EFFECT OF PLANTING DATE, PLANT POPULATION AND VARIETIES ON KEY RESOURCE USE EFFICIENCY OF SORGHUM (SORGHUM BICOLOR L. MOENCH)

MASTER OF SCIENCE IN CROP SCIENCE (AGRONOMY)

BY

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BUAN

BOTSWANA UNIVERSITY OF AGRICULTURE AND NATURAL RESOURCES

A dissertation submitted in partial fulfillment of the requirements for the award of the Master of Science Degree in Crop Science (Agronomy)

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DECLARATION

I hereby declare that this thesis is my own work except where highlighted. To the best of my knowledge this work has not been awarded or submitted for a degree or master of degree at any other universities.

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DEDICATION

I devote this beautiful work to parents for their encouragement and support during the difficult times I had encountered as a graduate student. Together with their unconditional love and patient I wouldn't be where I am now. They are my role models for they have taught me that hard work pays and that the way I can achieve my dreams is to be dedicated, and determined. I am very proud of them for they have raised me to be ambitious, self - determined and strive for what I desire. I cannot imagine I would have managed without them.

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ABSTRACT

Inappropriate selection of planting date, plant population and varieties choice have a negative impact on the efficient use of resources and yield returns resulting in some challenges that affect crop production. The experiment was carried out between January and June 2016 at Botswana University of Agriculture and Natural Resources (BUAN) Farm at Sebele to evaluate the effect of planting date, plant population and varieties on nitrogen use efficiency (NUE) and rainwater use efficiency (RWUE) of sorghum *(Sorghum bicolor* (L) Moench. A 2*3*4 factorial experiment was conducted in a split-split randomized block design with three treatments that were replicated four times. The main plot was the two planting date- factor A (January and February), the sub-plot was four plant populations (factor B) and the sub-sub plot were three sorghum varieties – factor C (Segaolane, PSL985050 and PSL985028). Data was collected on growth parameters, biomass and RWUE at vegetative, booting, flowering and physiological maturity, grain yield (Gy) and its components. Nitrogen Use Efficiency (NUE) and grain rain water use efficiency (RWUEgy) were assessed at harvest.

Data collected were affected by planting date causing a highly significant ($P<0.0001$) impact on biomass, RWUE, grain yield and NUE and its components. Late planting date resulted in reduction in biomass, RWUE, grain yield, NUE and its components which have been triggered by shorter day length and reduction in temperatures. Reduction in Gy and its components was observed as plant population decrease due to few plants per unit area. Increase in plant population led to decline in RWUE at different growth stage except in the vegetative stage. Regarding NUE and its components (uptake and utilization efficiency), high population lowered the nitrogen uptake and utilization hence reduction in efficient use of nitrogen due to interplants competition.

Different varieties varied significantly at P<0.0001 for Gy where Segaolane produced the highest yield of 234kg/ha at highest plant population as compared to PSL985050 and PSL985028. A significant difference of P<0.01 and P<0.05 was observed among varieties on RWUE at different stages as well as RWUEgy. Segaolane had the highest RWUEGy of 1.01kg/ha/mm as compared to PSL985050 and PSL985028. Given the yield components, panicle length and panicle weight differ significantly at P<0.0001; P<0.01 respectively among varieties. Nitrogen uptake and utilization efficiency differ significantly (P<0.05) among the varieties while a highly significant difference (P<0.0001) was noted for NUE. The highest NUE 9.38kg/ha was recorded for Segaolane and the lowest NUE of 2.9 recorded for PSL985050. Strong and significant correlations were observed between RWUE & Gy, RWUE & NUE, and Gy & NUE. Therefore Segaolane, January planting date and medium low density are highly recommended for farmers in these changing climatic conditions which are threatening the agricultural sector in Botswana.

Key words: biomass, grain yield, nitrogen use efficiency and rain water use efficiency.

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ACRONYMS

AASR	Annual Agricultural Survey Research
AGB	Above ground biomass
ANOVA	Analysis of Variance
ANPP	Aboveground Net Primary Production
AOAC	Association of Official Analytical Chemists
BUAN	Botswana University of Agriculture and Natural Resources
BVg	Biomass at Vegetative stage
BBt	Biomass at booting stage
BFl	Biomass at flowering stage
BPm	Biomass at physiological maturity
$CACL_2$	Calcium Chloride
CEC	Cation Exchange Capacity
DAR	Department of Agricultural Research
EC	Electrical Conductivity
FAO	Food and Agricultural Organization
FAOSTAT	Food and Agricultural Organization Statistics
GA	Ground Area
GDD	Growing Degree Days
Gy	Grain yield
HCL	Hydrochloric Acid
H_2SO4	Sulphuric Acid
HI	Harvest Index
INIP	National Institute of Industrial Property
IPCC	Intergovernmental Panel on Climate Change
LA	Leaf Area
LAI	Leaf Area Index
LAN	Limestone Ammonium Nitrate

