.43	92.24	120.13
LSD $_{(0.05)}$	2.31	2.36	2.67	2.02
Density				
High	99.91	122.31	91.03	129.26
Low	100.96	120.01	91.67	126.99
LSD $_{(0.05)}$	2.31	2.36	2.67	2.02
Nitrogen rate				
0 kg/ha	99.76	121.56	88.94	131.06
100 kg/ha	101.36	120.96	94.04	127.65
150 kg/ha	100.17	120.96	91.06	125.66
LSD $_{(0.05)}$	2.83	2.88	3.27	2.47
Location				
Mafikeng	96.28	123.73	89.88	128.42
Taung	104.59	118.60	92.82	127.83
LSD $_{(0.05)}$	2.31	2.36	2.67	2.02

3.3.2 The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum plant height at 51 DAP during 2016/17 planting season

During the 2016/17 planting season, the interactions of nitrogen fertiliser rate x cultivar x location had a significant effect ($P < 0.049$) on the sorghum plant height at 51 DAP (Table 3.3).

Table 3.3. The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum plant height at 51 DAP during 2016/17 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	90.41	106.90	92.92	108.83
100 kg/ha	102.86	105.08	93.85	103.63
150 kg/ha	104.77	100.71	92.84	102.37
LSD $_{(0.05)}$	5.657			

3.3.3 The interaction effects of cultivar x location on the sorghum plant height at 74 DAP during the 2016/17 planting season

During the 2016/17 planting season, the interactions of cultivar x location also had a significant effect ($P = 0.003$) on the sorghum plant height at 74 DAP (Table 3.4)

Table 3.4. The interaction effects of cultivar x location on the sorghum plant height at 74 DAP during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	129.23	120.53
PAN 8816	118.20	116.67
LSD $_{(0.05)}$	3.330	

3.3.4 The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum plant height at 51 DAP during the 2017/18 planting season

During the 2017/18 planting season, the interactions of nitrogen fertiliser rate x cultivar x location had a significant effect ($P = 0.036$) on the sorghum plant height at 51 DAP (Table 3.5).

Table 3.5. The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum plant height at 51 DAP during the 2017/18 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	83.45	85.32	91.80	95.20
100 kg/ha	97.75	91.83	90.21	96.39
150 kg/ha	87.90	96.51	88.16	91.68
LSD $_{(0.05)}$	6.542			

3.3.5 The interaction effects of nitrogen fertiliser rate x cultivar x location on sorghum plant height at 74 DAP during the 2017/18 planting season

During the 2017/18 planting season, the interactions of nitrogen fertiliser rate x cultivar x location also had a significant effect (P = 0.045) on sorghum plant height at 74 DAP (Table 3.6).

Table 3.6. The interaction effects of nitrogen fertiliser rate x cultivar x location on sorghum plant height at 74 DAP during the 2017/18 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	141.63	139.15	120.27	123.21
100 kg/ha	134.19	136.77	121.75	117.90
150 kg/ha	132.15	132.87	120.55	117.08
LSD $_{(0.05)}$	4.94			

3.3.6 The effects of treatment factors on the sorghum stem diameter (cm) at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect ($P < 0.01$) on the sorghum stem diameter at 51 and 74 DAP during the 2016/17 planting season (Table 3.7). Sorghum cultivar PAN 8625 had a significantly larger stem diameter of 2.63 cm than PAN 8816 which had 2.39 cm at 51 DAP. Sorghum cultivar PAN 8625 also had a significantly larger stem diameter of 3.25 cm than PAN 8816 at 74 DAP. During the 2017/18 planting season, the cultivar had a significant effect ($P < 0.001$) on the sorghum stem diameter at 51 and 74 DAP. Sorghum cultivar PAN 8625 had a significantly larger stem diameter of 3.02 cm than PAN 8816 which had 2.65 cm at 51 DAP. Sorghum cultivar PAN 8625 also had a significantly larger stem diameter of 4.20 cm than PAN 8816 which had 3.39 cm at 74 DAP. This result could be attributed to differences in the genetic composition of the planted cultivars. This corroborates the findings by Yousef *et al*. (2009), who reported that there is variation in the stem diameter among sorghum cultivars.

During the 2016/17 planting season, location had a significant effect ($P \leq 0.05$) on the sorghum stem diameter at 51 and 74 DAP. Sorghum planted at Mafikeng had a significantly larger stem diameter of 2.58 cm than sorghum planted at Taung (2.44 cm) at 51 DAP. Sorghum planted at Mafikeng also had a significantly larger stem diameter of 3.29 cm than sorghum planted at Taung (2.86 cm) at 74 DAP. During the 2017/18 planting season, location had a significant effect ($P < 0.001$) on the sorghum stem diameter at 51 DAP. Sorghum planted at Taung had a significantly larger stem diameter of 2.94 cm than sorghum planted at Mafikeng (2.73 cm) at 51 DAP. This could be attributed to prevailing weather and environmental conditions, particularly moisture, which supports the early vegetative stages of plant growth. This corroborates the findings by Khan *et al*. (2005) and Valero *et al*. (2005), who reported that favourable environmental conditions have a positive influence on seedling establishment and cereal crop growth.

During the 2016/17 planting season, plant density and nitrogen fertiliser rate had no significant effect on the sorghum stem diameter at 51 and 74 DAP. During the 2017/18 planting season, plant density and nitrogen fertiliser rate did not have a significant effect on the sorghum stem diameter at 51 DAP. The plant density, nitrogen fertiliser rate and location also had no significant effect on the sorghum stem diameter at 74 DAP.

Table 3.7. The main effects of treatment factors on the sorghum stem diameter (cm) at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Treatment factors	2016/17		2017/18	
	51 DAP	74 DAP	51 DAP	74 DAP
Cultivar	Means	Means	Means	Means
PAN 8625	2.63	3.25	3.02	4.20
PAN 8816	2.39	2.89	2.65	3.39
LSD $_{(0.05)}$	0.09	0.12	0.12	0.33
Density				
High	2.49	3.05	2.81	3.87
Low	2.53	3.10	2.86	3.73
LSD $_{(0.05)}$	0.09	0.12	0.12	0.33
Nitrogen rate				
0 kg/ha	2.49	3.12	2.80	3.87
100 kg/ha	2.56	3.03	2.85	3.89
150 kg/ha	2.49	3.07	2.85	3.63
LSD $_{(0.05)}$	0.11	0.15	0.14	0.40
Location				
Mafikeng	2.58	3.29	2.73	3.78
Taung	2.44	2.86	2.94	3.82
LSD $_{(0.05)}$	0.09	0.12	0.12	0.33

3.3.7 The interaction effects of nitrogen fertiliser rate x cultivar on the sorghum stem diameter at 51 DAP during 2016/17 planting season

During the 2016/17 planting season, the interactions of nitrogen fertiliser rate x cultivar had a significant effect (P = 0.048) on the sorghum stem diameter at 51DAP (Table 3.8).

Table 3.8. The interaction effects of nitrogen fertiliser rate x cultivar on the sorghum stem diameter at 51DAP during 2016/17 planting season

Nitrogen rate	PAN 8625	PAN 8816
0 kg/ha	2.53	2.44
100 kg/ha	2.69	2.43
150 kg/ha	2.67	2.31
LSD $_{(0.05)}$	0.15	

3.3.8 The interaction effects of nitrogen fertiliser rate x location on the sorghum stem diameter at 51 DAP during 2016/17 planting season

The interactions of nitrogen fertiliser rate x location also had a significant effect (P = 0.026) on the sorghum stem diameter at 51 DAP during 2016/17 planting season (Table 3.9).

Table 3.9. The interaction effects of nitrogen fertiliser rate x location on the sorghum stem diameter at 51 DAP during 2016/17 planting season

Nitrogen rate	Maf	Taung
0 kg/ha	2.48	2.50
100 kg/ha	2.64	2.47
150 kg/ha	2.63	2.35
LSD $_{(0.05)}$	0.15	

3.3.9 The interaction effects of cultivar x location on the sorghum stem diameter at 74 DAP during the 2016/17 planting season

During the 2016/17 planting season, the interaction of cultivar x location had a significant effect (P = 0.05) on the sorghum stem diameter at 74 DAP (Table 3.10).

Table 3.10. The interaction effects of cultivar x location on the sorghum stem diameter at 74 DAP during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	3.55	2.95
PAN 8816	3.02	2.77
LSD $_{(0.05)}$	0.17	

3.4. The interaction effects of nitrogen fertiliser rate x location on the sorghum stem diameter at 51 DAP during the 2017/18 planting season

During the 2017/18 planting season, the interaction of nitrogen fertiliser rate x location also had a significant effect (P = 0.045) on the sorghum stem diameter at 51 DAP (Table 3.11).

Table 3.11. The interaction effects of nitrogen fertiliser rate x location on the sorghum stem diameter at 51 DAP during the 2017/18 planting season

Nitrogen rate	Maf	Taung
0 kg/ha	2.69	2.90
100 kg/ha	2.84	2.87
150 kg/ha	2.66	3.05
LSD $_{(0.05)}$	0.20	

3.4.1 The effects of treatment factors on the number of leaves per plant at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect ($P < 0.001$) on the number of leaves per plant at 51 and 74 DAP during the 2016/17 planting season (Table 3.12). Sorghum cultivar PAN 8625 had a significantly higher number of 13.29 leaves than PAN 8816 which had 11.50 leaves at 51 DAP. Sorghum cultivar PAN 8625 also had a significantly higher number of 12.71 leaves than PAN 8816 which had 10.40 leaves at 74 DAP. During the 2017/18 planting season, the cultivar had a significant effect ($P < 0.001$) on the number of leaves per plant at 51 and 74 DAP. Sorghum cultivar PAN 8625 had a significantly higher number of 14.09 leaves than PAN 8816 which had 12.94 leaves at 51 DAP. Sorghum cultivar PAN 8625 also had a significantly higher number of 16.35 leaves than PAN 8816 which had 11.61 leaves at 74 DAP. These results could be attributed to the length of the growth cycle of the cultivars which solely depends on the genetic makeup of the cultivars. This corroborates the findings by Meena and Mann (2007), who reported that the differential behaviour of sorghum varieties in respect of growth parameters could be explained by the variation in the genetic constitution of the cultivars.

During the 2016/17 planting season, location had a significant effect ($P < 0.001$) on the number of leaves per plant at 51 and 74 DAP. Sorghum planted at Mafikeng had a significantly higher number of 13.25 leaves than sorghum planted at Taung which had 11.54 leaves at 51 DAP. Sorghum planted at Mafikeng also had a significantly higher number of 12.60 leaves than sorghum planted at Taung which had 10.50 leaves at 74 DAP. This could be attributed to the fact that the number of leaves per plant varies widely depending on the climatic conditions. According to the weather data (Fig. 3.1), the average rainfall was higher at Mafikeng during both planting seasons. This corroborates the findings by Bahar *et al.* (2015), who reported that a higher rainfall at the onset of the rainy season and good distribution make conditions suitable for intensive germination and the vegetative growth of sorghum.

During the 2017/18 planting season, the nitrogen fertiliser rate had a significant effect ($P < 0.001$) on the number of leaves per plant at 74 DAP. Sorghum fertilized with zero nitrogen fertiliser was found to have a significantly higher number of 15.03 leaves than sorghum fertilized with 100 (13.66) and 150 kg N/ha (13.26 leaves). This significant increase in the number of leaves under zero nitrogen was unexpected. These findings contradict the results by Badr and Authman (2006), who reported that by increasing the nitrogen fertiliser rate from zero to 250 kg N/ha significantly increased the number of leaves per plant of maize.

During the 2016/17 planting season, the plant density and nitrogen fertiliser rate had no significant effect on the number of leaves per plant at 51 and 74 DAP. During the 2017/18 planting season, the plant density, nitrogen fertiliser rate and location had no significant effect on the number of leaves per plant at 51 DAP, while location and plant density had no significant effect on the number of leaves per plant at 74 DAP.

Table 3.12. The main effects of treatment factors on the number of leaves per plant at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Treatment factors	2016/17		2017/18	
	51 DAP	74 DAP	51 DAP	74 DAP
Cultivar	Means	Means	Means	Means
PAN 8625	13.29	12.71	14.09	16.35
PAN 8816	11.50	10.40	12.94	11.61
LSD $_{(0.05)}$	0.49	0.46	0.63	0.44
Density				
High	12.21	11.73	13.72	14.19
Low	12.58	11.38	13.32	13.77
LSD $_{(0.05)}$	0.49	0.46	0.63	0.44
Nitrogen rate				
0 kg/ha	12.47	11.59	13.76	15.03
100 kg/ha	12.22	11.47	13.53	13.66
150 kg/ha	12.50	11.59	13.27	13.26
LSD $_{(0.05)}$	0.60	0.57	0.78	0.54
Location				
Mafikeng	13.25	12.60	13.22	13.83
Taung	11.54	10.50	13.82	14.13
LSD $_{(0.05)}$	0.49	0.46	0.63	0.44

3.4.2 The interaction effects of cultivar x location on the number of leaves per plant at 74 DAP during the 2016/17 planting season

The interaction of cultivar x location had a significant effect (P = 0.007) on the number of leaves per plant at 74 DAP during the 2016/17 planting season (Table 3.13).

Table 3.13. The interaction effects of cultivar x location on the number of leaves per plant at 74 DAP during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	14.08	11.33
PAN 8816	11.13	9.67
LSD $_{(0.05)}$	0.65	

3.4.3 The interaction effects of nitrogen fertiliser rate x cultivar x location on the number of leaves per plant at 74 DAP during the 2017/18 planting season

The interaction of nitrogen fertiliser rate x cultivar x location also had a significant effect (P = 0.004) on the number of leaves per plant at 74 DAP during the 2017/18 planting season (Table 3.14).

Table 3.14. The interaction effects of nitrogen fertiliser rate x cultivar x location on the number of leaves per plant at 74 DAP during the 2017/18 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	18.10	16.90	12.02	13.08
100 kg/ha	15.77	16.48	11.27	11.10
150 kg/ha	14.83	16.04	11.00	11.19
LSD $_{(0.05)}$	1.084			

3.4.4 The effects of treatment factors on the sorghum chlorophyll content index (CCI) at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect ($P < 0.001$) on the sorghum chlorophyll content indexes at 51 DAP during the 2016/17 planting season (Table 3.15). Sorghum cultivar PAN 8816 had a significantly higher chlorophyll content index of 35.85 than PAN 8625 which had 30.98 at 51 DAP. During the 2017/18 planting season, the cultivar had a significant effect ($P < 0.001$) on the sorghum chlorophyll content index at 51 and 74 DAP. Sorghum cultivar PAN 8816 had a significantly higher chlorophyll content index of 47.09 than PAN 8625 which had 41.87 at 51 DAP. Sorghum cultivar PAN 8816 also had a significantly higher chlorophyll content index of 70.87 than PAN 8816 which had 53.62 at 74 DAP. The higher chlorophyll content under sorghum cultivar PAN 8816 could be attributed to differences in the maturity class of the cultivars planted which suggests that the cultivar with a higher chlorophyll content has a higher photosynthetic rate, which is indirectly proportional to the duration of the active growth stage. However, these results contradict the findings by Yamamoto *et al.* (2002), who did not find any significant difference in the chlorophyll content index among rice cultivars at the same growth stage.

During the 2016/17 planting season, location had a significant effect ($P < 0.001$) on the sorghum chlorophyll content index at 74 DAP. Sorghum planted at Mafikeng had a significantly higher chlorophyll content index of 59.31 than sorghum planted at Taung which had 38.05. During the 2017/18 planting season, location had a significant effect ($P \leq 0.05$) on the chlorophyll content index of sorghum plants at 51 and 74 DAP. Sorghum planted at Taung had a significantly higher chlorophyll content index of 45.93 than sorghum planted at Mafikeng which had 43.03 at 51 DAP. Sorghum planted at Taung also had a significantly higher chlorophyll content index of 65.59 than sorghum planted at Mafikeng which had 58.90 at 74 DAP. This could be attributed to seasonal variations in rainfall (Fig. 3.1) and temperature (Fig. 3.2) observed at both locations during the different stages of growth. This corroborates the findings by Mutava *et al.* (2011), who reported significant variations among grain sorghum cultivars for chlorophyll content under different environmental conditions, while Fox *et al.* (2001) also reported similar results on sorghum cultivars at different locations.

During the 2016/17 planting season, the plant density, nitrogen fertiliser rate and location had no significant effect on the sorghum chlorophyll content index at 51 DAP, while the cultivar, nitrogen fertiliser rate and plant density had no significant effect on the sorghum chlorophyll content index at 74 DAP. During the 2017/18 planting season, plant density and the nitrogen fertiliser rate had no significant effect on the sorghum chlorophyll content index at 51 and 74 DAP.

Table 3.15. The main effects of treatment factors on the sorghum chlorophyll content index at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Treatment factors	2016/17		2017/18	
	51 DAP	74 DAP	51 DAP	74 DAP
Cultivar	Means	Means	Means	Means
PAN 8625	30.98	47.63	41.87	53.62
PAN 8816	35.85	49.73	47.09	70.87
LSD $_{(0.05)}$	2.75	2.81	2.22	2.36
Density				
High	32.66	48.10	43.94	62.80
Low	34.16	49.26	45.02	61.69
LSD $_{(0.05)}$	2.75	2.81	2.22	2.36
Nitrogen rate				
0 kg/ha	33.29	49.69	44.15	62.58
100 kg/ha	33.13	48.73	45.59	62.51
150 kg/ha	33.82	47.63	43.71	61.64
LSD $_{(0.05)}$	3.37	3.44	2.72	2.89
Location				
Mafikeng	33.67	59.31	43.03	58.90
Taung	33.16	38.05	45.93	65.59
LSD $_{(0.05)}$	2.75	2.81	2.22	2.36

3.4.5 The interaction effects of nitrogen fertiliser rate x location on the sorghum chlorophyll content index at 51 DAP during the 2016/17 planting season

During the 2016/17 planting season, the interactions of nitrogen fertiliser rate x location had a significant effect ($P < 0.001$) on the sorghum chlorophyll content index at 51 DAP (Table 3.16).

Table 3.16. The interaction effects of nitrogen fertiliser rate x location on the sorghum chlorophyll content index at 51 DAP during the 2016/17 planting season

Nitrogen rate	Maf	Taung
0 kg/ha	29.05	37.53
100 kg/ha	34.42	31.84
150 kg/ha	37.53	30.11
LSD $_{(0.05)}$	4.77	

3.4.6 The interaction effects of plant density x location on the sorghum chlorophyll content index at 51 DAP during 2016/17 planting season

The interactions of plant density x location also had a significant effect ($P = 0.053$) on the sorghum chlorophyll content index at 51 DAP during 2016/17 planting season (Table 3.17).

Table 3.17. The interaction effects of plant density x location on the sorghum chlorophyll content index at 51 DAP during 2016/17 planting season

Density	Maf	Taung
High	34.28	31.05
Low	33.06	35.27
LSD $_{(0.05)}$	3.89	

3.4.7 The interaction effects of cultivar x location on the sorghum chlorophyll content index at 51 DAP during the 2017/18 planting season

During the 2017/18 planting season, the interactions of cultivar x location had a significant effect ($P = 0.042$) on the sorghum chlorophyll content index at 51 DAP (Table 3.18).

Table 3.18. The interaction effects of cultivar x location on the sorghum chlorophyll content index at 51 DAP during the 2017/18 planting season

Cultivar	Maf	Taung
PAN 8625	41.58	42.17
PAN 8816	44.49	49.70
LSD $_{(0.05)}$	3.14	

3.4.8 The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum chlorophyll content index at 74 DAP during the 2017/18 planting season

The interactions of nitrogen fertiliser rate x cultivar x location also had a significant effect (P = 0.018) on the sorghum chlorophyll content index at 74 DAP (Table 3.19).

Table 3.19. The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum chlorophyll content index at 74 DAP during the 2017/18 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	48.67	56.58	70.79	74.28
100 kg/ha	54.67	56.85	62.37	76.17
150 kg/ha	51.34	53.64	65.57	76.00
LSD $_{(0.05)}$	5.44			

3.4.9 The effects of treatment factors on the sorghum leaf area index (LAI) at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect (P < 0.001) on the sorghum leaf area index at 51 and 74 DAP during the 2016/17 planting season, as indicated in Table 3.20. Sorghum cultivar PAN 8625 had a significantly higher leaf area index of 2.65 than PAN 8816 which had leaf area index of 2.14 at 51 DAP. Sorghum cultivar PAN 8625 also had a significantly higher leaf area index of 2.60 than PAN 8816 which had leaf area index of 1.92 at 74 DAP. During the 2017/18 planting season, the cultivar had a significant effect (P < 0.001) on the sorghum leaf area index at 74 DAP. Sorghum cultivar PAN 8625 had a significantly higher leaf area index of 4.02 than PAN 8816 which had leaf area index of 2.53. The observed increase in the sorghum leaf area index during the critical stages of growth and development could be attributed to the higher leaf area recorded for the cultivars planted. This suggests variations in genetic composition since the leaf area of PAN 8625 is superior to the leaf area of PAN 8816, which results in a larger leaf area index for the former. This corroborates the findings by Bavec and Bavec (2002), who reported that the leaf area affects the leaf area index and it is genetically linked to the cultivar type.

During the 2016/17 planting season, plant density had a significant effect (P < 0.001) on the sorghum leaf area index at 51 and 74 DAP. Sorghum planted under high density had a significantly higher leaf area index of 2.86 than sorghum planted under low density which had leaf area index of 1.94 at 51 DAP. Sorghum planted under high density also had a significantly higher leaf area index of 2.77 than sorghum planted under low density which leaf area index of 1.77 at 74 DAP. During the 2017/18 planting season, plant density had a significant effect (P < 0.001) on the sorghum leaf area index at 51 and 74 DAP. Sorghum planted under high density had a significantly higher leaf area index of 3.00 than sorghum planted under low density which had leaf area index of 1.98 at 51 DAP. Sorghum planted under high density also had a significantly higher leaf area index of 4.00 than sorghum planted under low density which had leaf area index of 2.53 at 74 DAP. This could be attributed to the presence of more plants per unit area which favours leaf production per unit area. This corroborates the findings by Sangoi *et al.* (2002), who reported that an increase in the leaf area index with increasing planting density could be associated with effective light interception, which in turn allows high plant densities to attain greater photosynthetic output per unit area. Bayu *et al.* (2005) also reported an increased leaf area index with increasing population densities in sorghum.

During the 2016/17 planting season, location had a significant effect ($P < 0.001$) on the sorghum leaf area index at 51 and 74 DAP. Sorghum planted at Mafikeng had a significantly higher leaf area index of 2.83 than sorghum planted at Taung which had leaf area index of 1.97 at 51 DAP. Sorghum planted at Mafikeng also had a significantly higher leaf area index of 2.75 than sorghum planted at Taung which had leaf area index of 1.78 at 74 DAP. During the 2017/18 planting season, location had a significant effect ($P = 0.002$) on the sorghum leaf area index at 51 DAP. Sorghum planted at Taung had a significantly higher leaf area index of 2.63 than sorghum planted at Mafikeng which had leaf area index of 2.35 at 51 DAP. This observation could be attributed to the fertility status of the soil prior to planting, and environmental conditions which encourage the growth performance of sorghum. This agrees with the findings by Bavec and Bavec (2002), who reported that variations in soil fertility and weather conditions result in an increase in the leaf area index of maize.

During the 2017/18 planting season, the nitrogen fertiliser rate had a significant effect ($P < 0.001$) on the sorghum leaf area index at 74 DAP. Sorghum fertilized with zero nitrogen fertiliser had a significantly higher leaf area index than sorghum fertilized with 100 and 150 kg N/ha. This result was unexpected as nitrogen is essential for cell division and elongation. This contradicts the findings by Jasemi *et al.* (2013), who reported that a higher leaf area index is associated with nitrogen fertilized plants which is probably due to increased leaf production and leaf duration.

During the 2016/17 planting season, the nitrogen fertiliser rate had no significant effect on the sorghum leaf area index at 51 and 74 DAP. During the 2017/18 planting season, cultivar and nitrogen fertiliser rate had no significant effect on sorghum leaf area index at 51 DAP, while location also had no significant effect on the sorghum leaf area index at 74 DAP.

Table 3.20. The main effects of treatment factors on the sorghum leaf area index at 51 and 74 DAP during the 2016/17 and 2017/18 planting seasons

Treatment factors	2016/17		2017/18	
	51 DAP	74 DAP	51 DAP	74 DAP
Cultivar	Means	Means	Means	Means
PAN 8625	2.65	2.60	2.57	4.02
PAN 8816	2.14	1.92	2.41	2.53
LSD $_{(0.05)}$	0.16	0.16	0.17	0.17
Density				
High	2.86	2.77	3.00	4.00
Low	1.94	1.77	1.98	2.53
LSD $_{(0.05)}$	0.16	0.16	0.17	0.17
Nitrogen rate				
0 kg/ha	2.41	2.33	2.55	3.60
100 kg/ha	2.40	2.25	2.52	3.18
150 kg/ha	2.38	2.21	2.40	3.04
LSD $_{(0.05)}$	0.19	0.19	0.21	0.21
Location				
Mafikeng	2.83	2.75	2.35	3.22
Taung	1.97	1.78	2.63	3.34
LSD $_{(0.05)}$	0.16	0.16	0.17	0.17

3.5 The interaction effects of plant density x cultivar on the sorghum leaf area index at 51 DAP during the 2016/17 planting season

During the 2016/17 planting season, the interaction of plant density x cultivar had a significant effect ($P \leq 0.05$) on the sorghum leaf area index at 51 (Table 3.21).

Table 3.21. The interaction effects of plant density x cultivar on the sorghum leaf area index at 51 DAP during the 2016/17 planting season

Density	PAN 8625	PAN 8816
High	3.20	2.51
Low	2.10	1.78
LSD $_{(0.05)}$	0.22	

3.5.1 The interaction effects of plant density x location on the sorghum leaf area index at 74 DAP during the 2016/17 planting season

The interaction of plant density x location also had a significant effect ($P = 0.004$) on the sorghum leaf area index at 74 DAP during the 2016/17 planting season (Table 3.22).

Table 3.22. The interaction effects of plant density x location on the sorghum leaf area index at 74 DAP during the 2016/17 planting season

Density	Maf	Taung
High	3.33	2.20
Low	2.16	1.36
LSD $_{(0.05)}$	0.22	

3.5.2 The interaction effects of plant density x cultivar on the sorghum leaf area index at 74 DAP during the 2017/18 planting season

During the 2017/18 planting season, the interaction of plant density x cultivar had a significant effect ($P < 0.001$) on the sorghum leaf area index at 74 DAP (Table 3.23).

Table 3.23. The interaction effects of plant density x cultivar on the sorghum leaf area index at 74 DAP during the 2017/18 planting season

Density	PAN 8625	PAN 8816
High	4.95	3.06
Low	3.10	2.00
LSD $_{(0.05)}$	0.24	

3.5.3 The effects of treatment factors on days to the 50 and 100% flowering of sorghum during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect ($P \leq 0.05$) on days to the 50 and 100% flowering of sorghum during the 2016/17 planting season, as indicated in Table 3.24. Sorghum cultivar PAN 8816 flowered significantly earlier at 78.35 days during the 50% flowering stage than PAN 8625 (82.19 days). Sorghum cultivar PAN 8816 also flowered significantly earlier at 93.25 days during the 100% flowering stage than PAN 8625 (96.10 days). During the 2017/18 planting season, the cultivar had a significant effect ($P < 0.001$) on days to the 50 and 100% flowering of sorghum. Sorghum cultivar PAN 8816 flowered significantly earlier at 64.58 days during the 50% flowering stage than PAN 8625 (79.50 days). Sorghum cultivar PAN 8816 also flowered significantly earlier at 75.79 days during the 100% flowering stage than PAN 8625 (89.00 days). This observation could be attributed to the genetic makeup of the cultivars planted. Sorghum cultivar PAN 8816, which is a medium to late-maturing cultivar generally flowers earlier than PAN 8625, which is a late-maturing cultivar. This corroborates the findings by El Naim *et al.* (2012) and Hassan (2006), who reported that cultivars significantly differ in the number of days to the flowering stage.

During the 2016/17 planting season, the nitrogen fertiliser rate had a significant effect on days to the 50 and 100% flowering of sorghum. Sorghum fertilized with zero nitrogen fertiliser flowered significantly earlier at 76.91 days during the 50% flowering stage than sorghum fertilized with 100 (82.06 days) and 150 kg N/ha (81.84 days). Sorghum fertilized with zero nitrogen fertiliser also flowered significantly earlier at 92.34 days during the 100% flowering stage than sorghum fertilized with 100 (95.31 days) and 150 kg N/ha (96.38 days). This observation suggests that the application of nitrogen fertiliser increases the number of days to the flowering stage. This corroborates the findings by Amanullah *et al.* (2009), who reported that an increase in the application of nitrogen fertiliser delays silking in maize.

During the 2016/17 planting season, location had a significant effect ($P < 0.001$) on days to the 50 and 100% flowering of sorghum. Sorghum planted at Mafikeng flowered significantly earlier at 76.23 days during the 50% flowering stage than sorghum planted at Taung (84.31 days). Sorghum planted at Mafikeng also flowered significantly earlier at 84.35 days during the 100% flowering stage than sorghum planted at Taung (105.00 days). During the 2017/18 planting season, location had a significant effect ($P < 0.001$) on days to the 50 and 100% flowering of sorghum. Sorghum planted at Taung flowered significantly earlier at 70.58 days during the 50% flowering stage than sorghum planted at Mafikeng (73.50 days). Sorghum planted at Taung also flowered significantly earlier at 80.79 days during the 100% flowering stage than sorghum planted at Mafikeng (84.00 days). This could be attributed to changes in temperatures (Fig.2) observed at both locations during the different planting seasons. This corroborates the findings by Diawara (2012), who reported that most sorghum hybrids, classified as medium to medium-late maturity will flower in about 75-85 days, depending on the variations in temperatures over the years.

During the 2016/17 planting season, plant density had no significant effect on days to the 50 and 100% flowering of sorghum. During the 2017/18 planting season, plant density and nitrogen fertiliser rate had no significant effect on days to the 50% and 100% flowering of sorghum.

Table 3.24. The main effects of treatment factors on the days to the 50 and 100% flowering of sorghum during the 2016/17 and 2017/18 planting seasons

Treatment factors	2016/17		2017/18	
	50 %	100 %	50 %	100 %
Cultivar	Means	Means	Means	Means
PAN 8625	82.19	96.10	79.50	89.00
PAN 8816	78.35	93.25	64.58	75.79
LSD $_{(0.05)}$	2.49	1.69	0.81	0.40
Density				
High	79.73	94.31	71.75	82.25
Low	80.81	95.04	72.33	82.54
LSD $_{(0.05)}$	2.49	1.69	0.81	0.40
Nitrogen rate				
0 kg/ha	76.91	92.34	71.75	82.25
100 kg/ha	82.06	95.31	72.19	82.47
150 kg/ha	81.84	96.38	72.19	82.47
LSD $_{(0.05)}$	3.04	2.07	0.99	0.49
Location				
Mafikeng	76.23	84.35	73.50	84.00
Taung	84.31	105.00	70.58	80.79
LSD $_{(0.05)}$	2.49	1.69	0.81	0.40

3.5.4 The interaction effects of cultivar x location on days to the 50% flowering of sorghum during the 2016/17 planting season

During the 2016/17 planting season, the interactions of cultivar x location had a significant effect ($P < 0.001$) on days to the 50% flowering of sorghum (Table 3.25).

Table 3.25. The interaction effects of cultivar x location on days to the 50% flowering of sorghum during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	80.33	84.04
PAN 8816	72.12	84.58
LSD $_{(0.05)}$	3.514	

3.5.5 The interaction effects of nitrogen fertiliser rate x location on the days to the 50% flowering of sorghum during the 2016/17 planting season

The interactions of nitrogen fertiliser rate x location also had a significant effect ($P = 0.008$) on the days to the 50% flowering of sorghum (Table 3.26).

Table 3.26. The interaction effects of nitrogen fertiliser rate x location on the days to the 50% flowering of sorghum during the 2016/17 planting season

Nitrogen rate	Maf	Taung
0 kg/ha	70.31	83.50
100 kg/ha	78.19	85.94
150 kg/ha	80.19	83.50
LSD $_{(0.05)}$	4.30	

3.5.6 The interaction effects of cultivar x location on the days to the 100% flowering of sorghum during the 2016/17 planting season

The interactions of cultivar x location had a significant effect ($P < 0.001$) on the days to the 100% flowering of sorghum during the 2016/17 planting season (Table 3.27).

Table 3.27. The interaction effects of cultivar x location on the days to the 100% flowering of sorghum during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	87.21	105.00
PAN 8816	81.50	105.00
LSD $_{(0.05)}$	2.39	

3.5.7 The interaction effects of nitrogen fertiliser rate x location on the days to the 100% flowering of sorghum during the 2016/17 planting season

The interactions of nitrogen fertiliser rate x location also had a significant effect ($P< 0.001$) on the days to the 100% flowering stage of sorghum during 2016/17 season (Table 3.28).

Table 3.28. The interaction effects of nitrogen fertiliser rate x location on the days to the 100% flowering of sorghum during the 2016/17 planting season

Nitrogen rate	Maf	Taung
0 kg/ha	79.69	105.00
100 kg/ha	85.62	105.00
150 kg/ha	87.75	105.00
LSD $_{(0.05)}$	2.92	

3.5.8 The interaction effects of cultivar x location on the days to the 50% flowering of sorghum during the 2017/18 planting season

During the 2017/18 planting season, the interactions of cultivar x location had a significant effect ($P < 0.001$) on the days to the 50% flowering of sorghum (Table 3.29).

Table 3.29. The interaction effects of cultivar x location on the days to the 50% flowering of sorghum during the 2017/18 planting season

Cultivar	Maf	Taung
PAN 8625	82.00	77.00
PAN 8816	65.00	64.17
LSD $_{(0.05)}$	1.14	

3.5.9 The interaction effects of cultivar x location on the days to the 100% flowering of sorghum during the 2017/18 planting season

During the 2017/18 planting season, the interactions of cultivar x location had a significant effect ($P < 0.001$) on the days to the 100 % flowering of sorghum (Table 3.30).

Table 3.30. The interaction effects of cultivar x location on the days to the 100% flowering of sorghum during the 2017/18 planting season

Cultivar	Maf	Taung
PAN 8625	94.00	84.00
PAN 8816	74.00	77.58
LSD $_{(0.05)}$	0.57	

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CHAPTER 4

Effects of cultivar, nitrogen fertiliser rate and plant density on the yield and yield components of sorghum

4.1 Introduction

The superior adaptation of sorghum to difficult growing conditions and its good yields, makes it an important grain crop in semi-arid and tropical areas of the world, particularly in sub-Saharan Africa (Dicko *et al.,* 2006). Sorghum production in South Africa varies from 100 000 tons (130 000 ha) to 180 000 tons (150 000 ha) per annum (DAFF, 2010). Studies have shown that the sorghum grain yield varies significantly at different nitrogen (N) levels while grain yield increases with higher nitrogen application rates (Zand and Shakiba, 2013). The quantitative and qualitative characteristics of the sorghum grains are significantly influenced by nitrogen (Mousavi *et al.,* 2013). Applications of nitrogen of up to 150 kg/ha have been observed to increase the number of grains, grain yield, and the harvest index (Mousavi *et al.,* 2013). Nitrogen demand may also increase as plant density increases (Spiertz, 2010); therefore, it is necessary to apply a sufficient amount of nitrogen to achieve optimum grain yields (Strasil and Vorlicek, 2002).

Plant density is one of the major factors that determines crop yield (Hassan and Khaliq, 2008). Employing lower plant densities could result in low yields (Seran and Brintha, 2010), whereas higher plant densities may cause lodging, poor light penetration in the crop canopy (Muoneke *et al.*, 2007), a reduction in photosynthetic efficiency, and ultimately severely impact upon yields (Lemerle *et al.,* 2006), especially under moisture stress conditions. Higher plant densities of grain sorghum have been reported by Javadi *et al.* (2005) to increase grain and biological yields and lower grain number per panicle. However, plant density does not significantly affect traits such as the 1000 grain weight and the harvest index. Studies conducted by Mousavi *et al.* (2013) have reported the influence of various densities on the yield and yield components of grain sorghum, and indicate that higher densities result in a higher panicle number per unit area and maximum grain yield.

Previous research by Tolk *et al.* (2003) demonstrated that late-maturing sorghum cultivars perform best when planted at lower populations. However, Baumhardt *et al.* (2005) reported that the mean yield for late-maturing sorghum is significantly less than the yields of either early or medium-maturing sorghum cultivars. Nitrogen deficiency in soils can result in a reduction in dry matter, and grain yield in cereal crops (Ashiono *et al*., 2005). On the other hand, overpopulation might lead to a reduction in grain yield. Thus, the objective of this study was to determine the effect of cultivar, nitrogen fertiliser rate and plant density on the yield and yield components of sorghum planted under different environmental conditions.

4.2 MATERIALS AND METHODS

4.2.1 Site description

This study was conducted during the 2016/17 and 2017/18 planting seasons at two locations in North-West province. The first being the Department of Agriculture Experimental Station at Taung, and the second being the North West University Research Farm at Mafikeng, South Africa. The North West University Research Farm is situated at 25° 48′S and 45° 38′E and at an altitude of 1 012 m above sea level. It is located about eight kilometers from the city of Mafikeng towards the Botswana-South Africa border. It falls into a semi-arid tropical savanna region and receives a mean annual rainfall of 571 mm in summer (Kasirivu *et al*., 2011). Approximately 68 % of the annual precipitation in this area falls only occasionally between the months of November and January in relatively heavy downpours, with a pronounced dry season from April to September. The mean maximum temperature is 37°C, while the mean minimum temperature is 7° – 11°C. The annual average pan evaporation for North West is 1 023 mm (Kasirivu *et al.,* 2011). According to the South Africa soil classification system, the soil of the site belongs to the Hutton series and has a sandy, loam texture (Molope, 1987; Kasirivu *et al.,* 2011). According to the FAO-UNESCO system, the soil of the North West University Research Farm is classified as Ferric luvisol (FAO-UNESCO, 2006).

The Department of Agriculture's experimental station at Taung, about 293 km away from the North West University Mafikeng Campus, is situated at 27° 30′S and 24° 30′E and at an altitude of 1 111 m above sea level. Taung's experimental site is situated in a grassland savannah region with a mean rainfall of 1 061 mm, the rainy season usually starting in October (Pule-Meulenberg *et al.,* 2010). According to South Africa's soil classification system, the soils here belong to the Hutton series (Molope, 1987; Kasirivu *et al.*, 2011). Taung has deep but fine sandy soils dominated by red, freely-drained, eutrophic soils with parent material that originated from aeolian deposits (Staff, 1999).

4.2.2 Experimental design

The experimental design is a split-split plot arrangement fitted into a randomized complete block design (RCBD) with four (4) replicates. The experiment considers high and low plant densities as the main plot factor. The nitrogen fertiliser rates, 0, 100 and 150 kg N/ha, were the sub-plot factor, while the two sorghum cultivars, namely PAN 8625 and PAN 8816, were the sub-sub plot factor. The experiment involved a total of 48 plots and a total field area measuring 60 m x 36 m (2160 m^2) at each location.

4.2.3 Agronomic practices

The preparation of the seedbeds was done through disc ploughing and harrowing. Two sorghum cultivars were used, namely PAN 8816 (a medium to late maturing cultivar) and PAN 8625 (a late maturing cultivar). They were purchased from PANNAR Seed Company. The nitrogen fertiliser used was urea (46% nitrogen), while the phosphorus fertiliser was a single superphosphate (SSP). Fertiliser application was carried out through banding and the rates of nitrogen were 0, 100 and 150 kg/ha of urea while 60 kg/ha of phosphorus (SSP) was applied at planting. Thinning was carried out three weeks after emergence, leaving one plant per stand. Weeds were removed for the first time three (3) weeks after planting and subsequently at the vegetative and flowering stages and during grain filling to prevent pest infestation, and crop-weed competition for nutrients. Cypermethrin (pyrethroid) 200 EC was applied intermittently to control aphids and flies, while the sorghum panicles were protected from birds with the aid of monofilament bags.

A summary of events that occurred at various experimental sites

Taung

During the 2016/17 planting season, much rainfall was received between December and January which resulted in waterlogging. This impacted on the vegetative phase of crop development, and some plants did not survive. Seven plots were damaged by birds during the first planting season which lowered the grain yield. However, during the 2017/18 planting season, the rainfall received was very low and there were incidents of water shortage for irrigation, but on the positive side, there was a reduction in bird attacks.

Mafikeng

During the 2016/17 planting season, guinea fowl and birds caused a major reduction in yield, whereas in the 2017/18 planting season there were invasions of the experimental plots by cows and goats but the damage was limited to the border rows; hence there was no significant effect on grain yield. Rainfall was also low during the research period, but supplementary irrigation was supplied.

4.2.4 Data collection

Data considered for the yield and yield parameters were collected from 9.6 m^2 (harvesting area). Panicle length (cm) and panicle mass (g) per plant were determined by randomly selecting three sorghum panicles; their respective lengths and masses were measured and averaged. The total number of sorghum plants harvested within the harvesting area of 9.6 m^2 of each plot was recorded and converted into plant population per hectare. The total number of panicles harvested from each harvested area were weighed by means of a measuring scale, and panicle mass was converted to kg/ha. After threshing the sorghum panicles, the total grain mass per harvested area was measured and converted to grain yield (kg/ha). One thousand (1000) grains were counted and weighed per harvested area as 1000 grain mass. The field biomass yield was determined by harvesting all the plants from the harvesting area; the fresh weight was measured; and subsamples were taken and oven dried for 48 hours at 75^{o}C to a constant weight which was converted to kg/ha.

4.2.5 Data analysis

An analysis of variance was performed using GenStat: 11th edition (2008). The least significant difference (LSD) was used to separate the means, and a probability level of less than 0.05 was considered to be statistically significant (Gomez and Gomez, 1984). The high factor interactions were considered under each parameter that was measured.

4.3 RESULTS AND DISCUSSION

4.3.1 The effects of treatment factors on the sorghum panicle length (cm/plant) during the 2016/17 and 2017/18 planting seasons

Table 4.1 indicates that location had a significant effect (P = 0.002) on the sorghum panicle length during the 2016/17 planting season. Sorghum planted at Mafikeng had a significantly longer panicle length of 35.50 cm than sorghum planted at Taung which had 29.78 cm. The longer panicles observed in Mafikeng could be attributed to the higher volume of rainfall (Fig. 3.1) which had a positive impact on panicle length. It has been reported that moisture availability tends to encourage elongation of shoot. This corroborates the findings by Bayu *et al.* (2005), who reported similar variations in panicle length in different locations owing to amount of rainfall. Cultivar had a significant effect (P < 0.001) on the sorghum panicle length during the 2017/18 planting season. Sorghum cultivar PAN 8816 had a significantly longer panicle length of 39.61 cm than PAN 8625 which had 36.06 cm. This could be attributed to the genetic makeup of the cultivars. This observation agrees with the findings of Kenga *et al.* (2004), who reported variations in panicle length as a result of additive gene effects.

Cultivar, plant density and nitrogen fertiliser rate had no significant effect on the sorghum panicle length during the 2016/17 planting season. Plant density, nitrogen fertiliser rate and location also had no significant effect on the sorghum panicle length during the 2017/18 planting season.

4.3.2 The effects of treatment factors on the sorghum panicle mass (g/plant) during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect (P < 0.001) on the sorghum panicle mass per plant during the 2016/17 and 2017/18 planting seasons (Table 4.1). Sorghum cultivar PAN 8625 had a significantly higher panicle mass of 182.0 g/plant than PAN 8816 (119.40 g/plant) during the 2016/17 planting season. Sorghum cultivar PAN 8625 also had a significantly higher panicle mass of 243.1 g/plant than PAN 8816 (222.30 g/plant) during the 2017/18 planting season. This could be attributed to the differences in grain size of the cultivars. This observation agrees with the findings of Laza *et al.* (2004), who reported that differences in panicle weight could be due to dissimilarities in panicle and seed size among the cultivars.

During the 2016/17 planting season, the nitrogen fertiliser rate had a significant effect (P < 0.001) on the sorghum panicle mass per plant. Sorghum fertilized with zero nitrogen fertiliser had a significantly higher panicle mass of 167.0 g/plant than sorghum fertilized with 100 and

150 kg N/ha which had panicle masses of 154.9 g/plot and 130.1 g/plot respectively. This observation was unexpected and it contradicts the findings of Zhou *et al.* (2017), who reported that under high nitrogen levels both the grain weight and grain number of rice hybrids increased.