LSD	Least Significant Difference
LW	Leaf Weight
N	Nitrogen
MOA	Ministry of Agriculture
NAOH	Sodium hydroxide
NH3	Ammonia
NUE	Nitrogen Use Efficiency
NUTEff	Utilization Efficiency
NUPEff	Uptake Efficiency
NPGRC	National Plant Genetic Resources Centre
NPP	Net Primary Production
PL	Panicle Length
PT	Panicle Thickness
PW	Panicle Weight
RWUE	Rain Water Use Efficiency
RWUEVg	Rain Water Use Efficiency at vegetative stage
RWUEBt	Rain Water Use Efficiency at booting stage
RWUEFl	Rain Water Use Efficiency at flowering stage
RWUEPm	Rain Water Use Efficiency at Physiological maturity
RWUEGy	Grain Rain water Use Efficiency
SAS	Statistical Analysis Software
SLA	Specific Leaf Area
TP	Total Precipitation

CHAPTER ONE

INTRODUCTION

1.1 Background information

Sorghum (*Sorghum bicolor* (L. Moench) is a drought tolerant and nutritious cereal crop ordinarily cultivated for food, feeds and fodder by subsistence farmers. Elsewhere in the world especially in the arid and semi-arid regions where production is constrained by low, erratic rainfall and low soil fertility, it is grown and consumed as a staple food and used in the production of many products such as traditional beer and porridge (Statistic Botswana, 2006). The crop belongs to the tribe Andropogoneae under the grass family *Poaceae* (FAO, 1991). It is native to Africa which through commercial needs and uses remains a basic staple food for many people in the rural communities because of its adaptability to semi-arid environments.

In Botswana it is the most popular crop for small scale farmers under rain fed conditions that have been predicted to be adversely affected by climate change (Folliard *et al.*, 2004; IPCC, 2007). It is traditionally the most important crop best suited to Botswana's agro climatic condition (Stockbridge, 2006). Its performance under unfavorable, hot and dry conditions is only second to millet among the cereals. It is drought tolerant, which makes it especially important in dry regions such as northeast Africa (its center of diversity) and the southern plains of the United State (Patterson *et al.*, 2009). Of singular importance to productivity its C4 photosynthesis comprises of biochemical and morphological specializations that increase net carbon assimilation at high temperatures.

The sorghum plant uses the C4 pathway of the Calvin cycle hence possesses the most efficient form of photosynthesis. comprising biochemical and morphological specializations that increase net carbon assimilation at high temperatures, with greater water use efficiency (Blum and Sullivan, 1970). Its adaptability to environments of extreme abiotic stress has been prompted by some exclusive features that the crop possesses. Its adaptability features include prolific root systems, the ability to maintain stomatal opening at low levels of leaf water potential, high osmotic adjustment, waxy bloom substance on the leaves and stem, better adjustment in leaf angle and leaf rolling in low water conditions to help the crop cope with drought (Yared *et al.*, 2010). The roots can extend from 1m to 2m depth depending on the depth of soil wetting (Blum and Sullivan, 1970).

Its health effects as compared to other common starch diets have of late seen its demand increasing sharply in urban areas where it had been neglected as a staple starch. The crop is rich in fibre, bioactive compounds and antioxidant rich in phytochemicals that are desirable in human health (Awika & Rooney, 2004; Dicko *et al.*, 2005; Dykes *et al.*, 2005). Apart from its main use as grain crop, other uses of sorghum include; potential for lignocellulosic biofuel feedstock, forage biomass and sugar rich stem juice (Rooney *et al.*, 2007)

1.2 Domestication and spread

Ancient remains of sorghum found in the south of the Sahara Desert zone have led to the documentation of Africa as the center of origin and diversity for sorghum (Frederiksen and Smith, 2000; Patterson *et al.*, 2009). The cultivated *Sorghum bicolor* types have been selected around 3000 years ago. From north-eastern Africa it was distributed all over Africa and along shipping and trade routes through the Middle East to India. It was carried from India to China along the silk route and through coastal shipping to South-East Asia. Frederiksen and Smith (2000) further stated that, from West Africa sorghum was taken to the Americas through the slave trade. It was introduced into the United States for commercial cultivation from North Africa, South Africa and India in late 19^{th} century. It was consequently introduced into South America and Australia and now is widely cultivated in drier areas of Africa, Asia, the Americas, Europe and Australia (Dicko *et al.*, 2006).