Location had a significant effect (P < 0.001) on the sorghum panicle mass per plant during the 2016/17 and 2017/18 planting seasons. Sorghum planted at Mafikeng had a significantly higher panicle mass of 201.7 g/plant than sorghum planted at Taung which had panicle mass of 99.70 g/plant during the 2016/17 planting season. Sorghum planted at Mafikeng also had a significantly higher panicle mass of 256.4 g/plant than sorghum planted at Taung which had panicle mass of 209.0 g/plant during the 2017/18 planting season. This could be attributed to the large amount of rainfall received which enhanced the sorghum panicle mass per plant. This corroborates the findings by Hadebe *et al.* (2017), who reported that different sorghum hybrids show variable yield (panicle mass) advantages over one another under varying rainfall conditions.

During the 2016/17 planting season, plant density had no significant effect on the sorghum panicle mass per plant. During the 2017/18 planting season, plant density and nitrogen fertiliser rate had no significant effect on sorghum panicle mass per plant.

4.3.3 The effects of treatment factors on the sorghum panicle mass (kg/ha) during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect (P < 0.001) on the sorghum panicle mass during the 2016/17 planting season (Table 4.1). Sorghum cultivar PAN 8625 had a significantly higher panicle mass of 3034 kg/ha than PAN 8816 which had a panicle mass of 2106 kg/ha. The difference in the panicle mass (kg/ha) could be attributed to the panicle mass (g/plant) recorded per plant. This corroborates the findings by Chohan *et al.* (2006) and Mehmud *et al.* (2003), who reported differences in the grain weight of sorghum varieties.

Plant density had a significant effect (P < 0.001) on the sorghum panicle mass during the 2016/17 and 2017/18 planting seasons. Sorghum planted under high density had a significantly higher panicle mass of 2882 kg/ha than sorghum planted under low density during the 2016/17 planting season which had panicle mass of 2258 kg/ha. Sorghum planted under high density also had a significantly higher panicle mass of 7168 kg/ha than sorghum planted under low density during the 2017/18 planting season. This could be attributed to an increase in the number of panicles per unit area. These results agree with the findings of Bayu *et al*. (2005), who reported a significant increase in panicle mass under high plant density.

During the 2016/17 planting season, location had a significant effect ($P < 0.001$) on the sorghum panicle mass. Sorghum planted at Mafikeng had a significantly higher panicle mass of 3686 kg/ha than sorghum planted at Taung which had panicle mass of 1454 kg/ha. This could be attributed to variations in the environmental conditions. This corroborates the findings by Ezzat *et al.* (2010), who reported similar results on different cultivars of sorghum planted under different environmental conditions and at numerous locations.

During the 2016/17 and 2017/18 planting seasons, the nitrogen fertiliser rate had a significant effect ($P \leq 0.005$) on the sorghum panicle mass. Sorghum fertilized with zero nitrogen fertiliser had a significantly higher panicle mass of 2918 kg/ha than sorghum fertilized with 100 and 150 kg/ha which had 2435 kg/ha and 2357 kg/ha respectively during the 2016/18 planting season. Sorghum fertilized with zero nitrogen fertiliser also had a significantly higher panicle mass of 7149 kg/ha than sorghum fertilized with 100 and 150 kg/ha which had 5926 kg/ha and 5856 kg/ha respectively during the 2017/18 planting season. The highest panicle mass under zero nitrogen fertiliser was unexpected and this contradicts the findings by Băşa *et al.* (2016), who reported a significant increase in the cob weight of maize when the maize plants were supplied with 80 kg N/ha. During the 2017/18 planting season, cultivar and location had no significant effect on sorghum panicle mass.

Table 4.1. The main effects of treatment factors on the sorghum panicle length (cm/plant), panicle mass per plant (g/plant) and panicle mass (kg/ha) during the 2016/17 and 2017/18 planting seasons

Treatment factors	2016/17			2017/18		
	Panicle length (cm)	Panicle mass per plant (g/plant)	Panicle mass/ha (kg/ha)	Panicle length (cm)	Panicle mass per plant (g/plant)	Panicle mass/ha (kg/ha)
Cultivar	Means	Means	Means	Means	Means	Means
PAN 8625	34.25	182.00	3034	36.06	243.10	6489
PAN 8816	31.03	119.40	2106	39.61	222.30	6131
LSD $_{(0.05)}$	3.53	12.49	291.80	0.67	11.73	643.20
Density						
High	33.29	151.20	2882	37.97	236.80	7168
Low	31.99	150.10	2258	37.69	228.60	5452
LSD $_{(0.05)}$	3.53	12.49	291.80	0.67	11.73	643.20
Nitrogen rate						
0 kg/ha	34.54	167.0	2918	37.99	239.5	7149
100 kg/ha	33.19	154.9	2435	37.60	226.90	5926
150 kg/ha	30.18	130.1	2357	37.90	231.70	5856
LSD $_{(0.05)}$	4.32	15.30	357.40	0.82	14.37	787.8
Location						
Mafikeng	35.50	201.7	3686	37.80	256.4	6322
Taung	29.78	99.70	1454	37.86	209.0	6299
LSD $_{(0.05)}$	3.53	12.49	291.8	0.67	11.73	643.20

4.3.4 The interaction effects of cultivar x location on the sorghum panicle length (cm) during the 2016/17 planting season

The interaction of cultivar x location had a significant effect (P = 0.016) on the sorghum panicle length during the 2016/17 planting season (Table 4.2).

Table 4.2. The interaction effects of cultivar x location on the sorghum panicle length (cm) during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	34.92	33.58
PAN 8816	36.08	25.98
LSD $_{(0.05)}$	4.99	

4.3.5 The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum panicle length (cm) during the 2017/18 planting season

The interaction of nitrogen fertiliser rate x cultivar x location had a significant effect (P = 0.019) on the sorghum panicle length during the 2017/18 planting season (Table 4.3).

Table 4.3. The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum panicle length (cm) during the 2017/18 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	36.12	36.40	40.02	39.44
100 kg/ha	35.71	35.85	38.81	40.02
150 kg/ha	35.37	36.87	40.75	38.60
LSD $_{(0.05)}$	1.63			

4.3.6 The interaction effects of nitrogen fertiliser rate x cultivar x location on sorghum panicle mass per plant (g/plant) during the 2016/17 planting season

The interaction of nitrogen fertiliser rate x cultivar x location had a significant effect ($P \leq 0.05$) on sorghum panicle mass per plant during the 2016/17 planting season (Table 4.4).

Table 4.4. The interaction effects of nitrogen fertiliser rate x cultivar x location on sorghum panicle mass per plant (g/plant) during the 2016/17 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	277.8	145.1	170.8	74.3
100 kg/ha	209.8	149.9	187.3	72.7
150 kg/ha	184.8	124.4	179.6	31.6
LSD $_{(0.05)}$	30.60			

4.3.7 The interaction effects of nitrogen fertiliser rate x cultivar x location on sorghum panicle mass per plant (g/plant) during the 2017/18 planting season

The interaction of nitrogen fertiliser rate x cultivar x location had a significant effect ($P \leq 0.05$) on sorghum panicle mass per plant during the 2017/18 planting season (Table 4.5).

Table 4.5. The interaction effects of nitrogen fertiliser rate x cultivar x location on sorghum panicle mass per plant (g/plant) during the 2017/18 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	282.6	205.3	249.6	220.5
100 kg/ha	259.8	218.2	236.9	192.7
150 kg/ha	261.3	231.0	248.0	186.3
LSD $_{(0.05)}$	28.74			

4.3.8 The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum panicle mass (kg/ha) during the 2016/17 planting season

The interaction of nitrogen fertiliser rate x cultivar x location had a significant effect (P = 0.002) on the sorghum panicle mass during the 2016/17 planting season (Table 4.6).

Table 4.6. The interaction effects of nitrogen fertiliser rate x cultivar x location on the sorghum panicle mass (kg/ha) during the 2016/17 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	5137	2025	3457	1055
100 kg/ha	3301	2122	3483	833
150 kg/ha	3411	2207	3327	482
LSD $_{(0.05)}$	714.9			

4.3.9 The effects of treatment factors on the sorghum grain yield (kg/ha) during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect ($P < 0.001$) on the sorghum grain yield during 2016/17 planting season, as indicated in Table 4.7. Sorghum cultivar PAN 8625 had a significantly higher grain yield of 1820 kg/ha which was 18.37% higher than that of PAN 8816 (1255 kg/ha). This could be attributed to differences among the cultivars with regards to panicles per plant, weight and number of grains or kernel per panicle. This corroborates the findings by Maman *et al.* (2004) who reported that yield differences in sorghum are associated with panicles per square meter or panicles per plant, kernels per panicle and kernel weight.

Plant density had a significant effect ($P \leq 0.005$) on the sorghum grain yield during the 2016/17 and 2017/18 planting seasons. Sorghum planted under high density had a significantly higher grain yield of 1744 kg/ha than sorghum planted under low density which had grain yield of 1331 kg/ha during the 2016/17 planting season. Sorghum planted under high density also had a significantly higher grain yield of 4621 kg N/ha than sorghum planted under low density which had grain yield of 3467 kg/ha during the 2017/18 planting season. This could be attributed to increased grain yield per panicle as sorghum planted under high density conditions produces more plants and panicles per unit area. Sorghum planted in narrower rows would probably allow for the more efficient use of available sunlight, moisture and nutrients than sorghum planted in wider rows; hence, the increased grain yield. This corroborates the findings by Lafarge and Hammer (2002) and Conley *et al.* (2005), who indicated that higher plant densities enhance sorghum grain yields.

During the 2016/17 and 2017/18 planting seasons, the nitrogen fertiliser rate had a significant effect ($P \leq 0.05$) on the sorghum grain yield. Sorghum fertilized with zero nitrogen fertiliser had a significantly higher grain yield of 1796 kg/ha than sorghum fertilized with 100 and 150 kg N/ha which had grain yields of 1404 kg/ha and 1413 kg/ha respectively during the 2016/17 planting season. Sorghum fertilized with zero nitrogen fertiliser also had a significantly higher grain yield of 4623 kg N/ha than sorghum fertilized with 100 and 150 kg N/ha during the 2017/18 planting season which had grain yield of 3820 and 3680 kg/ha. This result was unexpected and it contradicts the findings by Ahmad (2010) and Lehmann *et al*. (1999), who reported that nitrogen fertilized plots have significantly higher grain yields than unfertilized plots.

Location had a significant effect (P < 0.001) on the sorghum grain yield during the 2016/17 planting season. Sorghum planted at Mafikeng had a significantly higher grain yield of 2342 kg/ha than sorghum planted at Taung which had grain yield of 733 kg/ha. The higher grain yield observed could be attributed to the amount of rainfall and the temperature which support sorghum development and grain filling. This corroborates the findings by Conley *et al.* (2005), who reported that the grain sorghum yield is generally variable and dependent upon the environment. During the 2017/18 planting season, cultivar and location had no significant effect on the sorghum grain yield.

4.4 The effects of treatment factors on the sorghum 1000 seed mass (g/plot) during the 2016/17 and 2017/18 planting seasons

As indicated in Table 4.7, the nitrogen fertiliser rate had a significant effect (P = 0.005) on the sorghum 1000 seed mass during the 2016/17 planting season. Sorghum fertilized with zero nitrogen fertiliser had a significantly higher 1000 seed mass of 28.03 g/plot than sorghum fertilized with 100 and 150 kg N/ha which had seed mass of 24.91 and 22.92 g/plot respectively. This observation suggests that increased nitrogen levels might not necessarily have an impact on the 1000 seed mass of sorghum. This corroborates the findings of Bayu *et al*. (2005), who indicated that the 1000 seed weight responds negatively to nitrogen fertilisation.

Location had a significant effect (P < 0.001) on the 1000 seed mass of sorghum during the 2016/17 and 2017/18 planting seasons. Sorghum planted at Mafikeng had a significantly higher 1000 seed mass of 30.24 g/plot than sorghum planted at Taung which had seed mass of 20.33 g/plot during the 2016/17 planting season. Sorghum planted at Mafikeng also had a significantly higher 1000 seed mass of 34.59 g/plot than sorghum planted at Taung during the 2017/18 planting season. This could be attributed to the amount of rainfall received during the season which has a positive effect on grain production and the eventual sorghum grain mass. This corroborates the findings by Fernandez *et al*. (2012), who reported a significant increase in the 1000 seed mass under irrigated conditions as opposed to that under dryland conditions.

During the 2017/18 planting season, the cultivar had a significant effect (P < 0.001) on the 1000 seed mass of sorghum. Sorghum cultivar PAN 8816 had a significantly higher 1000 seed mass of 33.68 g/plot than PAN 8625 which had seed mass of 29.97 g/plot. The observed differences in grain mass amongst the cultivars could be attributed to variations in grain size among them. This corroborates the findings of Lamptey *et al.* (2014) and Sandeep *et al.* (2011), who reported similar results on the influence of cultivar on the 1000 grain mass of sorghum. During the 2016/17 planting season, plant density and cultivar had no significant effect on the 1000 grain mass. During the 2017/18 planting season, plant density and nitrogen fertiliser rate had no significant effect on the 1000 grain mass of sorghum.

Table 4.7. The main effects of treatment factors on the sorghum grain yield (kg/ha) and the 1000 seed mass (g/plot) during the 2016/17 and 2017/18 planting seasons

Treatment factors	2016/17		2017/18	
	Grain yield (kg/ha)	1000 seed mass (g/plot)	Grain yield (kg/ha)	1000 seed mass (g/plot)
Cultivar	Means	Means	Means	Means
PAN 8625	1820	24.86	3972	29.97
PAN 8816	1255	25.70	4116	33.68
LSD $_{(0.05)}$	198.70	2.47	418.90	0.42
Density				
High	1744	25.73	4621	31.53
Low	1331	24.84	3467	32.13
LSD $_{(0.05)}$	198.70	2.47	418.90	0.42
Nitrogen fertiliser rates				
0 kg/ha	1796	28.03	4623	31.21
100 kg/ha	1404	24.91	3820	32.33
150 kg/ha	1413	22.92	3680	31.94
LSD $_{(0.05)}$	243.40	3.03	513.00	0.42
Location				
Mafikeng	2342	30.24	4073	34.59
Taung	733	20.33	4016	29.06
LSD $_{(0.05)}$	198.70	2.47	418.90	0.42

4.4.1 The interaction effects of nitrogen fertiliser rate x cultivar x location on sorghum grain yield (kg/ha) during the 2016/17 planting season

The interaction of nitrogen fertiliser rate x cultivar x location had a significant effect ($P < 0.001$) on sorghum grain yield during the 2016/17 planting season (Table 4.8).

Table 4.8. The interaction effects of nitrogen fertiliser rate x cultivar x location on sorghum grain yield (kg/ha) during the 2016/17 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	3322	1215	2182	466
100 kg/ha	1930	1147	2289	249
150 kg/ha	2059	1250	2271	72
LSD $_{(0.05)}$	486.8			

4.4.2 The interaction effects of nitrogen fertiliser rate x cultivar x location on the 1000 seed mass (g/plot) of sorghum during the 2016/17 planting season

The interaction of nitrogen fertiliser rate x cultivar x location had a significant effect ($P = 0.008$) on the 1000 seed mass of sorghum during the 2016/17 planting season (Table 4.9).

Table 4.9. The interaction effects of nitrogen fertiliser rate x cultivar x location on the 1000 seed mass (g/plot) of sorghum during the 2016/17 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	29.29	22.85	31.94	28.02
100 kg/ha	27.73	22.40	33.19	16.31
150 kg/ha	26.09	20.83	33.19	11.58
LSD $_{(0.05)}$	6.05			

4.4.3 The interaction effects of nitrogen fertiliser rate x cultivar x location on the 1000 seed mass (g/plot) of sorghum during the 2017/18 planting season

The interaction of nitrogen fertiliser rate x cultivar x location had a significant effect (P = 0.022) on the 1000 seed mass of sorghum during the 2017/18 planting season (Table 4.10).

Table 4.10. The interaction effects of nitrogen fertiliser rate x cultivar x location on the 1000 seed mass (g/plot) of sorghum during the 2017/18 planting season

Nitrogen rate	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
0 kg/ha	33.20	25.67	34.09	31.90
100 kg/ha	33.65	27.70	37.17	30.80
150 kg/ha	31.93	27.69	37.52	30.62
LSD $_{(0.05)}$	2.91			

4.4.4 The interaction effects of plant density x cultivar x location on the 1000 seed mass (g/plot) of sorghum during the 2017/18 planting season

The interaction of plant density x cultivar x location also had a significant effect (P = 0.013) on the 1000 seed mass of sorghum during the 2017/18 planting season (Table 4.11).

Table 4.11. The interaction effects of plant density x cultivar x location on the 1000 seed mass (g/plot) of sorghum during the 2017/18 planting season

Density	PAN 8625		PAN 8816	
	Maf	Taung	Maf	Taung
High	32.76	26.24	34.92	32.18
Low	33.09	27.80	37.59	30.03
LSD $_{(0.05)}$	2.37			

4.4.5 The effects of treatment factors on the sorghum biomass yield (kg/ha) during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect ($P < 0.001$) on the sorghum biomass yield during the 2016/17 and 2017/18 planting seasons, as indicated in Table 4.12. Sorghum cultivar PAN 8625 had a significantly higher biomass yield of 6252 kg/ha than PAN 8816 which had biomass yield of 3725 kg/ha during the 2016/17 planting season. Sorghum cultivar PAN 8625 also had a significantly higher biomass yield of 12706 kg/ha than PAN 8816 during the 2017/18 planting season. This could be attributed to the superior response of growth parameters at 51 and 74 DAP. These results agree with the findings of Sher (2013), Sarfraz *et al.* (2012) and Ayub *et al.* (2010), who reported a significant increase in biomass yield as a result of an increase in the plant height, stem diameter and leaf area of sorghum.

Plant density had a significant effect ($P < 0.001$) on the sorghum biomass yield during the 2016/17 and 2017/18 planting seasons. Sorghum planted under high density had a significantly higher biomass yield of 5589 kg/ha than sorghum planted under low density which had biomass yield of 4388 kg/ha during the 2016/17 planting season. Sorghum planted under high density also had a significantly higher biomass yield of 10896 kg/ha than sorghum planted under low density during the 2017/18 planting season. This result could be attributed to a larger number of plants per unit area. This corroborates the findings by Parija (2011), who reported that sorghum biomass yield increases with increasing plant density.

During the 2016/17 and 2017/18 planting seasons, the nitrogen fertiliser rate had a significant effect ($P \leq 0.031$) on the sorghum biomass yield. Sorghum fertilized with zero nitrogen fertiliser had a significantly higher biomass yield of 5539 kg/ha than sorghum fertilized with 100 and 150 kg N/ha which biomass yields of 4787 and 4639 kg/ha during the 2016/17 planting season. Sorghum fertilized with zero nitrogen fertiliser also had a significantly higher biomass yield of 11956 kg/ha than sorghum fertilized with 100 and 150 kg N/ha which had biomass yields of 8620 and 8408 kg/ha respectively during 2017/18 planting season. This result was unexpected and it contradicted the findings by Parija (2011), who reported that increased nitrogen fertiliser levels result in an increase in the biomass yield in sorghum. Turgut (2000) also indicated that an increase in the nitrogen fertiliser rate results in a proportional increase in the biomass yield in maize.

Location had a significant effect ($P < 0.001$) on the sorghum biomass yield during the 2016/17 planting season. Sorghum planted at Mafikeng had a significantly higher biomass yield of 7110 kg/ha than sorghum planted at Taung which had biomass yield of 2867 kg/ha. This observation could be attributed to the positive response of sorghum cultivars to varying soil types and different environmental conditions. This corroborates the findings of Hadebe (2016), who reported significant differences in biomass yield between individual agro-ecologies.

During the 2017/18 planting season, location had no significant effect on the biomass yield of sorghum.

4.4.6 The effects of treatment factors on the sorghum plant population/ha during the 2016/17 and 2017/18 planting seasons

Nitrogen fertiliser rate had a significant effect ($P \leq 0.05$) on the sorghum plant population during the 2016/17 and 2017/18 planting seasons as indicated in Table 4.12. Sorghum fertilized with zero nitrogen fertiliser had a significantly higher plant population of 21061 plants/ha than sorghum fertilized with 100 (19987 plants/ha) and 150 kg N/ha (19564 plants/ha) during the 2016/17 planting season. Sorghum fertilized with zero nitrogen fertiliser also had a significantly higher plant population of 35840 plants/ha than sorghum fertilized with 100 (31055 plants/ha) and 150 kg N/ha (29707 plants/ha) during the 2017/18 planting season. This study showed an insignificant increase in plant population as nitrogen levels increase which corroborates the findings by Imran *et al.* (2015), who reported that applications of nitrogen fertilisers have no significant effect on the plant population.

During the 2017/18 planting season, plant density had a significant effect ($P < 0.001$) on the sorghum plant population. Sorghum planted under high density had a significantly higher plant population of 36871 plants/ha than sorghum planted under low density which had 27530 plants/ha. This could be attributed to the larger number of plants per unit area which are then able to maximize the available nutrients necessary for development. This corroborates the findings by Sher (2017), who reported an improvement in the morphological and physiological development of maize plants grown under high density and resulting in larger plant populations.

Location had a significant effect ($P < 0.001$) on the sorghum plant population during the 2016/17 and 2017/18 planting seasons. Sorghum planted at Mafikeng had a significantly larger plant population of 25195 plants/ha than sorghum planted at Taung which had 15213 plants/ha during the 2016/17 planting season. Sorghum planted at Taung also had a significantly larger plant population of 36471 plants/ha than sorghum planted at Mafikeng which had 27930 plants/ha during the 2017/18 planting season. This could be attributed to the favourable weather conditions and the high nutrient status of the soils at Taung (Table 3.1) prior to planting which resulted in a larger plant population. This corroborates the findings by Sangoi *et al.* (2001), who reported that the combination of high soil fertility levels and adequate water distribution during the growth cycle increases the sorghum plant population.

During the 2016/17 planting season, cultivar and plant density had no significant effect on the plant population. During the 2017/18 planting season, cultivar and location had no significant effect on the plant population of sorghum.