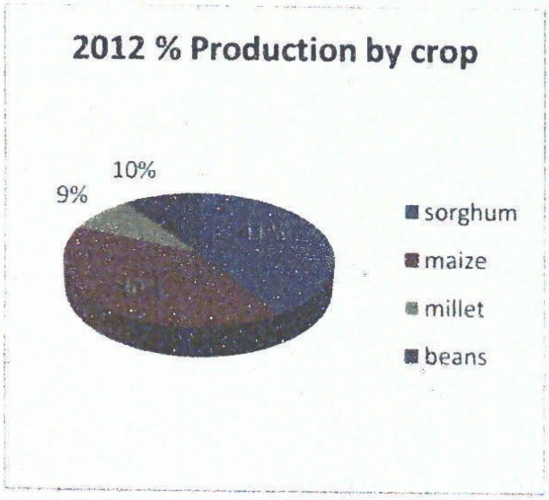
1.3 Ecophysiology and agro-ecology

Vanderlip (1993) categorized sorghum as a crop with nine growth stages similar to maize with environmental factors such as soil fertility, water availability, climatic conditions and management strategies having a significant impact on the time required for completion of each stage. The crop is genetically suited to hot and dry agro-ecologies where other cereals cannot survive except millet. It is known to grow in a wide range of soils but, light to medium textured soils are most preferred. The soil should be well drained, aerated and loamy with pH range of 5 to 8.5 (Fageria *et al.*, 1991). The pH values between 6 and 7.5 are most appropriate for sorghum growth because at this range most nutrients are easily accessible to plants.

It tolerates periods of short waterlogging and salinity but, prolonged periods of salinity will inhibit growth (Carter *et al.*, 1989). Sorghum crop requires a temperature range of $27^{0}C$ to $35^{0}C$ while the sorghum seed requires a minimum temperature of $8-10^{0}C$ for germination. Thomas and Vince- Prunce (1997) noted that sorghum is a short-day plant, in which panicle initiation is prompted by photoperiodic sensitivity where the varieties differ in both sensitivity to temperature and photoperiod. The crop requires an annual rainfall of 325 to 425mm (Balasubramaniyan and Palanlappan, 2007). It is mostly grown in areas which are too dry for major starch crops like maize, wheat and rice. Under rain fed conditions seasonal rainfall water use of sorghum ranges between 179mm and 540 mm which is slightly different under irrigated conditions with a range of 321mm to 645mm showing that sorghum is more efficient with rain water than when it is irrigated.

1.4 Crop production, constraints and their management

Sorghum is the fifth most produced cereal crop worldwide (FAO STAT, 2014). In Africa, it is the second highly produced cereal after maize (Gerda and Christopher, 2007). In Botswana, a survey made by Statistics Botswana (2012) showed that, maize, sorghum, millet and beans/ pulses are the most grown field crops in the country. Figure 2.1 shows % production by crop in 2012 and 2013. In both years sorghum was the leading crop in terms of production, which stood at over 40% of the total arable crop production. The environment in which arable crop production takes place is constrained by the following biophysical factors; low and unreliable rainfall, recurrent droughts, very high summer temperatures and relatively poor soils. Therefore it is not surprising that sorghum production leads in production and other indicators.



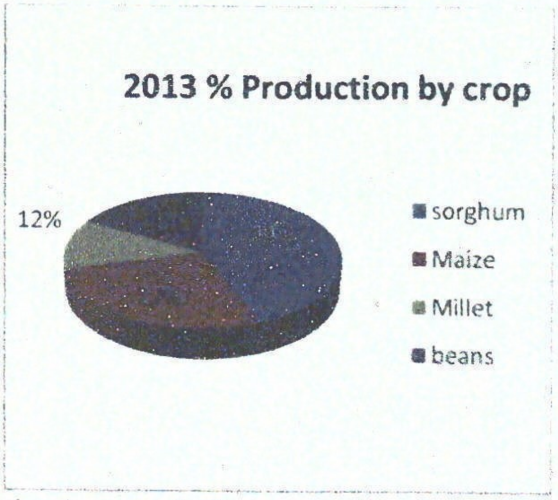


Figure 1.1 Comparison of 2012 and 2013 % production by crop in Botswana. Source: Annual Agricultural Survey Research (AASR), 2013.

1.5 Resource Use Efficiency

In sorghum production, resource use efficiency is one of the most important aspects to be considered for better yield returns. It entails producing a profitable product using the least amount of resources. Those resources include water, nutrients, radiation, capital and land. In Botswana, crop production is based on rain- fed farming and as such water availability is probably the most important uncontrollable factor affecting sorghum production especially under rain-fed conditions. Therefore the minimal amount of water captured during the rainy season has to be used as efficiently as possible for obtaining normal to above normal crop yields.

Compared to other cereals, sorghum can tolerate water stress at various growth stages and effectively use limited water and produce adequately under dryer conditions where other cereals like maize strive to survive even to produce minimally. It has been documented that, sorghum requires 332kg of water per kg of accumulated dry matter whereas maize requires 368kg of water; barley requires 434 of water and wheat requires 678kg of water (House, 1985).

Due to financial constraints, most small scale farmers grow sorghum without application of fertilizers over successive years but still get promising yields. Even though farmers can get promising yields, nutrients are regarded as one of the factors limiting crop production. Those nutrients include nitrogen and phosphorus even though they can be made unavailable by other resources like water and temperature. Among all nutrients, nitrogen is often considered a very important nutrient required for plant growth. This brings in the concept of nitrogen use efficiency (NUE) which can be defined as the ratio between the amounts of nitrogen fertilizer applied and the amount fertilizer removed by the plants from the soil (Jonston and Poulton, 2009).