Table 4.12. The main effects of treatment factors on the plant population (plants/ha) and biomass yield (kg/ha) of sorghum during the 2016/17 and 2017/18 planting seasons

Treatment factors	2016/17		2017/18	
	Plant population (plants/ha)	Biomass yield (kg/ha)	Plant population (plants/ha)	Biomass yield (kg/ha)
Cultivar	Means	Means	Means	Means
PAN 8625	21311	6252	31988	12706
PAN 8816	19097	3725	32413	6617
LSD $_{(0.05)}$	2625.40	580.60	2854.80	1106.00
Density				
High	22656	5589	36871	10896
Low	17752	4388	27530	8427
LSD $_{(0.05)}$	2625.40	580.60	2854.80	1106.00
Nitrogen rate				
0 kg/ha	21016	5539	35840	11956
100 kg/ha	19987	4787	31055	8620
150 kg/ha	19564	4639	29707	8408
LSD $_{(0.05)}$	3215.50	711.10	3496.40	1354.60
Location				
Mafikeng	25195	7110	27930	9286
Taung	15213	2867	36471	10037
LSD $_{(0.05)}$	2625.40	580.60	2854.80	1106.00

4.4.7 The interaction effects of cultivar x location on the sorghum plant population (plants/ha) during the 2016/17 planting season

The interaction of cultivar x location had a significant effect ($P < 0.001$) on the plant population during the 2016/17 planting season (Table 4.13).

Table 4.13. The interaction effects of cultivar x location on the sorghum plant population (plants/ha) during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	24045	18576
PAN 8816	26345	11849
LSD $_{(0.05)}$	3712.9	

4.4.8 The interaction effects of cultivar x location on the sorghum biomass yield (kg/ha) during the 2016/17 planting season

The interaction of cultivar x location had a significant effect ($P < 0.001$) on the sorghum biomass yield during the 2016/17 planting season (Table 4.14).

Table 4.14. The interaction effects of cultivar x location on the sorghum biomass yield (kg/ha) during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	9119	3385
PAN 8816	5102	2349
LSD $_{(0.05)}$	821.1	

4.4.9 The interaction effects of plant density x cultivar on the sorghum biomass yield (kg/ha) during the 2017/18 planting season

The interaction of plant density x cultivar had a significant effect ($P = 0.002$) on the sorghum biomass yield during the 2017/18 planting season (Table 4.15).

Table 4.15. The interaction effects of plant density x cultivar on the sorghum biomass yield (kg/ha) during the 2017/18 planting season

Density	PAN 8625	PAN 8816
High	14839	6953
Low	10573	6280
LSD $_{(0.05)}$	1564.2	

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CHAPTER 5

Effects of cultivar, nitrogen fertiliser rate and plant density on the grain quality of sorghum

5.1 Introduction

Cereals are the major sources of calories and protein for human consumption and livestock feeds (Lafiandra *et al.,* 2014). Sorghum is a major source of carbohydrates and protein in the diets of rural communities in sub-Saharan Africa (Rohrbach and Obilana, 2003). Nutritionally, sorghum is high in its carbohydrate content in the form of starch, while some cultivars are high in dietary fibre content (Jimoh and Abdullahi, 2017). Typical analytical figures for sorghum grains are: ash 2%, fat 3%, fibre 2%, food energy 394 calories, moisture 11-12%, protein 10-15% and starch 68-80 % (Jimoh and Abdullahi, 2017). Although the protein content of sorghum is considered to be of low quality, the cultivars with higher levels of these nutrients could be of great importance in food production (Moraes *et al.,* 2012).

The level of nitrogen fertilisation is one of the factors limiting grain quality, as variable responses to the application of nitrogen fertiliser have been observed in cereal crops such as sorghum and maize (Almodares *et al.,* 2009). The effect of nitrogen fertilisers on the grain quality of many cereals has also been investigated extensively (Sedlář *et al.,* 2011; Valkama *et al.,* 2013). Some experiments on wheat have indicated that increasing nitrogen levels lead to an increase in the wheat protein content, and similar effects have been found in sorghum (Kaufman *et al.,* 2013) and maize (Wang *et al.,* 2008). Previous findings have indicated that the application of nitrogen fertiliser results in a decline in the fibre content of sorghum. (Amman, 2010)

Plant density has no clear effect on the ash content of sorghum (Mahmood *et al.,* 2013). On the other hand, sorghum planted under high plant densities shows a definite increase in protein content, while a decline in protein content was observed when sorghum is planted under lower and medium plant densities. Generally, grain quality varies among the different cultivars of sorghum and according to the prevailing environmental conditions under which the plants are cultivated (Oyier *et al.,* 2017). Reports by Dotlačil *et al.* (2000) indicate that a high protein content was observed in early maturing cultivars of wheat.

Furthermore, the methods adopted in grain processing differ across several locations which may in turn alter the quality and nutritional value of grain sorghum (Polycarpe Kayode *et al.,* 2005). Since nitrogen is a critical nutrient for many cereal cultivars, low applications of nitrogen may also have an impact on grain quality, besides limiting its yield (Diallo, 2012). On the other hand, over fertilisation tends to decrease the quality of grains. Therefore, the objective of this study was to determine the influence of cultivar, nitrogen fertiliser rates and plant density on sorghum grain quality.

5.2 MATERIALS AND METHOD

5.2.1 Site description

This study was conducted during the 2016/17 and 2017/18 planting seasons at two locations in the North-West province. The soils at these two locations had different chemical and physical properties (Table 3.1) and the environmental conditions also differed (Figs.1 and 2). The first being the Department of Agriculture Experimental Station at Taung and the second being the North West University Research Farm at Mafikeng, South Africa. The North West University Research Farm is situated at 25^{o} 48′S and 45^{o} 38′E and at an altitude of 1 012 m above sea level. It is located about eight kilometers from the city of Mafikeng towards the Botswana-South Africa border. This is a semi-arid tropical savanna region, which receives a mean annual rainfall of 571 mm in summer (Kasirivu *et al*., 2011). Approximately 68% of the annual precipitation in this area falls only occasionally between the months of November and January in heavy downpours, with a pronounced dry season being experienced from April to September. The mean maximum temperature is 37^{o}C, while the mean minimum temperature is 7^{o} – 11^{o}C. The annual average pan evaporation for North West province is 1 023 mm (Kasirivu *et al.,* 2011). According to the South African soil classification system, the soils at North West University Research farm, at Mafikeng belongs to the Hutton series, and has a sandy loam texture (Molope, 1987; Kasirivu *et al.,* 2011). According to the FAO-UNESCO system, the soil at this site is classified as Ferric luvisol (FAO-UNESCO, 2006).

The Department of Agriculture's experimental station at Taung, about 293 km from the North West University's Mafikeng Campus is situated at 27^{o} 30′S and 24^{o} 30′E and at an altitude of 1 111 m above sea level. The Taung experimental site is situated in a grassland savannah region with a mean rainfall of 1 061 mm, the rainy season usually starting in October (Pule-Meulenberg *et al.,* 2010). According to the South Africa soil classification system, the soils of this site belong to the Hutton series (Molope, 1987; Kasirivu *et al.,* 2011). Taung has deep, fine, sandy soils dominated by red freely-drained, eutrophic soils with parent material that originated from aeolian deposits (Staff, 1999).

5.2.2 Experimental design

The experimental design was a split-split plot arrangement fitted into a randomized complete block design (RCBD) with four (4) replicates. The experiment considered high (33 333 plants/ha) with 1 x 0.3 m spacing and low plant densities (22 222 plants/ha) with 1.5 x 0.3 m spacing; as the main plot factor. The nitrogen fertiliser rates of 0, 100 and 150 kg N/ha, were considered as the sub-plot factor, while two sorghum cultivars, PAN 8625 and PAN 8816 were considered to be the sub-sub plot factor. The experiment involved a total of 48 plots and a total field area measuring 60 m x 36 m (2160 m^2) at each location.

5.2.3 Agronomic practices

The preparation of the seed beds was carried out through disc ploughing and harrowing. Two sorghum cultivars were used, namely; PAN 8816 (a medium to late-maturity cultivar) and PAN 8625 (a late-maturity cultivar). They were purchased from PANNAR Seed Company. Each plot measured 6 m x 4 m, and there were five rows under low plant density (22 222 plants/ha) and seven rows under high plant density (33 333 plants/ha). The nitrogen fertiliser used was urea (46% nitrogen) and the phosphorus fertiliser used was single superphosphate (SSP). The fertiliser was applied through banding, and the rates for the application of nitrogen fertiliser were 0, 100 and 150 kg/ha of urea while 60 kg/ha of phosphorus (SSP) was applied at planting. Thinning was carried three weeks after emergence, leaving one plant per stand. Weeds were first removed three (3) weeks after planting, and subsequently at the vegetative and flowering stages, and also during grain filling to prevent pest infestation, and crop-weed competition for nutrients. Cypermethrin (pyrethroid) 200 EC was applied intermittently to control aphids and flies, while the sorghum panicles were protected from birds by means of monofilament bags.

5.2.4 Data collection

Field dried sorghum panicles were hand-harvested from a harvesting area of 9.6 m^2. The panicles from the harvesting area were threshed and winnowed. Approximately 500 g of grain samples were sub-sampled per plot and used for grain analysis. A total of 48 samples per location were then analysed for their protein, oil, starch, sugar, ash and fibre content in percentages by using the Spectra Star XL near Infrared Analyser (NIR) machine.

5.2.5 Data analysis

An Analysis of variance was performed on data generated using the GenStat: 11th edition (2008). The least significant difference (LSD) was used to separate the means and a probability level of less than 0.05 was considered to be statistically significant (Gomez and Gomez, 1984). The high factor interactions were considered under each parameter that was measured.

5.3 RESULTS AND DISCUSSION

5.3.1 The effects of treatment factors on the sorghum ash content during the 2016/17 and 2017/18 planting seasons

Figure 5.1 indicates that cultivar had a significant effect ($P < 0.001$) on the sorghum ash content during 2016/17 planting season. Sorghum cultivar PAN 8625 had a significantly higher ash content of 4.47% than PAN 8816 which had 3.54%. These differences could be attributed to the genetic constitution of the cultivars used. This corroborates the findings by Ayub *et al.* (2002), who reported similar differences for ash content among sorghum cultivars.

As indicated, the nitrogen fertiliser rate and location had a significant effect ($P \leq 0.05$) on the sorghum ash content during 2017/18 planting season (Figures 5.2 and 5.3, respectively). Sorghum fertilized with zero nitrogen fertiliser had a significantly higher ash content of 4.44% than sorghum fertilized with 100 (4.32%) and 150 kg N/ha (4.31%). These results contradict the findings by Ayub *et al.* (1999) who reported an increase in ash content with increased applications of nitrogen. Sorghum planted at Taung had a significantly higher ash content of 4.40% than sorghum planted at Mafikeng (4.31%). This could be attributed to the type of soil at the location and its nitrogen content as indicated in Table 3.1. This corroborates the findings by Jimoh and Abdullahi (2017), who reported that an increase in ash content of sorghum could be affected by the nature of the soil and the amounts of nutrient in the soil. During the 2016/17 planting season, plant density, nitrogen fertiliser rate and location had no significant effect on the sorghum ash content. During 2017/18 planting season, cultivar and plant density had no significant effect on the sorghum ash content.

5.3.2 The effects of treatment factors on the sorghum fibre content during 2016/17 and 2017/18 planting seasons

Figure 5.1 indicates that cultivar had a significant effect ($P < 0.001$) on the sorghum fibre content during the 2016/17 and 2017/18 planting seasons. Sorghum cultivar PAN 8625 had a significantly higher fibre content of 10.60% than PAN 8816 (7.35%) during the 2016/17 planting season. Sorghum cultivar PAN 8625 also had a significantly higher fibre content of 9.67% than PAN 8816 (7.13%) during the 2017/18 planting season. This could be attributed to genetic differences among the cultivars planted. This corroborates the findings by Ayub *et al.* (2010), who reported that all of the eight varieties of sorghum that were tested differed significantly in their fibre and maximum fibre contents. Variations in the crude fibre contents of various sorghum cultivars were also reported by Panwar *et al.* (2000) and Hunsigi *et al.* (2010).

Location had a significant effect (P = 0.005) on the sorghum fibre content during 2016/17 planting season as indicated in Figure 5.3. Sorghum planted at Taung had a significantly higher fibre content of 9.80% than sorghum planted at Mafikeng (8.14%). This could be attributed to variations in the environmental conditions such as rainfall. This corroborates the findings by Queiroz *et al.* (2015), who reported variations in the fibre content of sorghum cultivated under different rainfall conditions.

During the 2016/17 and 2017/18 planting seasons, plant density and nitrogen fertiliser rate had no significant effect on the sorghum fibre content. During the 2017/18 planting season, location had no significant effect on the sorghum fibre content.

5.3.3 The effects of treatment factors on the sorghum oil content during the 2016/17 and 2017/18 planting seasons

Figure 5.3 indicates that location had a significant effect (P < 0.001) on the sorghum oil content during the 2016/17 and 2017/18 planting seasons. Sorghum planted at Mafikeng had a significantly higher oil content of 5.01% than sorghum planted at Taung (4.54%) during the 2016/17 planting season. Sorghum planted at Mafikeng also had a significantly higher oil content of 5.01% than sorghum planted at Taung during the 2017/18 planting season. This could be attributed to differences in soil type. This corroborates the findings by De Geus *et al.* (2008), who reported that oil content is affected by the soil type. Figure 3 indicates that cultivar had a significant effect (P < 0.001) on the sorghum oil content during the 2017/18 planting season. Sorghum cultivar PAN 8816 had a significantly higher oil content of 5.45% than PAN 8625 (4.1%). This could be attributed to the differences in genetic composition of the cultivars planted since the sizes of the cultivar seeds vary**.** This corroborates the findings by Shen *et al.* (2010), who reported that the oil content in maize seed is influenced by the size of the seed embryo and the oil concentration in the embryo, as well as the oil content in the endosperm.

During the 2016/17 planting season, the cultivar had no significant effect on the sorghum oil content. During the 2016/17 and 2017/18 planting seasons, plant density and the nitrogen fertiliser rate had no significant effect on the sorghum oil content.

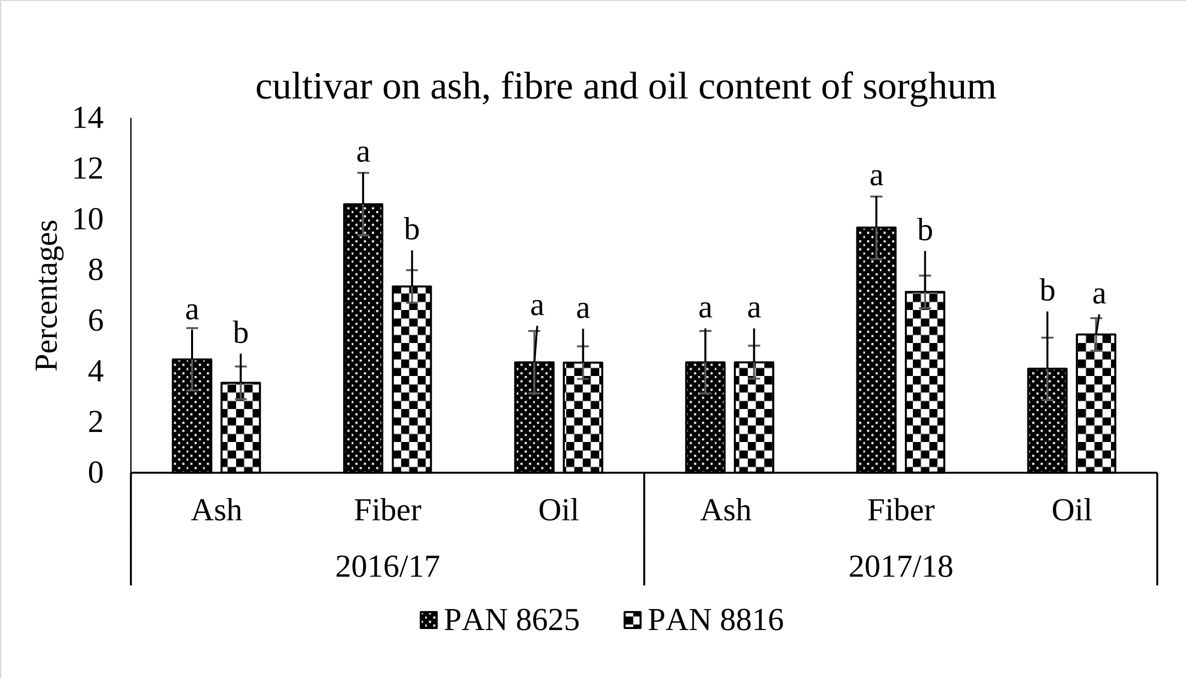

Figure 5.1. The main effects of cultivar on sorghum ash, fibre and oil content during the 2016/17 and 2017/18 planting seasons

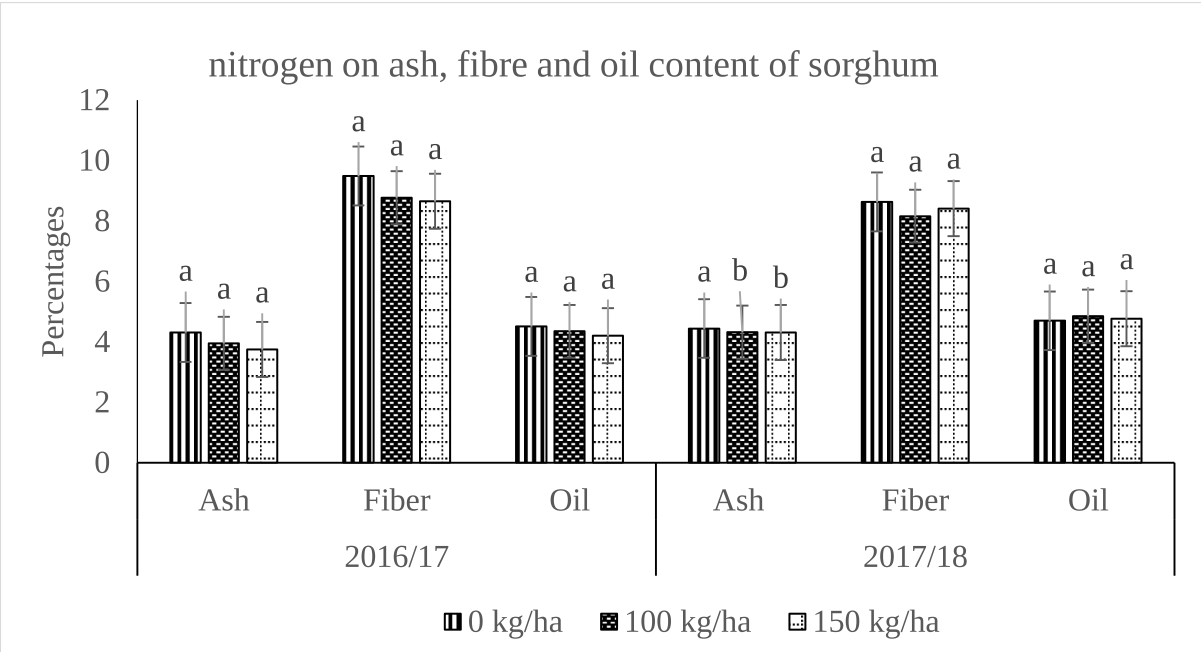

Figure 5.2. The main effects of nitrogen fertiliser rate on sorghum ash, fibre and oil content during the 2016/17 and 2017/18 planting seasons

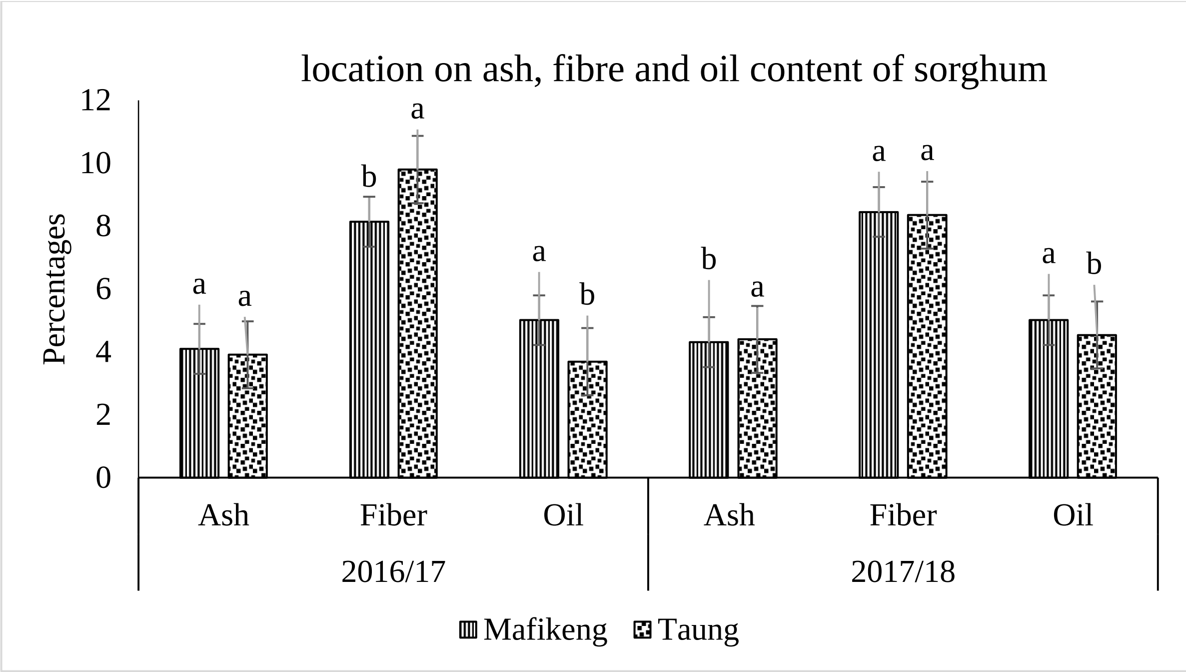

Figure 5.3. The main effects of location on sorghum ash, fibre and oil content during the 2016/17 and 2017/18 planting seasons

5.3.4 The interaction effects of nitrogen fertiliser rate x plant density x location on the sorghum ash content during 2017/18 planting season

During the 2017/18 planting season, the interactions of nitrogen fertiliser rate x plant density x location had a significant effect (P = 0.009) on the sorghum ash content (Table 5.1).