Availability and efficient use of water coupled with nitrogen cannot only play the role in improving grain sorghum production as there are several other factors which also have great influence in the production, such factors include planting dates, plant population, growing season and climatic conditions (Drew, 2009). Among these factors planting date, plant population and variety choice are of particular importance in managing efficient utilization of available resources (water and nitrogen). Crop productivity is related to plant population per area therefore, plant population refers to the number of plants per unit area and normally determined by the spacing between the plants and between rows (Palle Pedorson, 2003). Plant population is one of the important factors which determine growth, development and yield (McMurray, 2004; McRae *et al.*, 2008) and for the efficient utilization of water and nitrogen without or with minimum competition. In every field, agronomic practice such as weeding and cultivation have to be under taken therefore optimal plant population is important for the efficient execution of such practices. The optimum plant population has to be maintained and most importantly has to be planted at the right planting date and using the appropriate varieties so that the desired yields can be obtained. Thus planting dates and variety need to be considered at all times for successful yield outcomes.

In Botswana, the time of planting depends on the region, variety and season. Late November to early December is considered a good planting period. The risk of crop failure increases with delay in planting. February planting is risky particularly in the Southern part of the country where frost occurs early (Tsuaneng and Maphanyane, 2000). Due to climatic change November and December planting are no longer favorable planting dates to farmers because of low and erratic rainfall which comes late in most part of the country. Most climate models predict a 50–100 mm decline in rainfall in the most parts of the country and an increase in annual maximum temperature from 1.5 °C to 2.5 °C (Zhou *et al.*, 2013). The above scenario could be quite significant for an area that was already marginal for agriculture. This presents a challenge as the planting date may be as late as mid- February in which significant rainfall is experienced. The choice of variety is also important in sorghum production. Sorghum varieties differ in utilization of water and nitrogen due to their genetic makeup. Therefore, for the successful sorghum production, planting date, plant population and variety choice have to be considered for efficient utilization of water and nitrogen as key production resources.

1.6 Justification of study

The threat of increasing water scarcity in the wake of climate change for both home use and agriculture will in the near future call for less irrigated agriculture production than in the past. It is clear that supplemental irrigation can benefit yields and water use efficiency in water limited environments (Oweis *et al.*, 2000; Turner, 2004), but the potential of even limited supplemental irrigation is decreasing, with competition for water for urban and industrial uses and in order to maintain environmental flows. Thus, agriculture will become increasingly dependent on rainfall as it's a sole source of water and maximizing the efficiency of its use to produce a crop will be paramount. Given the little rainfall received in Botswana and the poor soil fertility, this research will focus on how efficiency of the low rainwater received and low soil fertility can be improved in rain-fed agriculture to increase crop production and feed the increasing population in Botswana.

In crop production, water plays a critical role in plant development as it aids the plant to exploit nutrients in the soil effectively (Gonzalez *et al.*, 2010). To maximize the little available moisture in the soil and also to aid full exploitation of nitrogen, factors like time of planting, plant population and selection of varieties have to be considered wisely. Soils of Botswana are sandy with low organic matter and these contribute to low nitrogen levels. Given the erratic, low and unreliable rainfall and poor soil fertility, challenges arise in choosing the appropriate agronomic practices such as planting dates, plant population and suitable crop varieties to grow. A solution to this remains a challenge to both researchers and farmers countrywide. Therefore improving crop management practices to mitigate climate change effects will lead to desirable use of resources with the aim of increasing yields. Hence the aim of this study was to focus on how planting date, plant population and varieties affect rainwater use efficiency and nitrogen use efficiency of sorghum. The information on the effect of planting date, plant population and variety selection on nitrogen and rainwater use efficiency of sorghum will therefore come in handy to plant breeders and crop producers.

1.7 Hypotheses

1) **Null hypothesis:** Planting date, plant population and varieties do not affect nitrogen use efficiency (NUE) and rainwater use efficiency (RWUE) of sorghum.

   Alternative hypothesis: Planting date plant population and varieties affect NUE and RWUE of sorghum.

2) **Null hypothesis:** There is no relationship between RWUE and NUE.

   Alternative hypothesis: There is a relationship between RWUE and NUE

1.8 Objectives

- To evaluate the effects of planting dates, plant population and varieties on RWUE of sorghum based on the above ground biomass and grain yield of sorghum.
- To evaluate the effects of planting date, plant population and varieties on NUE of sorghum.
- To establish the relationship between (RWUE) and (NUE).

CHAPTER TWO

LITERATURE REVIEW

2.1.0 Resource use efficiency in crop production

Successful crop production requires an analysis of resource use efficiency as it is a major concern in any crop production activity. The term "resource use efficiency" may be generally described to include the concept of technical efficiency, allocative efficiency and environmental efficiency within the farm (Haque, 2006). Given the production environmental perspective; resource use efficiency is defined as the amount of profitable yield per unit of input. Typical inputs in crop production include water, land, labour, nutrients, capital, and radiation. These resources have to be utilized efficiently in order to optimize production. According to Fan *et al.* (2011), it is important to; develop integrated soil-crop systems management, which will address constraints in existing varieties, and develop or select new crop varieties that offer high yields but use less water, fertilizer among others. Therefore the main focus of this study will be on use efficiency of water and nitrogen as they are important limiting variables in crop production.