Table 5.1. The interaction effects of nitrogen fertiliser rate x plant density x location on the sorghum ash content during 2017/18 planting season

Nitrogen rate	High		Low	
	Maf	Taung	Maf	Taung
0 kg/ha	4.43	4.50	4.40	4.42
100 kg/ha	4.26	4.51	4.29	4.23
150 kg/ha	4.29	4.30	4.20	4.46
LSD $_{(0.05)}$	0.18			

5.3.5 The interaction effects of nitrogen fertiliser rate x plant density x location on the sorghum fibre content during the 2017/18 planting season

During the 2017/18 planting season, the interaction of nitrogen fertiliser rate x plant density x location had significant effect (P = 0.027) on the sorghum fibre content (Table 5.2).

Table 5.2. The interaction effects of nitrogen fertiliser rate x plant density x location on the sorghum fibre content during the 2017/18 planting season

Nitrogen rate	High		Low	
	PAN 8625	PAN 8816	PAN 8625	PAN 8816
0 kg/ha	10.57	7.48	9.21	7.24
100 kg/ha	9.36	6.99	9.38	6.93
150 kg/ha	9.88	7.01	9.64	7.12
LSD $_{(0.05)}$	1.05			

5.3.6 The interaction effects of cultivar x location on the sorghum oil content during the 2016/17 planting season

During the 2016/17 planting season, the interactions of cultivar x location had a significant effect ($P < 0.001$) on the sorghum oil content (Table 5.3).

Table 5.3. The interaction effects of cultivar x location on the sorghum oil content during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	4.58	4.15
PAN 8816	5.45	3.24
LSD $_{(0.05)}$	0.87	

5.3.7 The interaction effects of cultivar x location on the sorghum oil content during the 2017/18 planting season

The interactions of cultivar x location had a significant effect ($P = 0.038$) on the sorghum oil content during the 2017/18 planting season (Table 5.4).

Table 5.4. The interaction effects of cultivar x location on the sorghum oil content during the 2017/18 planting season

Cultivar	Maf	Taung
PAN 8625	4.19	4.01
PAN 8816	5.82	5.07
LSD $_{(0.05)}$	0.37	

5.3.8 The effects of treatment factors on the sorghum protein content during the 2016/17 and 2017/18 planting seasons

Figures 5.4 and 5.5 indicates that cultivar and location (respectively) had a significant effect ($P < 0.001$) on the sorghum protein content during the 2017/18 planting season. Sorghum cultivar PAN 8816 had a significantly higher protein content of 8.87% than PAN 8625 (6.74%). These results could be attributed to inherent genetic variations in the cultivars planted. This corroborates the findings by Miron *et al*. (2007) and Tauqir *et al*. (2009), who reported significant differences among sorghum cultivars for crude protein contents.

Sorghum planted at Taung had a significantly higher protein content of 8.31% than sorghum planted at Mafikeng (7.31%). This could be attributed to variations in climatic factors such as temperature. This corroborates the findings by Krejčířová *et al.* (2007) and Haberle *et al.* (2008), who reported that the protein content in wheat is affected climatic factors such as temperature.

During the 2016/17 planting season, the cultivar, plant density, nitrogen fertiliser rate and location had no significant effect on the protein content of sorghum. During the 2017/18 planting season, plant density and nitrogen fertiliser rate had no significant effect on the protein content of sorghum.

5.3.9 The effects of treatment factors on the sorghum starch content during the 2016/17 and 2017/18 planting seasons

As indicated in Figure 5.5, location had a significant effect ($P < 0.001$) on the sorghum starch content during the 2016/17 planting season. Sorghum planted at Mafikeng had a significantly higher starch content of 38.50% than sorghum planted at Taung**.** This could be attributed to differences in rainfall and temperature prevailing under different environmental conditions. This corroborates the findings by Labuschagne *et al.* (2007), who reported that the starch content in wheat is significantly influenced by the rainfall and environmental conditions under which the wheat plants are cultivated. Figure 5.4 indicates that cultivar had a significant effect ($P < 0.001$) on the sorghum starch content during the 2016/17 planting season. Sorghum cultivar PAN 8816 had a significantly higher starch content of 43.55% than PAN 8625 (35.79%). This could be attributed to differences in the genetic constitution of the cultivars planted. This corroborates the findings by Olaoye *et al.* (2009), who reported that cultivars differ significantly in terms of their carbohydrate content.

During the 2016/17 and 2017/18 planting seasons, plant density, cultivar and the nitrogen fertiliser rate had no significant effect on the starch content of sorghum except in 2017/18 planting season when differences were observed in cultivar. During the 2017/18 planting season, location had no significant effect on the starch content of sorghum.

5.4 The effects of treatment factors on the sorghum sugar content during the 2016/17 and 2017/18 planting seasons

Cultivar had a significant effect ($P < 0.001$) on the sorghum sugar content during the 2016/17 planting season, as indicated in Figure 5.4. Sorghum cultivar PAN 8816 had a significantly higher sugar content of 0.21% than PAN 8625. These results could be attributed to the inherent genetic properties of the cultivars. This was similar to the findings of Rao *et al.* (2013), who reported differences in sugar content among the different cultivars of sorghum. During the 2016/17 and 2017/18 planting seasons, location had a significant effect ($P < 0.001$) on the sorghum sugar content. Sorghum planted at Taung had a significantly higher sugar content of -0.04% than sorghum planted at Mafikeng during the 2016/17 planting season. Sorghum planted at Taung also had a significantly higher sugar content of -0.84% than sorghum planted at Mafikeng during the 2017/18 planting season. This could be attributed to the variable rainfall recorded at the different locations. This corroborates the findings by Gerrano *et al.* (2014), who reported that the amount of rainfall has significant effect on the mean values for the sugar content of sorghum.

The nitrogen fertiliser rate had a significant effect ($P = 0.044$) on the sorghum sugar content during 2017/18 planting season, as indicated in Figure 5.6. Sorghum fertilized with 100 kg N/ha had a significantly higher sugar content of -1.042 % than sorghum fertilized with 0 and 150 kg N/ha. This corroborates the findings by Dhillon *et al.* (2018), who reported that the application of 120 kg N/ha results in an increase in sugar content of rice.

During the 2016/17 and 2017/18 planting season, plant density had no significant effect on the sorghum sugar content. During the 2016/17 planting season, nitrogen fertiliser rate had no significant effect on the sorghum sugar content. During the 2017/18 planting season, cultivar had no significant effect on the sorghum sugar content.

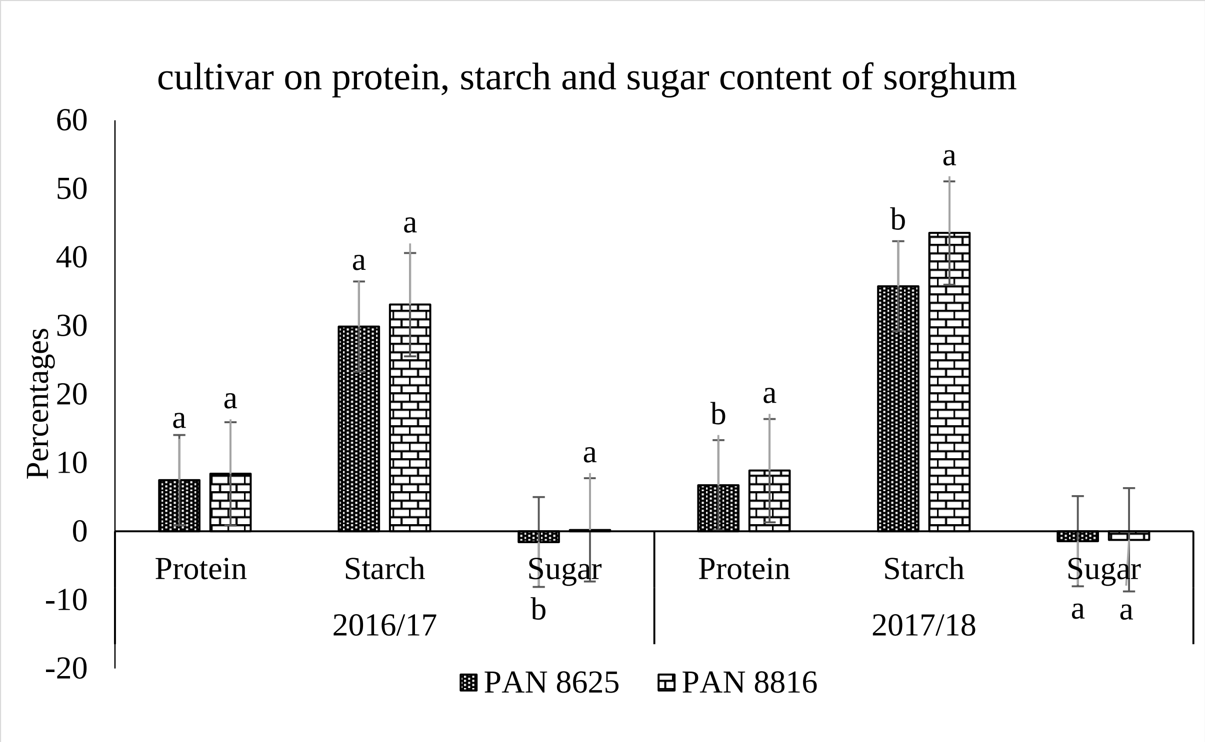

Figure 5.4. The main effects of cultivar on sorghum protein, starch and sugar content during the 2016/17 and 2017/18 planting seasons

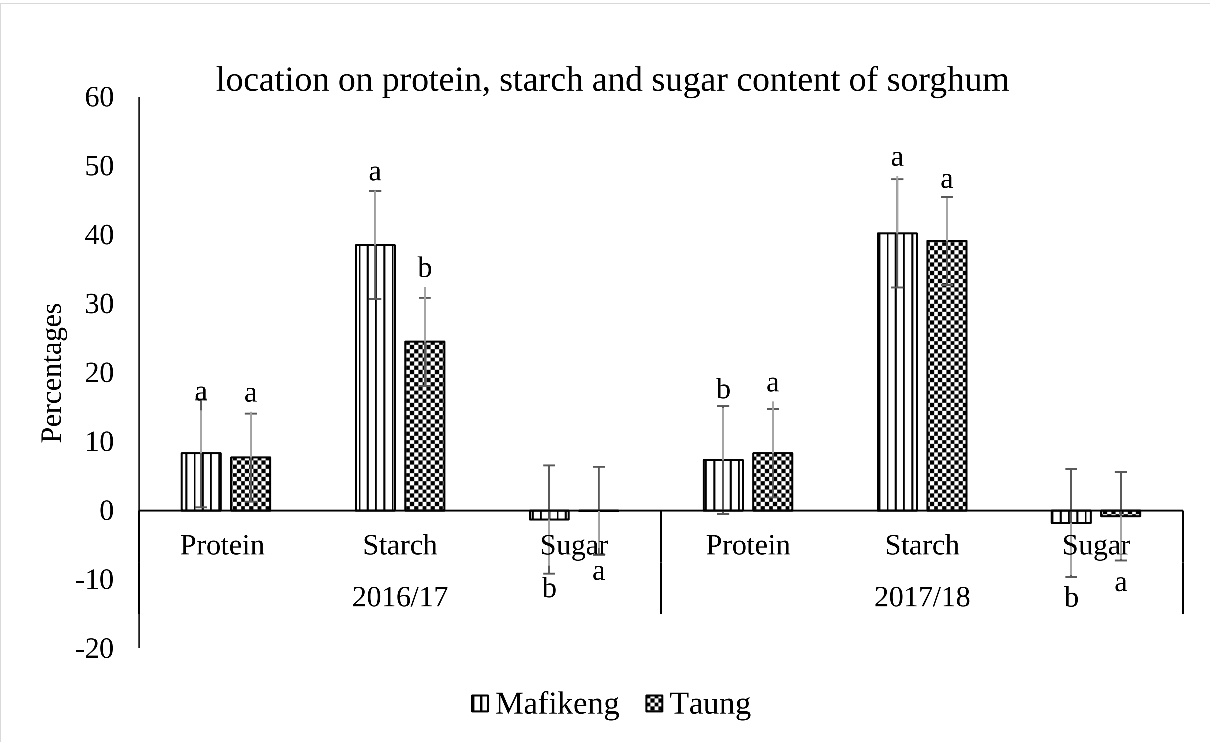

Figure 5.5. The main effects of location on sorghum protein, starch and sugar content during the 2016/17 and 2017/18 planting seasons

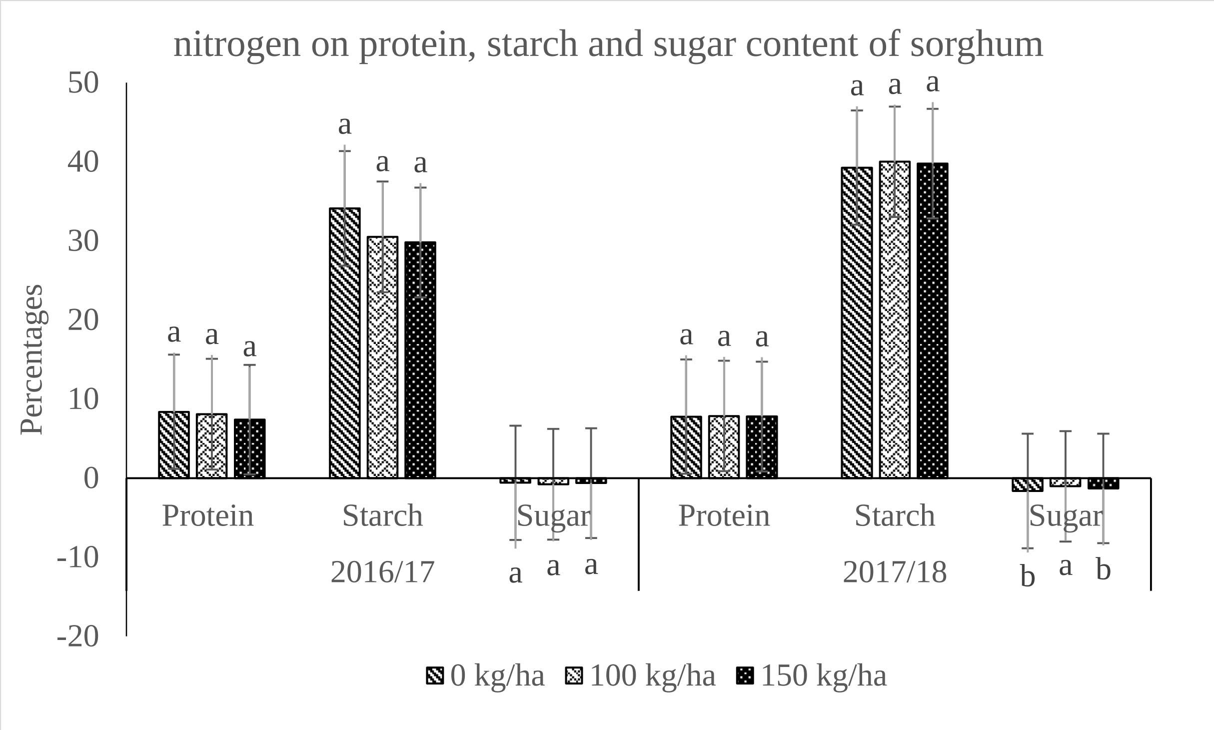

Figure 5.6. The main effects of nitrogen fertiliser rate on sorghum protein, starch and sugar content during the 2016/17 and 2017/18 planting seasons

5.4.1 The interaction effects of nitrogen fertiliser rate x location on the sorghum protein content during the 2016/17 planting season

During the 2016/17 planting season, the interactions of nitrogen fertiliser rate x location had a significant effect ($P < 0.045$) on the sorghum protein content (Table 5.6).

Table 5.6. The interaction effects of nitrogen fertiliser rate x location on the sorghum protein content during the 2016/17 planting season

Nitrogen rate	Maf	Taung
0 kg/ha	8.39	8.38
100 kg/ha	7.74	8.42
150 kg/ha	8.71	6.08
$LSD_{(0.05)}$	1.93	

5.4.2 The interaction effects of cultivar x location on the sorghum protein content during the 2017/18 planting season

During the 2017/18 planting season, the interactions of cultivar x location had a significant effect ($P = 0.032$) on the sorghum protein content (Table 5.7).

Table 5.7. The interaction effects of cultivar x location on the sorghum protein content during the 2017/18 planting season

Cultivar	Maf	Taung
PAN 8625	6.37	7.11
PAN 8816	8.24	9.51
$LSD_{(0.05)}$	0.34	

5.4.3 The interaction effects of cultivar x location on the starch content of sorghum during the 2016/17 planting season

During the 2016/17 planting season, the interactions of cultivar x location had a significant effect (P = 0.003) on the starch content of sorghum (Table 5.8).

Table 5.8. The interaction effects of cultivar x location on the starch content of sorghum during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	33.5	26.2
PAN 8816	43.4	22.8
LSD $_{(0.05)}$	6.10	

5.4.4 The interaction effects of cultivar x location on the starch content of sorghum during the 2017/18 planting season

During the 2017/18 planting season, the interactions of cultivar x location had a significant effect (P = 0.028) on the starch content of sorghum (Table 5.9).

Table 5.9. The interaction effects of cultivar x location on the starch content of sorghum during the 2017/18 planting season

Cultivar	Maf	Taung
PAN 8625	35.39	36.18
PAN 8816	45.04	42.05
LSD $_{(0.05)}$	2.38	

5.4.5 The interaction effects of cultivar x location on the sorghum sugar content during the 2016/17 planting season

During the 2016/17 planting season, the interactions of cultivar x location had a significant effect (P = 0.046) on the sorghum sugar content (Table 5.10).

Table 5.10. The interaction effects of cultivar x location on the sorghum sugar content during the 2016/17 planting season

Cultivar	Maf	Taung
PAN 8625	-2.39	-0.70
PAN 8816	-0.22	0.63
LSD $_{(0.05)}$		

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CHAPTER 6

GENERAL CONCLUSION AND RECOMMENDATIONS

The study revealed that sorghum cultivar PAN 8625 performed better than PAN 8816. This was evident from the measured growth parameters where PAN 8625 demonstrated superior performance over PAN 8816. Although, PAN8816 appeared better than PAN 8625 with regard to photosynthetic ability, but this was not reflected in the assimilate partitioning into economic or biological factors. Sorghum cultivar PAN 8816 flowered earlier in both planting seasons which means that the cultivar is a medium to late maturing type. Sorghum cultivar PAN 8625 can therefore be recommended to farmers because of its superior growth performance.

Sorghum planted under high plant densities (33 333 plants/ha) produced a higher leaf area index than sorghum planted under low plant densities (22 222 plants/ha) in both planting seasons. Appropriate plant densities promote the production of leaves with a larger leaf area index. Hence, farmers are advised to cultivate sorghum under high densities (1 m x 0.3 m) in order to promote better photosynthetic efficiency.

Sorghum performance was enhanced in plots fertilized with 100 kg N/ha; plants fertilised with 100 kg N/ha produced taller plants when compared to 0 and 150 kg N/ha. Sorghum farmers are therefore advised to apply 100 kg N/ha urea fertiliser to loamy sand soil in order to attain optimum growth performance. This application rate had a pronounced effect on the plant height which increased the chances of the crops exposure to sunlight and its effective utilization of growth resources hence the recommendation.

The growth performance of sorghum was found to be inconsistent across both locations. For instance, a larger stem diameter was recorded at Mafikeng during the first planting season while Taung recorded a larger stem diameter during the second planting season. During both planting seasons, plants were taller at Taung than at Mafikeng, while the other growth parameters responded differently. During the first planting season, sorghum planted at Mafikeng flowered earlier than sorghum planted at Taung, whereas, during the second planting season, sorghum planted at Taung flowered earlier than sorghum planted at Mafikeng.

These observations are presumed to be as a result of variations in weather conditions, soil type and the growing conditions at these locations. Consequently, cultural practices especially the application of fertilisers should be pursued on the basis of site specific nutrient requirements.

This study recommends that farmers should base their cultural practises on the requirements of the location where sorghum is to be cultivated, rather than on blanket recommendations.

Sorghum cultivar PAN 8625 proved to be superior to PAN 8816 in terms of the yield and yield parameters measured. Sorghum cultivar PAN 8625 is recommended to farmers in both locations because it can serve as food for humans, on account of its high grain yield potential, and as fodder for livestock because of its higher biomass production over PAN 8816.

This study also revealed that planting late maturing cultivars of sorghum (PAN 8625) tends to outperform the medium to late maturing cultivar (PAN 8816) as the former remains on the field for a longer period and tends to produce more grain as a result of a longer grain filling period, while adjusting to variations in the weather and environmental conditions during the planting seasons.

High plant densities (33 333 plants/ha) increased panicle mass/ha, grain and biomass yield than low plant densities during both planting seasons. Farmers are therefore advised to practice high plant density farming in order to increase their sorghum grain and biomass yields.

Sorghum yield and its components were found to be higher at Mafikeng than at Taung during both planting seasons. The grain yield was better at Mafikeng than at Taung. This is probably because the weather conditions at Mafikeng are more favourable for supporting sorghum production than those at Taung. It is recommended that Mafikeng farmers plant sorghum because the weather condition supports its cultivation.

This study revealed that sorghum cultivar PAN 8625 and PAN 8816 differ in grain quality. Sorghum cultivar PAN 8816 had a higher protein, sugar and starch content than PAN 8625. On the other hand, PAN 8625 had higher ash and fibre contents than PAN 8816. Since both cultivars differ in nutrient content, it is recommended that farmers cultivate cultivars that best suit their field of interest and the demands of their surrounding markets. For instance, PAN 8625 which has a low sugar and high fibre content, would be preferred by farmers targeting diabetic patients. On the other hand, PAN 8816 would be recommended to farmers interested in clients that produce infant meals because of its higher starch, sugar and protein content.

The sugar content in sorghum was found to be affected by applications of nitrogen fertiliser. In order to enhance the quality of sorghum grains on soils that are low in nitrogen, applications of 100 kg N/ha urea fertiliser are recommendable to improve the fertility of loamy sand soil.

In both seasons, there was an inconsistent response as to the measured quality parameters across both locations. The fibre and ash content of sorghum were found to be higher at Taung than at Mafikeng in the first and second planting seasons. On the other hand, the oil content of sorghum proved to be higher at Mafikeng than at Taung during both planting seasons. Furthermore, the starch content of sorghum was higher at Mafikeng than at Taung in the first planting season. The sugar content of sorghum was also higher in the first planting season at Taung than at Mafikeng.

The varying responses observed for the sorghum grain quality parameters across the different locations is an indication that grain quality is affected by cultivar, weather, soil type and environmental conditions. Therefore, sorghum farmers are encouraged to purchase sorghum cultivars that are suited to their locations. Since a greater proportion of the rural farmers harvest sorghum grain for food, further studies that could lead to improvements in its nutritional quality is equally recommended.

The study further recommends research in the following areas;

- study on the effects of rainfall on sorghum production
- study on the effects of different forms of nitrogen fertilisers on sorghum production under multiple locations
- study on the timing and method of nitrogen fertilizer application under different moisture conditions

APPENDICES

Appendix 1. Analysis of variance of the sorghum plant height at 51 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	83.47	27.82	0.86	
Replication.*Units* stratum					
Nitrogen_rate	2	43.83	21.91	0.68	0.509
Density	1	26.41	26.41	0.82	0.368
Cultivar	1	176.88	176.88	5.50	0.022
Location	1	1657.60	1657.60	51.53	<.001
Nitrogen_rate.Density	2	61.51	30.76	0.96	0.389
Nitrogen_rate.Cultivar	2	292.41	146.21	4.55	0.014
Density.Cultivar	1	12.72	12.72	0.40	0.531
Nitrogen_rate.Location	2	789.70	394.85	12.28	<.001
Density.Location	1	4.36	4.36	0.14	0.714
Cultivar.Location	1	282.12	282.12	8.77	0.004
Nitrogen_rate.Density.Cultivar	2	21.44	10.72	0.33	0.718
Nitrogen_rate.Density.Location	2	13.18	6.59	0.20	0.815
Nitrogen_rate.Cultivar.Location	2	202.29	101.14	3.14	0.049
Density.Cultivar.Location	1	100.39	100.39	3.12	0.082
Nitrogen_rate.Density.Cultivar.Location	2	56.44	28.22	0.88	0.420
Residual	69	2219.52	32.17		
Total	95	6044.26			

Appendix 2. Analysis of variance of the sorghum plant height at 74 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	39.83	13.28	0.40	
Replication.*Units* stratum					
Nitrogen_rate	2	7.89	3.95	0.12	0.889
Density	1	127.56	127.56	3.82	0.055
Cultivar	1	1331.17	1331.17	39.82	<.001
Location	1	628.43	628.43	18.80	<.001
Nitrogen_rate.Density	2	34.56	17.28	0.52	0.599
Nitrogen_rate.Cultivar	2	48.20	24.10	0.72	0.490
Density.Cultivar	1	52.51	52.51	1.57	0.214
Nitrogen_rate.Location	2	95.31	47.65	1.43	0.247
Density.Location	1	116.29	116.29	3.48	0.066
Cultivar.Location	1	307.45	307.45	9.20	0.003
Nitrogen_rate.Density.Cultivar	2	36.00	18.00	0.54	0.586
Nitrogen_rate.Density.Location	2	81.10	40.55	1.21	0.304
Nitrogen_rate.Cultivar.Location	2	32.07	16.04	0.48	0.621
Density.Cultivar.Location	1	7.41	7.41	0.22	0.639
Nitrogen_rate.Density.Cultivar.Location	2	33.95	16.97	0.51	0.604
Residual	69	2306.83	33.43		
Total	95	5286.56			

Appendix 3. Analysis of variance of the sorghum plant height at 51 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	474.78	158.26	3.68	
Replication.*Units* stratum					
Nitrogen_rate	2	420.37	210.18	4.89	0.010
Density	1	10.12	10.12	0.24	0.629
Cultivar	1	75.85	75.85	1.76	0.189
Location	1	207.78	207.78	4.83	0.031
Nitrogen_rate.Density	2	286.78	143.39	3.33	0.041
Nitrogen_rate.Cultivar	2	648.45	324.23	7.54	0.001
Density.Cultivar	1	17.03	17.03	0.40	0.531
Nitrogen_rate.Location	2	141.85	70.92	1.65	0.200
Density.Location	1	99.36	99.36	2.31	0.133
Cultivar.Location	1	48.40	48.40	1.13	0.292
Nitrogen_rate.Density.Cultivar	2	182.36	91.18	2.12	0.128
Nitrogen_rate.Density.Location	2	24.96	12.48	0.29	0.749
Nitrogen_rate.Cultivar.Location	2	300.63	150.32	3.49	0.036
Density.Cultivar.Location	1	1.57	1.57	0.04	0.849
Nitrogen_rate.Density.Cultivar.Location	2	136.21	68.11	1.58	0.213
Residual	69	2967.92	43.01		
Total	95	6044.43			

Appendix 4. Analysis of variance of sorghum the plant height at 74 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	689.42	229.81	9.37	
Replication.*Units* stratum					
Nitrogen_rate	2	477.03	238.52	9.72	<.001
Density	1	123.53	123.53	5.03	0.028
Cultivar	1	6142.40	6142.40	250.34	<.001
Location	1	8.42	8.42	0.34	0.560
Nitrogen_rate.Density	2	10.26	5.13	0.21	0.812
Nitrogen_rate.Cultivar	2	99.58	49.79	2.03	0.139
Density.Cultivar	1	227.45	227.45	9.27	0.003
Nitrogen_rate.Location	2	10.26	5.13	0.21	0.812
Density.Location	1	9.73	9.73	0.40	0.531
Cultivar.Location	1	18.17	18.17	0.74	0.392
Nitrogen_rate.Density.Cultivar	2	2.54	1.27	0.05	0.950
Nitrogen_rate.Density.Location	2	40.50	20.25	0.83	0.442
Nitrogen_rate.Cultivar.Location	2	158.67	79.34	3.23	0.045
Density.Cultivar.Location	1	2.42	2.42	0.10	0.755
Nitrogen_rate.Density.Cultivar.Location	2	112.62	56.31	2.30	0.108
Residual	69	1693.00	24.54		
Total	95	9826.01			

Appendix 5. Analysis of variance of the sorghum stem diameter at 51 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	0.05442	0.01814	0.39	
Replication.*Units* stratum					
Nitrogen_rate	2	0.09244	0.04622	0.99	0.376
Density	1	0.03450	0.03450	0.74	0.393
Cultivar	1	1.34427	1.34427	28.82	<.001
Location	1	0.49020	0.49020	10.51	0.002
Nitrogen_rate.Density	2	0.00313	0.00156	0.03	0.967
Nitrogen_rate.Cultivar	2	0.29714	0.14857	3.18	0.048
Density.Cultivar	1	0.00602	0.00602	0.13	0.721
Nitrogen_rate.Location	2	0.35943	0.17971	3.85	0.026
Density.Location	1	0.06934	0.06934	1.49	0.227
Cultivar.Location	1	0.01402	0.01402	0.30	0.585
Nitrogen_rate.Density.Cultivar	2	0.06040	0.03020	0.65	0.527
Nitrogen_rate.Density.Location	2	0.11071	0.05535	1.19	0.311
Nitrogen_rate.Cultivar.Location	2	0.05583	0.02791	0.60	0.553
Density.Cultivar.Location	1	0.09627	0.09627	2.06	0.155
Nitrogen_rate.Density.Cultivar.Location	2	0.07536	0.03768	0.81	0.450
Residual	69	3.21873	0.04665		
Total	95	6.38220			

Appendix 6. Analysis of variance of the sorghum stem diameter at 74 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	0.57134	0.19045	2.15	
Replication.*Units* stratum					
Nitrogen_rate	2	0.10931	0.05465	0.62	0.543
Density	1	0.06563	0.06563	0.74	0.393
Cultivar	1	3.10680	3.10680	35.01	<.001
Location	1	4.34776	4.34776	48.99	<.001
Nitrogen_rate.Density	2	0.20551	0.10275	1.16	0.320
Nitrogen_rate.Cultivar	2	0.22336	0.11168	1.26	0.291
Density.Cultivar	1	0.02071	0.02071	0.23	0.631
Nitrogen_rate.Location	2	0.07442	0.03721	0.42	0.659
Density.Location	1	0.01525	0.01525	0.17	0.680
Cultivar.Location	1	0.74026	0.74026	8.34	0.005
Nitrogen_rate.Density.Cultivar	2	0.43383	0.21691	2.44	0.094
Nitrogen_rate.Density.Location	2	0.01226	0.00613	0.07	0.933
Nitrogen_rate.Cultivar.Location	2	0.14297	0.07149	0.81	0.451
Density.Cultivar.Location	1	0.01955	0.01955	0.22	0.640
Nitrogen_rate.Density.Cultivar.Location	2	0.17226	0.08613	0.97	0.384
Residual	69	6.12368	0.08875		
Total	95	16.38490			

Appendix 7. Analysis of variance of the sorghum stem diameter at 51 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	0.74158	0.24719	3.13	
Replication.*Units* stratum					
Nitrogen_rate	2	0.07261	0.03630	0.46	0.634
Density	1	0.04667	0.04667	0.59	0.445
Cultivar	1	3.20836	3.20836	40.58	<.001
Location	1	0.99023	0.99023	12.52	<.001
Nitrogen_rate.Density	2	0.10862	0.05431	0.69	0.507
Nitrogen_rate.Cultivar	2	0.19734	0.09867	1.25	0.294
Density.Cultivar	1	0.00065	0.00065	0.01	0.928
Nitrogen_rate.Location	2	0.51366	0.25683	3.25	0.045
Density.Location	1	0.05591	0.05591	0.71	0.403
Cultivar.Location	1	0.00278	0.00278	0.04	0.852
Nitrogen_rate.Density.Cultivar	2	0.25314	0.12657	1.60	0.209
Nitrogen_rate.Density.Location	2	0.01337	0.00669	0.08	0.919
Nitrogen_rate.Cultivar.Location	2	0.32872	0.16436	2.08	0.133
Density.Cultivar.Location	1	0.00354	0.00354	0.04	0.833
Nitrogen_rate.Density.Cultivar.Location	2	0.11327	0.05663	0.72	0.492
Residual	69	5.45585	0.07907		
Total	95	12.10632			

Appendix 8. Analysis of variance of the sorghum stem diameter at 74 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	1.1249	0.3750	0.59	
Replication.*Units* stratum					
Nitrogen_rate	2	1.3256	0.6628	1.04	0.360
Density	1	0.4765	0.4765	0.74	0.391
Cultivar	1	15.7329	15.7329	24.58	<.001
Location	1	0.0336	0.0336	0.05	0.819
Nitrogen_rate.Density	2	1.3273	0.6636	1.04	0.360
Nitrogen_rate.Cultivar	2	2.0417	1.0208	1.59	0.210
Density.Cultivar	1	1.0011	1.0011	1.56	0.215
Nitrogen_rate.Location	2	1.1401	0.5700	0.89	0.415
Density.Location	1	0.1064	0.1064	0.17	0.685
Cultivar.Location	1	0.5051	0.5051	0.79	0.377
Nitrogen_rate.Density.Cultivar	2	0.1170	0.0585	0.09	0.913
Nitrogen_rate.Density.Location	2	1.6041	0.8021	1.25	0.292
Nitrogen_rate.Cultivar.Location	2	1.7708	0.8854	1.38	0.258
Density.Cultivar.Location	1	0.0688	0.0688	0.11	0.744
Nitrogen_rate.Density.Cultivar.Location	2	1.7836	0.8918	1.39	0.255
Residual	69	44.1612	0.6400		
Total	95	74.3206			

Appendix 9. Analysis of variance of the sorghum number of leaves at 51 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	1.375	0.458	0.32	
Replication.*Units* stratum					
Nitrogen_rate	2	1.521	0.760	0.53	0.591
Density	1	3.375	3.375	2.35	0.130
Cultivar	1	77.042	77.042	53.63	<.001
Location	1	70.042	70.042	48.76	<.001
Nitrogen_rate.Density	2	0.812	0.406	0.28	0.755
Nitrogen_rate.Cultivar	2	2.521	1.260	0.88	0.420
Density.Cultivar	1	0.042	0.042	0.03	0.865
Nitrogen_rate.Location	2	0.646	0.323	0.22	0.799
Density.Location	1	1.042	1.042	0.73	0.397
Cultivar.Location	1	1.042	1.042	0.73	0.397
Nitrogen_rate.Density.Cultivar	2	3.396	1.698	1.18	0.313
Nitrogen_rate.Density.Location	2	2.521	1.260	0.88	0.420
Nitrogen_rate.Cultivar.Location	2	8.396	4.198	2.92	0.061
Density.Cultivar.Location	1	2.042	2.042	1.42	0.237
Nitrogen_rate.Density.Cultivar.Location	2	0.021	0.010	0.01	0.993
Residual	69	99.125	1.437		
Total	95	274.958			

Appendix 10. Analysis of variance of the sorghum number of leaves at 74 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	6.781	2.260	1.76	
Replication.*Units* stratum					
Nitrogen_rate	2	0.333	0.167	0.13	0.878
Density	1	3.010	3.010	2.35	0.130
Cultivar	1	128.344	128.344	100.10	<.001
Location	1	106.260	106.260	82.88	<.001
Nitrogen_rate.Density	2	4.083	2.042	1.59	0.211
Nitrogen_rate.Cultivar	2	1.750	0.875	0.68	0.509
Density.Cultivar	1	0.094	0.094	0.07	0.788
Nitrogen_rate.Location	2	0.083	0.042	0.03	0.968
Density.Location	1	0.844	0.844	0.66	0.420
Cultivar.Location	1	10.010	10.010	7.81	0.007
Nitrogen_rate.Density.Cultivar	2	7.000	3.500	2.73	0.072
Nitrogen_rate.Density.Location	2	1.000	0.500	0.39	0.679
Nitrogen_rate.Cultivar.Location	2	4.333	2.167	1.69	0.192
Density.Cultivar.Location	1	0.094	0.094	0.07	0.788
Nitrogen_rate.Density.Cultivar.Location	2	3.250	1.625	1.27	0.288
Residual	69	88.469	1.282		
Total	95	365.740			

Appendix 11. Analysis of variance of the sorghum number of leaves at 51 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	46.553	15.518	6.42	
Replication.*Units* stratum					
Nitrogen_rate	2	3.845	1.922	0.80	0.456
Density	1	3.761	3.761	1.56	0.217
Cultivar	1	31.511	31.511	13.03	<.001
Location	1	8.560	8.560	3.54	0.064
Nitrogen_rate.Density	2	1.908	0.954	0.39	0.675
Nitrogen_rate.Cultivar	2	3.367	1.683	0.70	0.502
Density.Cultivar	1	0.974	0.974	0.40	0.528
Nitrogen_rate.Location	2	2.143	1.072	0.44	0.644
Density.Location	1	0.000	0.000	0.00	1.000
Cultivar.Location	1	1.338	1.338	0.55	0.459
Nitrogen_rate.Density.Cultivar	2	7.650	3.825	1.58	0.213
Nitrogen_rate.Density.Location	2	3.318	1.659	0.69	0.507
Nitrogen_rate.Cultivar.Location	2	4.022	2.011	0.83	0.440
Density.Cultivar.Location	1	2.449	2.449	1.01	0.318
Nitrogen_rate.Density.Cultivar.Location	2	5.810	2.905	1.20	0.307
Residual	69	166.824	2.418		
Total	95	294.030			

Appendix 12. Analysis of variance of the sorghum number of leaves at 74 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	16.076	5.359	4.54	
Replication.*Units* stratum					
Nitrogen_rate	2	54.746	27.373	23.19	<.001
Density	1	4.321	4.321	3.66	0.060
Cultivar	1	540.076	540.076	457.49	<.001
Location	1	2.150	2.150	1.82	0.182
Nitrogen_rate.Density	2	0.056	0.028	0.02	0.977
Nitrogen_rate.Cultivar	2	1.900	0.950	0.80	0.451
Density.Cultivar	1	1.410	1.410	1.19	0.278
Nitrogen_rate.Location	2	2.399	1.200	1.02	0.367
Density.Location	1	0.607	0.607	0.51	0.476
Cultivar.Location	1	0.096	0.096	0.08	0.777
Nitrogen_rate.Density.Cultivar	2	0.444	0.222	0.19	0.829
Nitrogen_rate.Density.Location	2	1.316	0.658	0.56	0.575
Nitrogen_rate.Cultivar.Location	2	13.816	6.908	5.85	0.004
Density.Cultivar.Location	1	0.030	0.030	0.03	0.874
Nitrogen_rate.Density.Cultivar.Location	2	4.061	2.030	1.72	0.187
Residual	69	81.455	1.181		
Total	95	724.960			

Appendix 13. Analysis of variance of the sorghum chlorophyll content index at 51 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	313.32	104.44	2.29	
Replication.*Units* stratum					
Nitrogen_rate	2	8.27	4.14	0.09	0.914
Density	1	53.84	53.84	1.18	0.281
Cultivar	1	569.94	569.94	12.49	<.001
Location	1	6.21	6.21	0.14	0.713
Nitrogen_rate.Density	2	94.00	47.00	1.03	0.363
Nitrogen_rate.Cultivar	2	267.57	133.78	2.93	0.060
Density.Cultivar	1	2.53	2.53	0.06	0.815
Nitrogen_rate.Location	2	1062.43	531.22	11.64	<.001
Density.Location	1	176.72	176.72	3.87	0.053
Cultivar.Location	1	15.26	15.26	0.33	0.565
Nitrogen_rate.Density.Cultivar	2	7.59	3.80	0.08	0.920
Nitrogen_rate.Density.Location	2	94.31	47.16	1.03	0.361
Nitrogen_rate.Cultivar.Location	2	49.41	24.70	0.54	0.585
Density.Cultivar.Location	1	18.95	18.95	0.42	0.522
Nitrogen_rate.Density.Cultivar.Location	2	18.57	9.28	0.20	0.816
Residual	69	3149.82	45.65		
Total	95	5908.71			

Appendix 14. Analysis of variance of the sorghum chlorophyll content index at 74 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	385.30	128.43	2.69	
Replication.*Units* stratum					
Nitrogen_rate	2	68.07	34.04	0.71	0.493
Density	1	32.34	32.34	0.68	0.413
Cultivar	1	106.30	106.30	2.23	0.140
Location	1	10850.68	10850.68	227.68	<.001
Nitrogen_rate.Density	2	113.01	56.51	1.19	0.312
Nitrogen_rate.Cultivar	2	11.83	5.92	0.12	0.883
Density.Cultivar	1	10.43	10.43	0.22	0.641
Nitrogen_rate.Location	2	110.33	55.16	1.16	0.320
Density.Location	1	1.34	1.34	0.03	0.867
Cultivar.Location	1	32.13	32.13	0.67	0.414
Nitrogen_rate.Density.Cultivar	2	26.45	13.22	0.28	0.759
Nitrogen_rate.Density.Location	2	54.11	27.06	0.57	0.569
Nitrogen_rate.Cultivar.Location	2	67.24	33.62	0.71	0.497
Density.Cultivar.Location	1	84.08	84.08	1.76	0.188
Nitrogen_rate.Density.Cultivar.Location	2	27.02	13.51	0.28	0.754
Residual	69	3288.34	47.66		
Total	95	15269.01			

Appendix 15. Analysis of variance of the sorghum chlorophyll content index at 51 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	232.09	77.36	2.60	
Replication.*Units* stratum					
Nitrogen_rate	2	62.36	31.18	1.05	0.356
Density	1	28.00	28.00	0.94	0.335
Cultivar	1	654.76	654.76	22.00	<.001
Location	1	202.07	202.07	6.79	0.011
Nitrogen_rate.Density	2	60.94	30.47	1.02	0.365
Nitrogen_rate.Cultivar	2	74.33	37.16	1.25	0.293
Density.Cultivar	1	24.79	24.79	0.83	0.365
Nitrogen_rate.Location	2	9.54	4.77	0.16	0.852
Density.Location	1	19.40	19.40	0.65	0.422
Cultivar.Location	1	128.30	128.30	4.31	0.042
Nitrogen_rate.Density.Cultivar	2	6.75	3.37	0.11	0.893
Nitrogen_rate.Density.Location	2	64.79	32.40	1.09	0.342
Nitrogen_rate.Cultivar.Location	2	7.49	3.75	0.13	0.882
Density.Cultivar.Location	1	59.24	59.24	1.99	0.163
Nitrogen_rate.Density.Cultivar.Location	2	5.32	2.66	0.09	0.915
Residual	69	2053.56	29.76		
Total	95	3693.74			

Appendix 16. Analysis of variance of the sorghum chlorophyll content index at 74 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	62.15	20.72	0.62	
Replication.*Units* stratum					
Nitrogen_rate	2	17.67	8.84	0.26	0.769
Density	1	29.61	29.61	0.88	0.350
Cultivar	1	7134.89	7134.89	213.00	<.001
Location	1	1071.89	1071.89	32.00	<.001
Nitrogen_rate.Density	2	38.39	19.20	0.57	0.566
Nitrogen_rate.Cultivar	2	177.62	88.81	2.65	0.078
Density.Cultivar	1	10.81	10.81	0.32	0.572
Nitrogen_rate.Location	2	22.13	11.07	0.33	0.720
Density.Location	1	15.70	15.70	0.47	0.496
Cultivar.Location	1	156.87	156.87	4.68	0.034
Nitrogen_rate.Density.Cultivar	2	164.09	82.05	2.45	0.094
Nitrogen_rate.Density.Location	2	23.94	11.97	0.36	0.701
Nitrogen_rate.Cultivar.Location	2	285.00	142.50	4.25	0.018
Density.Cultivar.Location	1	1.07	1.07	0.03	0.858
Nitrogen_rate.Density.Cultivar.Location	2	54.63	27.32	0.82	0.447
Residual	69	2311.27	33.50		
Total	95	11577.75			

Appendix 17. Analysis of variance of the days to the 50% flowering of sorghum during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	375.38	125.13	3.36	
Replication.*Units* stratum					
Nitrogen_rate	2	544.15	272.07	7.31	0.001
Density	1	28.17	28.17	0.76	0.387
Cultivar	1	352.67	352.67	9.47	0.003
Location	1	1568.17	1568.17	42.11	<.001
Nitrogen_rate.Density	2	3.15	1.57	0.04	0.959
Nitrogen_rate.Cultivar	2	118.27	59.14	1.59	0.212
Density.Cultivar	1	2.04	2.04	0.05	0.816
Nitrogen_rate.Location	2	391.40	195.70	5.25	0.008
Density.Location	1	7.04	7.04	0.19	0.665
Cultivar.Location	1	459.38	459.38	12.34	<.001
Nitrogen_rate.Density.Cultivar	2	30.77	15.39	0.41	0.663
Nitrogen_rate.Density.Location	2	136.40	68.20	1.83	0.168
Nitrogen_rate.Cultivar.Location	2	32.69	16.34	0.44	0.647
Density.Cultivar.Location	1	16.67	16.67	0.45	0.506
Nitrogen_rate.Density.Cultivar.Location	2	47.02	23.51	0.63	0.535
Residual	69	2569.62	37.24		
Total	95	6682.96			