2.1.1 Rainwater use efficiency of sorghum

In the arid and semi-arid lands, water is one of the limiting factors in agricultural production. This is becoming a problem in those areas as water is the main resource needed for crop production with crop growth and economic yield being severely affected by its unavailability (Araus *et al.*, 2002). FAOSTAT (2014) has indicated that almost 80% of the world's agricultural production is under rain fed conditions and provides 62% of the staple foods. As such rain fed agriculture will continue supporting the world's food security for the most increasing population (Hartfield and Prueger, 2001). This is likely to be a concern as rainfall, which is the key source of water is one of the climatic conditions predicted to be severely affected by the climate change that is approximately to account for about 20% of the global increase in water shortage. Therefore, the efficient use of water is a key factor in rain fed plant production that can be resulting in more crops produced per limited amount of water (Blum, 2009). Crop plants require adequate water if they are to grow to their optimum levels and water requirements vary depending on the type of the crop and the environmental conditions they grow.

Water use efficiency under the rain fed agriculture is mostly associated with the effective use of precipitation as it is the only source of water, as a result; its effectiveness is well emphasized. Jones (2004), described water use efficiency under irrigation conditions as the ratio of biomass accumulation or above ground biomass or harvested yield against total available water, or evapotranspiration or plant transpiration or total water input in the soil. It is affected by several factors such as runoff, drainage, irrigation and rainfall amount. Rainwater use efficiency as a surrogate of WUE is hereby defined as the ratio of net primary productions (NPP) or aboveground NPP (ANPP) and rainfall (Le Houèrou, 1984). It has been increasingly used to analyze the variability of both vegetation and crop production in arid and semi- arid biomes, where rainfall is a major limiting factor for plant growth.

Basically, RWUE is designed to separate rainfall contribution to vegetation/ crop production from other factors such as nutrient status, management and cropping practices (Dardel *et al.*, 2014). Furthermore, RWUE can be elaborated as the ratio of accumulated aboveground dry matter and grain yield per total precipitation using the accumulated rainfall from emergence to the maturity stages for the growing season (Le Houèrou, 1984; Chen *et al.*, 2003). Thus rain water captured in the soil has to be effectively used by the plant, for optimum plant yield (Moll *et al.*, (1982).

Precipitation can be categorized into effective and ineffective and these have an influence on the RWUE. Causes for ineffective rainfall include runoff and soil evaporation while for effective includes transpiration (Noy-Meir, 1973). There are several factors that can have an influence on RWUE and these include; climatic conditions, management, varieties and soil properties which affect plant growth and development and consequently yield (Garcia *et al*., 2009; Sandra and Rodriguez, 2007; Ben-Asher *et al*., 2008). Among these factors, climatic conditions can have some impact on RWUE by changing the efficiency of plant use of the effective precipitation or by changing the allocation between effective and ineffective (Rustad *et al*., 2001; Lin *et al*., 2010). Other contributing factors include time of planting, waterlogging, planting depth, fertilizers and certified seeds (Shajari *et al*., 2008). Skovmad *et al.* (2001) stated that, the growing demand of world cereal at present will result in more water required in expanding agriculture in the near future and as such, the little water that is captured has to be utilized appropriately.

Reports on sorghum reported that, sorghum daily water- requirements vary according to crop growth stage (Boyer, 1982; Abdel-Matagally, 2010) with maximal water requirement occurring from booting until after anthesis. Accordingly, at this stage sorghum is mostly sensitive to water stress and during grain filling stage and physiological maturity, water requirements decrease gradually. Assefa *et al.* (2010) stated that sorghum maximum yield requires 450-650mm of water distributed evenly over the growing season. Sorghum yields are normally higher than other major cereals like maize under optimal water availability. Under water stress sorghum produces more yield than other cereal due to superior water use efficiency. This reaffirms the fact that sorghum possesses drought tolerant attributes which enables the crop to produce yields under limited water (Tack *et al*., 2017). Therefore sorghum is distinctively poised as a niche crop in the semi-arid regions. Maman *et al.* (2003) reported under the sub- tropical rainfed agriculture. optimal sorghum water use is reported to be 12.4-13.4kg/ha/mm. Hadebe *et al.* (2015) also carried a study on sorghum and reported that sub-optimal plant water availability resulted in sub-optimal water use efficiency.

2. 1.2 Nitrogen use efficiency of sorghum

Successful crop production can be influenced by nutrients added or lacking in the soil. As much as water is a limiting factor in crop production, nutrition also has a large influence on the final yield. Among the essential macro nutrients for crop growth, nitrogen is often the most limiting for crop yield in many regions of the world (Giller *et al.*, 2004) and in a pursuit of high yields, it is applied in large amounts from external sources resulting in low nitrogen use efficiency (NUE) which is roughly 33% for cereal production (Raun and Johnson, 1999). Therefore balanced and efficient use of applied N is of paramount importance in the overall nutrient management system than any other nutrients with the aim of reducing its negative impact on the environment. Its effectiveness encompassing two main components are; uptake efficiency and utilization efficiency. These two components contribute to variation in N use efficiency; increase in nitrogen uptake efficiency (NUPEff) and/or nitrogen utilization efficiency (NUTEff) will lead to an increase of NUE. Nitrogen uptake efficiency (NUPEff) is a measure of how much N the plant absorb in relation to the N supplied or plant available N. It is associated with assimilation, the incorporation of N compounds into plants tissues. This normally varies among and within crops such as grain sorghum (Jiang *et al.*, 2001: Huggins and Paan, 2003). Nitrogen utilization efficiency (NUTEff) indicates how the absorbed N is effectively used by the crop for growth and yield production (Janssen, 1998; Shchenk, 2006).

Nutrient uptake by sorghum is influenced by several factors including nutrient availability, soil water availability, soil organic matter, soil chemistry and physical properties, type of previous crop grown, plant population and variety (Wortmann, 2007). Several studies have determined how to obtain desired yields with minimum fertilizers hence limited environmental side effects related to N leaching (Agostini *et al.*, 2011; Burns, 2006; Neeteson and Carton, 2001; Rahn, 2002). In sweet sorghum, nitrogen is the most essential element in obtaining high yield (Balasubramania *et al.*, 2010), but overall, sweet sorghum has less nitrogen necessity as compared to sugarcane (Almodares and Hadi, 2009) and maize (Anderson *et al.*, 1995).

2.2.0 Factors affecting resource Use Efficiency

There are numerous factors that affect efficient use of resources in crop production and such factors include crop variety, soil properties, plant stand, weeds and timing of planting. These factors have to be considered for the efficient use of resources in order to optimize yield. Among them, planting date and plant population are to be evaluated to find out how they influence the use of the available resources.

2.2.1 Plant population

Plant population is one of the variables that have to be considered carefully so as to meet the farmers' desired net returns as it affects production and quality of most crops. According to Miah *et al.* (1990), ensuring optimum plant population will allow plants to grow appropriately with their aerial and underground part consuming enough sunlight, water and soil nutrients with limited competition. Closer spacing interferes with the cultural practices to be undertaken in the field and in a closely populated plant community, competition within the plants for nutrients, air, light and water is very high and often leads to mutual shading of plants, lodging and promotes more production of straw than grain yield (Bhowmik *et al.*, 2012).

Various investigations on the effects of plant population have been done in cereal crop production and different results have been obtained. Moosavi *et al.* (2013) conducted a study on the influence of plant population on yield and yield components of grain sorghum. The results revealed that increase in plant population leads to significant loss of 1000-grain mass, grain number per panicle and harvest index. Despite that, grain yield showed a significant improvement due to increase in panicle number per square meter. Other researchers reported that as plant population increased number of tillers (Pawlowski *et al.*, 1993; Ibrahim and Hala, 2007; Caliskan *et al.*, 2007), plant height (Garrison and Briggs, 1972; Shepel and Aristarjkova, 1982; Ayub *et al.*, 2003) and stem diameter decerased (Caravetta *et al.*, 1990), but grain yield per unit area increased (Caliskan *et al.*, 2007). Different researches have been conducted in the Northern and Southern part of Botswana by the Department of Agricultural Research to find the optimum plant population for sorghum (DSFRS, 1985; Jones, 1987). The reports revealed that plant population of 40 000plants/ha is the appropriate plant population due to low and erratic rainfall received in the southern part whereas plant population of 50 000plants/ha is the appropriate plant population in the northern part of the country due to high rainfall.

2.2.2 Planting date

Timing of planting is also a contributing factor to crop growth and development. The time of planting depends on region, variety and season. Previously late November to early December was considered to be the best planting dates in Botswana. Due to climatic change which had rendered rainfall more erratic and low, planting dates have had to be shifted and this has affected most of the crops due to the late plantings as the risk of crop failure increases with delayed planting date. February planting in Botswana is risky particularly in the southern part of the country where frost commences earlier. Therefore the timing of planting should be chosen so that the crop growth stages most susceptible to frost do not coincide with those frost spells. Puali *et al.* (1964) conducted a study in sorghum and found that, late planting results in reduced number of days to panicle initiation and flowering, which both may be the effect of both temperature and photoperiod as the day length reduces and cold temperatures commence. Caddel and Weibel (1971) added that, as the duration of the panicle development gets reduced, the panicle size and total yield also decline.