Appendix 18. Analysis of variance of the days to the 100% flowering of sorghum during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	100.86	33.62	1.96	
Replication.*Units* stratum					
Nitrogen_rate	2	279.40	139.70	8.14	<.001
Density	1	12.76	12.76	0.74	0.392
Cultivar	1	195.51	195.51	11.39	0.001
Location	1	10230.01	10230.01	595.98	<.001
Nitrogen_rate.Density	2	41.65	20.82	1.21	0.304
Nitrogen_rate.Cultivar	2	11.40	5.70	0.33	0.719
Density.Cultivar	1	5.51	5.51	0.32	0.573
Nitrogen_rate.Location	2	279.40	139.70	8.14	<.001
Density.Location	1	12.76	12.76	0.74	0.392
Cultivar.Location	1	195.51	195.51	11.39	0.001
Nitrogen_rate.Density.Cultivar	2	0.65	0.32	0.02	0.981
Nitrogen_rate.Density.Location	2	41.65	20.82	1.21	0.304
Nitrogen_rate.Cultivar.Location	2	11.40	5.70	0.33	0.719
Density.Cultivar.Location	1	5.51	5.51	0.32	0.573
Nitrogen_rate.Density.Cultivar.Location	2	0.65	0.32	0.02	0.981
Residual	69	1184.39	17.17		
Total	95	12608.99			

Appendix 19. Analysis of variance of the days to the 50% flowering of sorghum during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	24.500	8.167	2.09	
Replication.*Units* stratum					
Nitrogen_rate	2	4.083	2.042	0.52	0.595
Density	1	8.167	8.167	2.09	0.153
Cultivar	1	5340.167	5340.167	1367.24	<.001
Location	1	204.167	204.167	52.27	<.001
Nitrogen_rate.Density	2	4.083	2.042	0.52	0.595
Nitrogen_rate.Cultivar	2	4.083	2.042	0.52	0.595
Density.Cultivar	1	8.167	8.167	2.09	0.153
Nitrogen_rate.Location	2	4.083	2.042	0.52	0.595
Density.Location	1	8.167	8.167	2.09	0.153
Cultivar.Location	1	104.167	104.167	26.67	<.001
Nitrogen_rate.Density.Cultivar	2	4.083	2.042	0.52	0.595
Nitrogen_rate.Density.Location	2	4.083	2.042	0.52	0.595
Nitrogen_rate.Cultivar.Location	2	4.083	2.042	0.52	0.595
Density.Cultivar.Location	1	8.167	8.167	2.09	0.153
Nitrogen_rate.Density.Cultivar.Location	2	4.083	2.042	0.52	0.595
Residual	69	269.500	3.906		
Total	95	6007.833			

Appendix 20. Analysis of variance of the days to the 100% flowering of sorghum during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	6.1250	2.0417	2.09	
Replication.*Units* stratum					
Nitrogen_rate	2	1.0208	0.5104	0.52	0.595
Density	1	2.0417	2.0417	2.09	0.153
Cultivar	1	4187.0417	4187.0417	4288.03	<.001
Location	1	247.0417	247.0417	253.00	<.001
Nitrogen_rate.Density	2	1.0208	0.5104	0.52	0.595
Nitrogen_rate.Cultivar	2	1.0208	0.5104	0.52	0.595
Density.Cultivar	1	2.0417	2.0417	2.09	0.153
Nitrogen_rate.Location	2	1.0208	0.5104	0.52	0.595
Density.Location	1	2.0417	2.0417	2.09	0.153
Cultivar.Location	1	1107.0417	1107.0417	1133.74	<.001
Nitrogen_rate.Density.Cultivar	2	1.0208	0.5104	0.52	0.595
Nitrogen_rate.Density.Location	2	1.0208	0.5104	0.52	0.595
Nitrogen_rate.Cultivar.Location	2	1.0208	0.5104	0.52	0.595
Density.Cultivar.Location	1	2.0417	2.0417	2.09	0.153
Nitrogen_rate.Density.Cultivar.Location	2	1.0208	0.5104	0.52	0.595
Residual	69	67.3750	0.9764		
Total	95	5630.9583			

Appendix 21. Analysis of variance of the sorghum leaf area index at 51 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	0.5306	0.1769	1.20	
Replication.*Units* stratum					
Nitrogen_rate	2	0.0190	0.0095	0.06	0.937
Density	1	20.1768	20.1768	137.24	<.001
Cultivar	1	6.2139	6.2139	42.27	<.001
Location	1	17.6254	17.6254	119.89	<.001
Nitrogen_rate.Density	2	0.0332	0.0166	0.11	0.894
Nitrogen_rate.Cultivar	2	0.0739	0.0369	0.25	0.779
Density.Cultivar	1	0.8342	0.8342	5.67	0.020
Nitrogen_rate.Location	2	0.2772	0.1386	0.94	0.395
Density.Location	1	0.0959	0.0959	0.65	0.422
Cultivar.Location	1	0.0052	0.0052	0.04	0.851
Nitrogen_rate.Density.Cultivar	2	0.3186	0.1593	1.08	0.344
Nitrogen_rate.Density.Location	2	0.1793	0.0897	0.61	0.546
Nitrogen_rate.Cultivar.Location	2	0.1969	0.0984	0.67	0.515
Density.Cultivar.Location	1	0.3287	0.3287	2.24	0.139
Nitrogen_rate.Density.Cultivar.Location	2	0.1471	0.0735	0.50	0.609
Residual	69	10.1441	0.1470		
Total	95	57.1998			

Appendix 22. Analysis of variance of the sorghum leaf area index at 74 DAP during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	1.2502	0.4167	2.81	
Replication.*Units* stratum					
Nitrogen_rate	2	0.2184	0.1092	0.74	0.483
Density	1	24.2374	24.2374	163.29	<.001
Cultivar	1	11.1951	11.1951	75.42	<.001
Location	1	22.4729	22.4729	151.40	<.001
Nitrogen_rate.Density	2	0.6739	0.3370	2.27	0.111
Nitrogen_rate.Cultivar	2	0.0877	0.0439	0.30	0.745
Density.Cultivar	1	1.0580	1.0580	7.13	0.009
Nitrogen_rate.Location	2	0.1551	0.0776	0.52	0.595
Density.Location	1	0.6491	0.6491	4.37	0.040
Cultivar.Location	1	0.4654	0.4654	3.14	0.081
Nitrogen_rate.Density.Cultivar	2	0.2068	0.1034	0.70	0.502
Nitrogen_rate.Density.Location	2	0.0080	0.0040	0.03	0.973
Nitrogen_rate.Cultivar.Location	2	0.1792	0.0896	0.60	0.550
Density.Cultivar.Location	1	0.0097	0.0097	0.07	0.799
Nitrogen_rate.Density.Cultivar.Location	2	0.2559	0.1280	0.86	0.427
Residual	69	10.2419	0.1484		
Total	95	73.3648			

Appendix 23. Analysis of variance of the sorghum leaf area index at 51 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	3.5405	1.1802	6.83	
Replication.*Units* stratum					
Nitrogen_rate	2	0.3625	0.1812	1.05	0.356
Density	1	25.1983	25.1983	145.80	<.001
Cultivar	1	0.6133	0.6133	3.55	0.064
Location	1	1.8196	1.8196	10.53	0.002
Nitrogen_rate.Density	2	0.2083	0.1042	0.60	0.550
Nitrogen_rate.Cultivar	2	0.8890	0.4445	2.57	0.084
Density.Cultivar	1	0.1460	0.1460	0.84	0.361
Nitrogen_rate.Location	2	0.4145	0.2072	1.20	0.308
Density.Location	1	0.0489	0.0489	0.28	0.596
Cultivar.Location	1	0.0023	0.0023	0.01	0.909
Nitrogen_rate.Density.Cultivar	2	0.7659	0.3830	2.22	0.117
Nitrogen_rate.Density.Location	2	0.1966	0.0983	0.57	0.569
Nitrogen_rate.Cultivar.Location	2	1.0395	0.5197	3.01	0.056
Density.Cultivar.Location	1	0.0021	0.0021	0.01	0.913
Nitrogen_rate.Density.Cultivar.Location	2	0.2098	0.1049	0.61	0.548
Residual	69	11.9253	0.1728		
Total	95	47.3823			

Appendix 24. Analysis of variance of the sorghum leaf area index at 74 DAP during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	3	2.1196	0.7065	4.20	
Replication.*Units* stratum					
Nitrogen_rate	2	5.2735	2.6368	15.67	<.001
Density	1	50.6607	50.6607	301.02	<.001
Cultivar	1	53.5981	53.5981	318.48	<.001
Location	1	0.3427	0.3427	2.04	0.158
Nitrogen_rate.Density	2	0.3110	0.1555	0.92	0.402
Nitrogen_rate.Cultivar	2	0.2672	0.1336	0.79	0.456
Density.Cultivar	1	3.7769	3.7769	22.44	<.001
Nitrogen_rate.Location	2	0.4796	0.2398	1.42	0.248
Density.Location	1	0.0150	0.0150	0.09	0.766
Cultivar.Location	1	0.2588	0.2588	1.54	0.219
Nitrogen_rate.Density.Cultivar	2	0.0469	0.0234	0.14	0.870
Nitrogen_rate.Density.Location	2	0.5143	0.2572	1.53	0.224
Nitrogen_rate.Cultivar.Location	2	0.9508	0.4754	2.82	0.066
Density.Cultivar.Location	1	0.0694	0.0694	0.41	0.523
Nitrogen_rate.Density.Cultivar.Location	2	0.2890	0.1445	0.86	0.428
Residual	69	11.6124	0.1683		
Total	95	130.5859			

Appendix 25. Analysis of variance of the sorghum field biomass during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	4597569.	1532523.	0.75	
Rep.*Units* stratum					
Nitrogen_rate	2	14904502.	7452251.	3.67	0.031
Density	1	34635665.	34635665.	17.04	<.001
Cultivar	1	153237382.	153237382.	75.38	<.001
Location	1	432157276.	432157276.	212.59	<.001
Nitrogen_rate.Density	2	83120.	41560.	0.02	0.980
Nitrogen_rate.Cultivar	2	3867605.	1933803.	0.95	0.391
Density.Cultivar	1	2153309.	2153309.	1.06	0.307
Nitrogen_rate.Location	2	12332807.	6166403.	3.03	0.055
Density.Location	1	2598541.	2598541.	1.28	0.262
Cultivar.Location	1	53318583.	53318583.	26.23	<.001
Nitrogen_rate.Density.Cultivar	2	2687579.	1343789.	0.66	0.520
Nitrogen_rate.Density.Location	2	1089614.	544807.	0.27	0.766
Nitrogen_rate.Cultivar.Location	2	156193.	78096.	0.04	0.962
Density.Cultivar.Location	1	152782.	152782.	0.08	0.785
Nitrogen_rate.Density.Cultivar.Location	2	2687659.	1343830.	0.66	0.520
Residual	69	140267482.	2032862.		
Total	95	860927669.			

Appendix 26. Analysis of variance of the sorghum field biomass during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1.215E+08	4.049E+07	5.49	
Rep.*Units* stratum					
Nitrogen_rate	2	2.535E+08	1.268E+08	17.18	<.001
Density	1	1.464E+08	1.464E+08	19.84	<.001
Cultivar	1	8.899E+08	8.899E+08	120.64	<.001
Location	1	1.353E+07	1.353E+07	1.83	0.180
Nitrogen_rate.Density	2	1.173E+07	5.864E+06	0.79	0.456
Nitrogen_rate.Cultivar	2	6.059E+06	3.030E+06	0.41	0.665
Density.Cultivar	1	7.749E+07	7.749E+07	10.50	0.002
Nitrogen_rate.Location	2	1.725E+05	8.624E+04	0.01	0.988
Density.Location	1	3.190E+06	3.190E+06	0.43	0.513
Cultivar.Location	1	3.344E+06	3.344E+06	0.45	0.503
Nitrogen_rate.Density.Cultivar	2	2.828E+05	1.414E+05	0.02	0.981
Nitrogen_rate.Density.Location	2	1.574E+07	7.870E+06	1.07	0.350
Nitrogen_rate.Cultivar.Location	2	4.128E+06	2.064E+06	0.28	0.757
Density.Cultivar.Location	1	4.345E+05	4.345E+05	0.06	0.809
Nitrogen_rate.Density.Cultivar.Location	2	5.261E+06	2.631E+06	0.36	0.701
Residual	69	5.090E+08	7.377E+06		
Total	95	2.062E+09			

Appendix 27. Analysis of variance of the sorghum grain yield during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	5642469.	1880823.	7.90	
Rep.*Units* stratum					
Nitrogen_rate	2	3213640.	1606820.	6.75	0.002
Density	1	4098180.	4098180.	17.21	<.001
Cultivar	1	7676883.	7676883.	32.23	<.001
Location	1	62131133.	62131133.	260.84	<.001
Nitrogen_rate.Density	2	170375.	85188.	0.36	0.701
Nitrogen_rate.Cultivar	2	1901512.	950756.	3.99	0.023
Density.Cultivar	1	504584.	504584.	2.12	0.150
Nitrogen_rate.Location	2	1132578.	566289.	2.38	0.100
Density.Location	1	680897.	680897.	2.86	0.095
Cultivar.Location	1	3397880.	3397880.	14.27	<.001
Nitrogen_rate.Density.Cultivar	2	1235350.	617675.	2.59	0.082
Nitrogen_rate.Density.Location	2	209501.	104750.	0.44	0.646
Nitrogen_rate.Cultivar.Location	2	3938981.	1969490.	8.27	<.001
Density.Cultivar.Location	1	492128.	492128.	2.07	0.155
Nitrogen_rate.Density.Cultivar.Location	2	324380.	162190.	0.68	0.510
Residual	69	16435488.	238195.		
Total	95	113185959.			

Appendix 28. Analysis of variance of the sorghum grain yield during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	4687237.	1562412.	1.48	
Rep.*Units* stratum					
Nitrogen_rate	2	16442996.	8221498.	7.77	<.001
Density	1	31928465.	31928465.	30.18	<.001
Cultivar	1	499402.	499402.	0.47	0.494
Location	1	78828.	78828.	0.07	0.786
Nitrogen_rate.Density	2	806541.	403271.	0.38	0.685
Nitrogen_rate.Cultivar	2	2324621.	1162310.	1.10	0.339
Density.Cultivar	1	930872.	930872.	0.88	0.352
Nitrogen_rate.Location	2	5787115.	2893558.	2.73	0.072
Density.Location	1	235529.	235529.	0.22	0.639
Cultivar.Location	1	1087046.	1087046.	1.03	0.314
Nitrogen_rate.Density.Cultivar	2	1681040.	840520.	0.79	0.456
Nitrogen_rate.Density.Location	2	1023672.	511836.	0.48	0.619
Nitrogen_rate.Cultivar.Location	2	1044818.	522409.	0.49	0.612
Density.Cultivar.Location	1	482415.	482415.	0.46	0.502
Nitrogen_rate.Density.Cultivar.Location	2	211588.	105794.	0.10	0.905
Residual	69	73009196.	1058104.		
Total	95	142261381.			

Appendix 29. Analysis of variance of the sorghum panicle mass/ha during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	11721706.	3907235.	7.61	
Rep.*Units* stratum					
Nitrogen_rate	2	5920966.	2960483.	5.76	0.005
Density	1	9342416.	9342416.	18.19	<.001
Cultivar	1	20656521.	20656521.	40.22	<.001
Location	1	119562348.	119562348.	232.78	<.001
Nitrogen_rate.Density	2	134670.	67335.	0.13	0.877
Nitrogen_rate.Cultivar	2	2386977.	1193489.	2.32	0.106
Density.Cultivar	1	1187483.	1187483.	2.31	0.133
Nitrogen_rate.Location	2	3358683.	1679342.	3.27	0.044
Density.Location	1	1118988.	1118988.	2.18	0.144
Cultivar.Location	1	3847532.	3847532.	7.49	0.008
Nitrogen_rate.Density.Cultivar	2	930185.	465092.	0.91	0.409
Nitrogen_rate.Density.Location	2	548001.	274000.	0.53	0.589
Nitrogen_rate.Cultivar.Location	2	6872766.	3436383.	6.69	0.002
Density.Cultivar.Location	1	610623.	610623.	1.19	0.279
Nitrogen_rate.Density.Cultivar.Location	2	425733.	212867.	0.41	0.662
Residual	69	35440100.	513625.		
Total	95	224065697.			

Appendix 30. Analysis of variance of the sorghum panicle mass/ha during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	12652842.	4217614.	1.69	
Rep.*Units* stratum					
Nitrogen_rate	2	33873667.	16936834.	6.79	0.002
Density	1	70682950.	70682950.	28.33	<.001
Cultivar	1	3077343.	3077343.	1.23	0.271
Location	1	12690.	12690.	0.01	0.943
Nitrogen_rate.Density	2	96883.	48442.	0.02	0.981
Nitrogen_rate.Cultivar	2	3933610.	1966805.	0.79	0.459
Density.Cultivar	1	2509464.	2509464.	1.01	0.319
Nitrogen_rate.Location	2	6914439.	3457220.	1.39	0.257
Density.Location	1	1869376.	1869376.	0.75	0.390
Cultivar.Location	1	18530.	18530.	0.01	0.932
Nitrogen_rate.Density.Cultivar	2	69224.	34612.	0.01	0.986
Nitrogen_rate.Density.Location	2	961674.	480837.	0.19	0.825
Nitrogen_rate.Cultivar.Location	2	1780594.	890297.	0.36	0.701
Density.Cultivar.Location	1	364710.	364710.	0.15	0.703
Nitrogen_rate.Density.Cultivar.Location	2	533637.	266819.	0.11	0.899
Residual	69	172154746.	2494996.		
Total	95	311506381.			

Appendix 31. Analysis of variance of the sorghum panicle mass per plant during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	10651.9	3550.6	3.77	
Rep.*Units* stratum					
Nitrogen_rate	2	22601.3	11300.7	12.01	<.001
Density	1	30.9	30.9	0.03	0.857
Cultivar	1	94081.5	94081.5	100.00	<.001
Location	1	249820.5	249820.5	265.53	<.001
Nitrogen_rate.Density	2	1526.0	763.0	0.81	0.449
Nitrogen_rate.Cultivar	2	8296.8	4148.4	4.41	0.016
Density.Cultivar	1	1035.2	1035.2	1.10	0.298
Nitrogen_rate.Location	2	3062.4	1531.2	1.63	0.204
Density.Location	1	564.3	564.3	0.60	0.441
Cultivar.Location	1	7506.9	7506.9	7.98	0.006
Nitrogen_rate.Density.Cultivar	2	1288.5	644.3	0.68	0.508
Nitrogen_rate.Density.Location	2	4194.9	2097.5	2.23	0.115
Nitrogen_rate.Cultivar.Location	2	16456.3	8228.1	8.75	<.001
Density.Cultivar.Location	1	0.0	0.0	0.00	0.998
Nitrogen_rate.Density.Cultivar.Location	2	164.0	82.0	0.09	0.917
Residual	69	64918.8	940.9		
Total	95	486200.3			

Appendix 32. Analysis of variance of the sorghum panicle mass per plant during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	11667.5	3889.2	4.68	
Rep.*Units* stratum					
Nitrogen_rate	2	2583.7	1291.8	1.56	0.218
Density	1	1647.1	1647.1	1.98	0.164
Cultivar	1	10299.3	10299.3	12.40	<.001
Location	1	53844.1	53844.1	64.84	<.001
Nitrogen_rate.Density	2	2962.4	1481.2	1.78	0.176
Nitrogen_rate.Cultivar	2	1754.2	877.1	1.06	0.353
Density.Cultivar	1	2994.1	2994.1	3.61	0.062
Nitrogen_rate.Location	2	446.0	223.0	0.27	0.765
Density.Location	1	594.0	594.0	0.72	0.401
Cultivar.Location	1	139.0	139.0	0.17	0.684
Nitrogen_rate.Density.Cultivar	2	3167.7	1583.8	1.91	0.156
Nitrogen_rate.Density.Location	2	590.9	295.4	0.36	0.702
Nitrogen_rate.Cultivar.Location	2	6500.0	3250.0	3.91	0.025
Density.Cultivar.Location	1	57.6	57.6	0.07	0.793
Nitrogen_rate.Density.Cultivar.Location	2	63.7	31.8	0.04	0.962
Residual	69	57301.2	830.5		
Total	95	156612.3			

Appendix 33. Analysis of variance of the sorghum plant population/ha during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	8.167E+08	2.722E+08	6.55	
Rep.*Units* stratum					
Nitrogen_rate	2	3.814E+07	1.907E+07	0.46	0.634
Density	1	5.773E+08	5.773E+08	13.89	<.001
Cultivar	1	1.176E+08	1.176E+08	2.83	0.097
Location	1	2.392E+09	2.392E+09	57.54	<.001
Nitrogen_rate.Density	2	1.087E+07	5.437E+06	0.13	0.878
Nitrogen_rate.Cultivar	2	9.406E+07	4.703E+07	1.13	0.328
Density.Cultivar	1	1.130E+06	1.130E+06	0.03	0.870
Nitrogen_rate.Location	2	4.953E+07	2.476E+07	0.60	0.554
Density.Location	1	4.069E+07	4.069E+07	0.98	0.326
Cultivar.Location	1	4.890E+08	4.890E+08	11.76	0.001
Nitrogen_rate.Density.Cultivar	2	6.397E+06	3.199E+06	0.08	0.926
Nitrogen_rate.Density.Location	2	7.528E+06	3.764E+06	0.09	0.914
Nitrogen_rate.Cultivar.Location	2	7.896E+07	3.948E+07	0.95	0.392
Density.Cultivar.Location	1	2.188E+07	2.188E+07	0.53	0.471
Nitrogen_rate.Density.Cultivar.Location	2	1.725E+07	8.624E+06	0.21	0.813
Residual	69	2.868E+09	4.157E+07		
Total	95	7.627E+09			