In contrast, early planting may result in increased yield through increased tillering which leads to high number of heads per unit area. Early planting is associated with yield increment while late planting results in decline in straw yield. According to Maddonni *et al.* (2004), during grain filling delayed planting coincides with reduction in temperature and solar radiation while early sowing results in higher grain as compared to late sowing (Qamar *et al.*, 2004). Both early and late planting could have negative impacts on crops as there is possibility that unfavorable conditions may come after planting or during the growth period. In general, it is therefore convenient for farmers to safeguard against unfavorable conditions, by planting on more than one planting date (Norwood, 2001).

2.2.3 Varieties

Sorghum is becoming a high potential crop in Southern countries such as Botswana, South Africa and Zimbabwe due to its hardiness to harsh conditions but there are some production constraints concerning the crop. The poor sorghum production is associated with lack of selected improved varieties. Some varieties can be adapted to hot and dry conditions while others are more susceptible to such conditions due to their genetic make-up (Tekle and Zemach, 2014).

Different varieties of the same crop can differ in water and nitrogen usage, roots characteristics and days taken to reach maturity. Therefore it is important to develop or select crop varieties that can use the available water and nitrogen more efficiently so that crop production can be maintained, while leaving sufficient water for domestic and industrial users and the environment. Thus crop varieties that use nitrogen more efficiently will be critical for food security, and for the sustainability of rural economies that depend on the purchase of nitrogen fertilizers for crop production. Production of inorganic nitrogen fertilizers is a major source of carbon dioxide emissions, and price increases for nitrogen fertilizers will continue as energy prices increase. Breeding for increased nitrogen use efficiency varieties will therefore be important role to play in reducing nitrogen inputs (Carol *et al.*, 2012). There are number of recommended sorghum varieties in Botswana. Such varieties include Phofu which is known to be a medium maturity variety having a low tillering ability with a semi-dwarf stature and a yield potential of 1.5 to 3.5tons/ha. Another variety which had been appreciated by most farmers is BSHI due to its high yielding potential of 3 to 6tons/ha. The variety also possesses a good tillering ability with a semi-dwarf stature (Tsuaneng and Maphanyane, 2000).

2.3 Effects of planting date on WUE and RWUE

Farmers often use the onset of rainy season as a criterion for picking planting dates. Multiple planting dates can occur in a single rainy season, depending on the onset and longevity of rainy season, and optimal growing period. Successful rainfed agriculture is largely on the amount of stored rainwater but rainfall variability in both total amounts and seasonal distribution is a challenge (Rockström and Barron, 2007).

Inappropriate planting date can result in crop failure, usually requiring replanting or reduced yield as a consequence of unmet water requirements. According to Adetayo *et al.* (2008), one of the ways to manipulate the climatic condition in this climatic change era is to have adequate knowledge of optimal planting date so as to accurately synchronize rainfall incidences with crop development. Yamusa *et al.* (2013) stated delays in the onset of rainfall, drought season, and unpredictable periodic dry spells have led to shift in the recommended sorghum planting date. Sorghum WUE were highest for the optimal planting date relative to the late and lowest at early planting dates in South Africa (Hadebe, et al., 2017). Varietal differences and interaction with planting dates were also observed. Differential response to planting date were also observed in several studies involving sorghum (Blum, 1972; Allen and Musick, 1993); maize (Norwood, 2001; Chen *et al.*, 2003).

2.4 Effects of plant population on WUE and RWUE

Favorable water regimes, higher soil fertility, genetic potential of new varieties could result in increased yield potential with appropriate plant population. In order to obtain maximum desired yield, the crop has to utilize the available soil moisture as efficiently as possible. Accordingly soil moisture level should be optimal to ensure highest yield water use efficiency (WUE) (Rashid and Seilsepour, 2009). Increased plant population encourages competition between plants thus increase in water consumption as compared to when plants are grown uniformly with adequate space between them (Karasahin, 2013). As such there is a negative relation between high plant density and water use efficiency as more plants will consume more water from the soil than the recommended density thus reducing efficient use of water.

There is an interaction between precipitation, soil water and plant population, primarily during the rapid growth period of the crop. The interaction of these factors has an effect on the final yield and that is determined by the level of soil water available to plants at the beginning of rapid growth period. the amount and distribution of precipitation during this period and by the amount of water transpired by the canopy. In sorghum increasing crop density increased water use efficiencies of dry weight production, but decreased the proportions of dry weight allocated to grain (Rees, 1986). In a study involving maize, the use of high plant populations under limited water supply may increase plant water stress hence low RWUE and radically reduce grain yield, particularly if a water shortage coincides with the period of 2-3 weeks bracketing silking (Westgate, 1989).

2.5 Effects of variety on WUE and RWUE

Crops of the same species both differ in terms of their daily water consumption and the duration they took to reach their total full growing period. Accordingly crop species is a paramount factor influencing water consumption. Normally crops species with high daily water consumption and long total growing period require much more water as compared those with comparatively lower daily water needs and short growing period. There is no publication of effect of varieties on RWUE using local sorghum varieties therefore a key strategy towards increasing water use efficiency of local varieties and how they affect RWUE is by selecting those crops varieties that have minimum water requirements yet still provide adequate added value.