Appendix 34. Analysis of variance of the sorghum plant population/ha during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1.136E+08	3.786E+07	0.77	
Rep.*Units* stratum					
Nitrogen_rate	2	6.648E+08	3.324E+08	6.76	0.002
Density	1	2.094E+09	2.094E+09	42.60	<.001
Cultivar	1	4.342E+06	4.342E+06	0.09	0.767
Location	1	1.751E+09	1.751E+09	35.63	<.001
Nitrogen_rate.Density	2	1.562E+07	7.808E+06	0.16	0.853
Nitrogen_rate.Cultivar	2	8.378E+07	4.189E+07	0.85	0.431
Density.Cultivar	1	6.511E+04	6.511E+04	0.00	0.971
Nitrogen_rate.Location	2	1.011E+08	5.055E+07	1.03	0.363
Density.Location	1	9.650E+07	9.650E+07	1.96	0.166
Cultivar.Location	1	1.045E+07	1.045E+07	0.21	0.646
Nitrogen_rate.Density.Cultivar	2	1.907E+06	9.535E+05	0.02	0.981
Nitrogen_rate.Density.Location	2	3.055E+07	1.528E+07	0.31	0.734
Nitrogen_rate.Cultivar.Location	2	1.742E+08	8.709E+07	1.77	0.178
Density.Cultivar.Location	1	9.116E+06	9.116E+06	0.19	0.668
Nitrogen_rate.Density.Cultivar.Location	2	7.334E+07	3.667E+07	0.75	0.478
Residual	69	3.391E+09	4.915E+07		
Total	95	8.615E+09			

Appendix 35. Analysis of variance of the sorghum panicle length during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1076.87	358.96	4.78	
Rep.*Units* stratum					
Nitrogen_rate	2	318.62	159.31	2.12	0.127
Density	1	40.96	40.96	0.55	0.463
Cultivar	1	248.62	248.62	3.31	0.073
Location	1	784.96	784.96	10.46	0.002
Nitrogen_rate.Density	2	18.82	9.41	0.13	0.882
Nitrogen_rate.Cultivar	2	163.63	81.81	1.09	0.342
Density.Cultivar	1	7.08	7.08	0.09	0.760
Nitrogen_rate.Location	2	149.39	74.70	1.00	0.375
Density.Location	1	25.55	25.55	0.34	0.561
Cultivar.Location	1	460.73	460.73	6.14	0.016
Nitrogen_rate.Density.Cultivar	2	0.33	0.16	0.00	0.998
Nitrogen_rate.Density.Location	2	58.69	29.34	0.39	0.678
Nitrogen_rate.Cultivar.Location	2	158.08	79.04	1.05	0.354
Density.Cultivar.Location	1	0.00	0.00	0.00	0.997
Nitrogen_rate.Density.Cultivar.Location	2	20.52	10.26	0.14	0.872
Residual	69	5179.07	75.06		
Total	95	8711.91			

Appendix 36. Analysis of variance of the sorghum panicle length during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	12.320	4.107	1.53	
Rep.*Units* stratum					
Nitrogen_rate	2	2.735	1.368	0.51	0.603
Density	1	1.910	1.910	0.71	0.402
Cultivar	1	302.815	302.815	112.98	<.001
Location	1	0.103	0.103	0.04	0.845
Nitrogen_rate.Density	2	1.025	0.512	0.19	0.826
Nitrogen_rate.Cultivar	2	0.111	0.055	0.02	0.980
Density.Cultivar	1	4.664	4.664	1.74	0.191
Nitrogen_rate.Location	2	4.590	2.295	0.86	0.429
Density.Location	1	2.294	2.294	0.86	0.358
Cultivar.Location	1	7.912	7.912	2.95	0.090
Nitrogen_rate.Density.Cultivar	2	4.598	2.299	0.86	0.429
Nitrogen_rate.Density.Location	2	8.391	4.196	1.57	0.216
Nitrogen_rate.Cultivar.Location	2	22.367	11.184	4.17	0.019
Density.Cultivar.Location	1	4.092	4.092	1.53	0.221
Nitrogen_rate.Density.Cultivar.Location	2	12.400	6.200	2.31	0.107
Residual	69	184.945	2.680		
Total	95	577.271			

Appendix 37. Analysis of variance of the sorghum thousand grain mass during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	502.59	167.53	4.55	
Rep.*Units* stratum					
Nitrogen_rate	2	423.61	211.81	5.76	0.005
Density	1	18.99	18.99	0.52	0.475
Cultivar	1	16.98	16.98	0.46	0.499
Location	1	2355.01	2355.01	63.99	<.001
Nitrogen_rate.Density	2	1.59	0.79	0.02	0.979
Nitrogen_rate.Cultivar	2	115.88	57.94	1.57	0.214
Density.Cultivar	1	67.47	67.47	1.83	0.180
Nitrogen_rate.Location	2	289.59	144.79	3.93	0.024
Density.Location	1	89.20	89.20	2.42	0.124
Cultivar.Location	1	429.18	429.18	11.66	0.001
Nitrogen_rate.Density.Cultivar	2	28.79	14.39	0.39	0.678
Nitrogen_rate.Density.Location	2	14.44	7.22	0.20	0.822
Nitrogen_rate.Cultivar.Location	2	384.84	192.42	5.23	0.008
Density.Cultivar.Location	1	6.64	6.64	0.18	0.672
Nitrogen_rate.Density.Cultivar.Location	2	29.84	14.92	0.41	0.668
Residual	69	2539.27	36.80		
Total	95	7313.91			

Appendix 38. Analysis of variance of the sorghum thousand grain mass during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	28.384	9.461	1.12	
Rep.*Units* stratum					
Nitrogen_rate	2	20.549	10.275	1.21	0.304
Density	1	8.682	8.682	1.02	0.315
Cultivar	1	330.079	330.079	38.91	<.001
Location	1	733.444	733.444	86.46	<.001
Nitrogen_rate.Density	2	8.675	4.337	0.51	0.602
Nitrogen_rate.Cultivar	2	3.892	1.946	0.23	0.796
Density.Cultivar	1	2.791	2.791	0.33	0.568
Nitrogen_rate.Location	2	6.811	3.406	0.40	0.671
Density.Location	1	19.269	19.269	2.27	0.136
Cultivar.Location	1	3.379	3.379	0.40	0.530
Nitrogen_rate.Density.Cultivar	2	1.594	0.797	0.09	0.910
Nitrogen_rate.Density.Location	2	13.541	6.771	0.80	0.454
Nitrogen_rate.Cultivar.Location	2	68.063	34.031	4.01	0.022
Density.Cultivar.Location	1	54.979	54.979	6.48	0.013
Nitrogen_rate.Density.Cultivar.Location	2	2.032	1.016	0.12	0.887
Residual	69	585.336	8.483		
Total	95	1891.501			

Appendix 39. Analysis of variance of the sorghum ash content during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	13.848	4.616	2.56	
Rep.*Units* stratum					
Nitrogen_rate	2	5.209	2.604	1.44	0.243
Density	1	0.094	0.094	0.05	0.820
Cultivar	1	20.323	20.323	11.25	0.001
Location	1	0.958	0.958	0.53	0.469
Nitrogen_rate.Density	2	1.606	0.803	0.44	0.643
Nitrogen_rate.Cultivar	2	0.903	0.451	0.25	0.780
Density.Cultivar	1	0.040	0.040	0.02	0.883
Nitrogen_rate.Location	2	8.039	4.019	2.23	0.116
Density.Location	1	0.000	0.000	0.00	0.992
Cultivar.Location	1	4.204	4.204	2.33	0.132
Nitrogen_rate.Density.Cultivar	2	3.664	1.832	1.01	0.368
Nitrogen_rate.Density.Location	2	2.179	1.089	0.60	0.550
Nitrogen_rate.Cultivar.Location	2	0.426	0.213	0.12	0.889
Density.Cultivar.Location	1	3.416	3.416	1.89	0.173
Nitrogen_rate.Density.Cultivar.Location	2	0.284	0.142	0.08	0.924
Residual	69	124.594	1.806		
Total	95	189.787			

Appendix 40. Analysis of variance of the sorghum ash content during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.07452	0.02484	0.79	
Rep.*Units* stratum					
Nitrogen_rate	2	0.30631	0.15315	4.90	0.010
Density	1	0.05851	0.05851	1.87	0.176
Cultivar	1	0.00003	0.00003	0.00	0.977
Location	1	0.19530	0.19530	6.24	0.015
Nitrogen_rate.Density	2	0.10081	0.05040	1.61	0.207
Nitrogen_rate.Cultivar	2	0.09539	0.04769	1.52	0.225
Density.Cultivar	1	0.03118	0.03118	1.00	0.322
Nitrogen_rate.Location	2	0.02809	0.01404	0.45	0.640
Density.Location	1	0.00940	0.00940	0.30	0.585
Cultivar.Location	1	0.04996	0.04996	1.60	0.211
Nitrogen_rate.Density.Cultivar	2	0.23289	0.11644	3.72	0.029
Nitrogen_rate.Density.Location	2	0.31814	0.15907	5.08	0.009
Nitrogen_rate.Cultivar.Location	2	0.02011	0.01005	0.32	0.726
Density.Cultivar.Location	1	0.00863	0.00863	0.28	0.601
Nitrogen_rate.Density.Cultivar.Location	2	0.18304	0.09152	2.93	0.060
Residual	69	2.15876	0.03129		
Total	95	3.87104			

Appendix 41. Analysis of variance of the sorghum fibre content during the 2016/17 planting season

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	3		34.187	11.396	1.45	
Rep.*Units* stratum						
Nitrogen_rate	2		13.128	6.564	0.84	0.438
Density	1		16.898	16.898	2.15	0.147
Cultivar	1		253.962	253.962	32.36	<.001
Location	1		66.041	66.041	8.41	0.005
Nitrogen_rate.Density	2		13.367	6.683	0.85	0.431
Nitrogen_rate.Cultivar	2		10.033	5.017	0.64	0.531
Density.Cultivar	1		1.502	1.502	0.19	0.663
Nitrogen_rate.Location	2		11.738	5.869	0.75	0.477
Density.Location	1		6.488	6.488	0.83	0.367
Cultivar.Location	1		13.971	13.971	1.78	0.187
Nitrogen_rate.Density.Cultivar	2		9.126	4.563	0.58	0.562
Nitrogen_rate.Density.Location	2		10.954	5.477	0.70	0.501
Nitrogen_rate.Cultivar.Location	2		12.162	6.081	0.77	0.465
Density.Cultivar.Location	1		11.037	11.037	1.41	0.240
Nitrogen_rate.Density.Cultivar.Location	2		18.766	9.383	1.20	0.309
Residual	66	(3)	517.995	7.848		
Total	92	(3)	1010.059			

Appendix 42. Analysis of variance of the sorghum fibre content during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1.443	0.481	0.43	
Rep.*Units* stratum					
Nitrogen_rate	2	3.437	1.718	1.55	0.220
Density	1	2.077	2.077	1.87	0.176
Cultivar	1	155.652	155.652	140.14	<.001
Location	1	0.205	0.205	0.18	0.669
Nitrogen_rate.Density	2	3.064	1.532	1.38	0.259
Nitrogen_rate.Cultivar	2	0.316	0.158	0.14	0.868
Density.Cultivar	1	1.265	1.265	1.14	0.290
Nitrogen_rate.Location	2	3.760	1.880	1.69	0.192
Density.Location	1	0.440	0.440	0.40	0.531
Cultivar.Location	1	1.131	1.131	1.02	0.316
Nitrogen_rate.Density.Cultivar	2	1.489	0.745	0.67	0.515
Nitrogen_rate.Density.Location	2	8.490	4.245	3.82	0.027
Nitrogen_rate.Cultivar.Location	2	0.452	0.226	0.20	0.816
Density.Cultivar.Location	1	0.380	0.380	0.34	0.561
Nitrogen_rate.Density.Cultivar.Location	2	2.444	1.222	1.10	0.339
Residual	69	76.637	1.111		
Total	95	262.682			

Appendix 43. Analysis of variance of the sorghum protein content during the 2016/17 planting season

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	3		47.522	15.841	2.11	
Rep.*Units* stratum						
Nitrogen_rate	2		16.447	8.223	1.10	0.340
Density	1		0.430	0.430	0.06	0.812
Cultivar	1		20.410	20.410	2.72	0.104
Location	1		10.241	10.241	1.36	0.247
Nitrogen_rate.Density	2		9.397	4.698	0.63	0.538
Nitrogen_rate.Cultivar	2		13.418	6.709	0.89	0.414
Density.Cultivar	1		0.618	0.618	0.08	0.775
Nitrogen_rate.Location	2		48.683	24.341	3.24	0.045
Density.Location	1		3.069	3.069	0.41	0.525
Cultivar.Location	1		24.076	24.076	3.21	0.078
Nitrogen_rate.Density.Cultivar	2		24.306	12.153	1.62	0.206
Nitrogen_rate.Density.Location	2		8.309	4.155	0.55	0.578
Nitrogen_rate.Cultivar.Location	2		5.098	2.549	0.34	0.713
Density.Cultivar.Location	1		9.001	9.001	1.20	0.277
Nitrogen_rate.Density.Cultivar.Location	2		2.218	1.109	0.15	0.863
Residual	68	(1)	510.647	7.510		
Total	94	(1)	752.406			

Appendix 44. Analysis of variance of the sorghum protein content during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.4503	0.1501	0.44	
Rep.*Units* stratum					
Nitrogen_rate	2	0.1142	0.0571	0.17	0.847
Density	1	0.3267	0.3267	0.95	0.333
Cultivar	1	109.6110	109.6110	318.90	<.001
Location	1	24.0801	24.0801	70.06	<.001
Nitrogen_rate.Density	2	0.3989	0.1994	0.58	0.562
Nitrogen_rate.Cultivar	2	0.4515	0.2258	0.66	0.522
Density.Cultivar	1	0.9322	0.9322	2.71	0.104
Nitrogen_rate.Location	2	0.0125	0.0062	0.02	0.982
Density.Location	1	0.0228	0.0228	0.07	0.797
Cultivar.Location	1	1.6485	1.6485	4.80	0.032
Nitrogen_rate.Density.Cultivar	2	0.1872	0.0936	0.27	0.762
Nitrogen_rate.Density.Location	2	0.6999	0.3499	1.02	0.367
Nitrogen_rate.Cultivar.Location	2	1.0025	0.5012	1.46	0.240
Density.Cultivar.Location	1	0.4565	0.4565	1.33	0.253
Nitrogen_rate.Density.Cultivar.Location	2	0.3892	0.1946	0.57	0.570
Residual	69	23.7163	0.3437		
Total	95	164.5002			

Appendix 45. Analysis of variance of the sorghum starch content during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1006.8	335.6	2.99	
Rep.*Units* stratum					
Nitrogen_rate	2	349.3	174.6	1.56	0.218
Density	1	92.3	92.3	0.82	0.368
Cultivar	1	246.2	246.2	2.19	0.143
Location	1	4695.7	4695.7	41.86	<.001
Nitrogen_rate.Density	2	26.8	13.4	0.12	0.888
Nitrogen_rate.Cultivar	2	93.2	46.6	0.42	0.662
Density.Cultivar	1	2.6	2.6	0.02	0.880
Nitrogen_rate.Location	2	666.7	333.4	2.97	0.058
Density.Location	1	0.5	0.5	0.00	0.949
Cultivar.Location	1	1059.0	1059.0	9.44	0.003
Nitrogen_rate.Density.Cultivar	2	190.8	95.4	0.85	0.432
Nitrogen_rate.Density.Location	2	42.6	21.3	0.19	0.828
Nitrogen_rate.Cultivar.Location	2	335.7	167.8	1.50	0.231
Density.Cultivar.Location	1	205.4	205.4	1.83	0.180
Nitrogen_rate.Density.Cultivar.Location	2	136.1	68.1	0.61	0.548
Residual	69	7740.2	112.2		
Total	95	16889.8			

Appendix 46. Analysis of variance of the sorghum starch content during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	28.34	9.45	0.56	
Rep.*Units* stratum					
Nitrogen_rate	2	9.35	4.67	0.27	0.761
Density	1	4.25	4.25	0.25	0.619
Cultivar	1	1445.30	1445.30	84.93	<.001
Location	1	28.81	28.81	1.69	0.198
Nitrogen_rate.Density	2	49.76	24.88	1.46	0.239
Nitrogen_rate.Cultivar	2	22.34	11.17	0.66	0.522
Density.Cultivar	1	1.01	1.01	0.06	0.808
Nitrogen_rate.Location	2	24.64	12.32	0.72	0.488
Density.Location	1	3.16	3.16	0.19	0.668
Cultivar.Location	1	85.90	85.90	5.05	0.028
Nitrogen_rate.Density.Cultivar	2	99.95	49.98	2.94	0.060
Nitrogen_rate.Density.Location	2	55.31	27.65	1.63	0.204
Nitrogen_rate.Cultivar.Location	2	40.70	20.35	1.20	0.309
Density.Cultivar.Location	1	11.01	11.01	0.65	0.424
Nitrogen_rate.Density.Cultivar.Location	2	24.43	12.21	0.72	0.491
Residual	69	1174.18	17.02		
Total	95	3108.43			

Appendix 47. Analysis of variance of the sorghum sugar content during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	2.154	0.718	0.71	
Rep.*Units* stratum					
Nitrogen_rate	2	0.623	0.311	0.31	0.735
Density	1	0.149	0.149	0.15	0.702
Cultivar	1	73.640	73.640	73.06	<.001
Location	1	38.735	38.735	38.43	<.001
Nitrogen_rate.Density	2	1.438	0.719	0.71	0.494
Nitrogen_rate.Cultivar	2	0.503	0.252	0.25	0.780
Density.Cultivar	1	0.008	0.008	0.01	0.927
Nitrogen_rate.Location	2	1.839	0.920	0.91	0.406
Density.Location	1	0.807	0.807	0.80	0.374
Cultivar.Location	1	4.158	4.158	4.13	0.046
Nitrogen_rate.Density.Cultivar	2	1.183	0.591	0.59	0.559
Nitrogen_rate.Density.Location	2	0.381	0.190	0.19	0.828
Nitrogen_rate.Cultivar.Location	2	1.740	0.870	0.86	0.426
Density.Cultivar.Location	1	0.160	0.160	0.16	0.691
Nitrogen_rate.Density.Cultivar.Location	2	3.235	1.617	1.60	0.208
Residual	69	69.549	1.008		
Total	95	200.302			

Appendix 48. Analysis of variance of the sorghum sugar content during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.4792	0.1597	0.19	
Rep.*Units* stratum					
Nitrogen_rate	2	5.4601	2.7300	3.28	0.044
Density	1	0.0016	0.0016	0.00	0.966
Cultivar	1	0.9584	0.9584	1.15	0.287
Location	1	22.3957	22.3957	26.90	<.001
Nitrogen_rate.Density	2	0.5942	0.2971	0.36	0.701
Nitrogen_rate.Cultivar	2	3.2809	1.6404	1.97	0.147
Density.Cultivar	1	0.4582	0.4582	0.55	0.461
Nitrogen_rate.Location	2	2.8185	1.4093	1.69	0.192
Density.Location	1	0.7790	0.7790	0.94	0.337
Cultivar.Location	1	0.0257	0.0257	0.03	0.861
Nitrogen_rate.Density.Cultivar	2	3.1610	1.5805	1.90	0.158
Nitrogen_rate.Density.Location	2	2.4216	1.2108	1.45	0.241
Nitrogen_rate.Cultivar.Location	2	1.1009	0.5504	0.66	0.519
Density.Cultivar.Location	1	2.5781	2.5781	3.10	0.083
Nitrogen_rate.Density.Cultivar.Location	2	0.7710	0.3855	0.46	0.631
Residual	69	57.4439	0.8325		
Total	95	104.7280			

Appendix 49. Analysis of variance of the sorghum oil content during the 2016/17 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	15.322	5.107	2.24	
Rep.*Units* stratum					
Nitrogen_rate	2	1.591	0.796	0.35	0.706
Density	1	0.168	0.168	0.07	0.787
Cultivar	1	0.008	0.008	0.00	0.952
Location	1	41.738	41.738	18.32	<.001
Nitrogen_rate.Density	2	2.230	1.115	0.49	0.615
Nitrogen_rate.Cultivar	2	0.900	0.450	0.20	0.821
Density.Cultivar	1	0.972	0.972	0.43	0.516
Nitrogen_rate.Location	2	10.329	5.165	2.27	0.111
Density.Location	1	0.774	0.774	0.34	0.562
Cultivar.Location	1	18.744	18.744	8.23	0.005
Nitrogen_rate.Density.Cultivar	2	3.079	1.539	0.68	0.512
Nitrogen_rate.Density.Location	2	2.640	1.320	0.58	0.563
Nitrogen_rate.Cultivar.Location	2	4.802	2.401	1.05	0.354
Density.Cultivar.Location	1	2.741	2.741	1.20	0.277
Nitrogen_rate.Density.Cultivar.Location	2	1.468	0.734	0.32	0.726
Residual	69	157.168	2.278		
Total	95	264.676			

Appendix 50. Analysis of variance of the sorghum oil content during the 2017/18 planting season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.9318	0.3106	0.75	
Rep.*Units* stratum					
Nitrogen_rate	2	0.3710	0.1855	0.45	0.642
Density	1	0.7056	0.7056	1.69	0.197
Cultivar	1	43.5916	43.5916	104.72	<.001
Location	1	5.2313	5.2313	12.57	<.001
Nitrogen_rate.Density	2	2.1094	1.0547	2.53	0.087
Nitrogen_rate.Cultivar	2	0.5719	0.2860	0.69	0.506
Density.Cultivar	1	0.3071	0.3071	0.74	0.393
Nitrogen_rate.Location	2	0.1009	0.0504	0.12	0.886
Density.Location	1	0.1593	0.1593	0.38	0.538
Cultivar.Location	1	1.8621	1.8621	4.47	0.038
Nitrogen_rate.Density.Cultivar	2	1.6761	0.8381	2.01	0.141
Nitrogen_rate.Density.Location	2	0.7637	0.3819	0.92	0.404
Nitrogen_rate.Cultivar.Location	2	0.4367	0.2184	0.52	0.594
Density.Cultivar.Location	1	0.0491	0.0491	0.12	0.732
Nitrogen_rate.Density.Cultivar.Location	2	1.8662	0.9331	2.24	0.114
Residual	69	28.7217	0.4163		
Total	95	89.4554			