Bahar *et al.* (2015) stated that, the efficient use of limited rainfall remains a paramount importance to sorghum production. Maximizing rainwater use through better crop management practices such as well adopted cultivars is of importance to Batswana farmers. The specific adaptation of variety must include phenological development leading to maturing that fits well in the short rainy season to capture a bulk of rainfall and some degree of drought tolerance with speedy recovery after drought. Varietal influence of water use efficiency has been reported in sugar cane (Oliver and Singles, 2003) and sweet sorghum (Sawargaonka et al., 2013). To this end, breeding crop varieties that are more efficient in their water use is one of several strategies that will be required to improve the productivity of water use rain-fed agriculture (Wang et al., 2002).

2.6 Effects of planting date on nitrogen use efficiency (NUE)

The optimum planting date and the best nitrogen rate of sorghum in Botswana are one of the key components for better sorghum grain yields. Azrag and Dagash (2015) reported that the interaction between planting date and nitrogen had a significant effect on 1000 seed weight, grain yield and nitrogen use efficiency of sorghum under climatic conditions of Sudan. Nunes *et al.* (1996) observed that lack of nitrogen delays maize reproductive, vegetative stage, leaf expanding race and leaf area durability while delayed sowing date cause dry matter decline and leaf area index. Ehdaie *et al.* (2001) conducted a study on the response of wheat grain yield and nitrogen use efficiency to planting date. The results showed that both late and early planting may influence the nitrogen requirements of the crop by altering the potential for roots, plant development and the crop's capacity to recuperate soil nitrogen. Ehadaie and Wainess (2001) also conducted another study on wheat and found that, early planted crops turned to extract more nitrogen from the soil but less partitioning of nitrogen to grain as compared to those planted at the most ideal date. The response of nitrogen use efficiency to planting date of sorghum is not extensively studied, especially under local semi-arid environment of Botswana.

2.7 Effects of plant population on nitrogen use efficiency (NUE)

Availability of nitrogen in the soil provides effective means in increasing crop growth and hence yields increase. Optimum population for a crop increases with increase in N availability (Eckert and Martin, 1994). Optimum plant population has to be maintained so that maximum resources such as nutrients, sunlight and soil moisture are fully exploited to ensure reasonable growth and yield (Tajul *et al.*, 2013) as such high density is undesirable because it encourages inter plants competition for resources. Koochaki *et al.* (1994) found out that, increase in plant density per unit area will results in decrease in nitrogen efficiency as nitrogen use by the plant will increase.

Soleymani *et al.* (2011) stated that, sorghum is a C4 crop and uses nitrogen more efficiently than most C3 crops, and nitrogen is still one of the major factors limiting crop yield. Sorghum begins a period of rapid growth, biomass accumulation and nutrient uptake at the five leaf-stages and between this stage and booting about 70% of N will be taken up and as such nitrogen fertilizer timing should account for this rapid growth (IPNI, 2012). Fischer and Wilson, (1975); Ferraris and Charles, (1986) showed that the highest sorghum dry matter production was obtained with the highest plant densities (with increase in N application resulting in higher sorghum yield (Fischer and Wilson, 1975). Studies conducted on maize by Charles and Charles (2006) showed that under high plant densities, the efficiency of applied nitrogen to the crop decreased.

The efficient utilization of nitrogen is also dependent on the plant population of the crop as increase in plant population increase nitrogen use. Berenguer and Faci (2001) argued that lower plant densities are associated with greater number of grains per panicle and higher grain weight at the optimum nitrogen application. The interaction between plant density and nitrogen had a significant influence on seed vigor, viability, germination and health (Marsalis *et al.*, 2010). It is therefore important to establish the optimum plant density and nitrogen rate to maximize yield potential.

2.8 Effects of varieties on nitrogen use efficiency (NUE)

According to Shamme *et al.* (2016), the significant increase in fertilizer prices may fold over the recent decade. This dictates that farmers need to use more NUE crop varieties to reduce the cost experienced on the N fertilizers as a major nutrient input under the rain fed conditions. Crop varieties differ in response to nitrogen levels. They can be classified as the efficient, not efficient and the inferior type (Gerloff, 1976; Gourley *et al.*, 1993; Shulka *et al.*, 1998). The inferior types are those varieties that do not respond to increasing nitrogen supply because of their weak potential of adaptation to N supply or their weak productive capacities. Those that react well to lower N-soil and N-fertilizer as well as to high levels of N are categorized as "efficient" while those which respond to lower N supply but not to increasing N supply are termed "not efficient". Therefore the use of N efficient sorghum cultivars increased the production of sorghum cropping system in most part of Africa especially in the western part (Shamme *et al.*, 2016). Similar trends could be obtained once N efficient sorghum varieties are identified in Botswana conditions.

Differences observed in varieties in NUE as a result of differences in the absorption of nitrate (Rodgers and Barneix, 1988) and N remobilization (Van Sanford and MacKown, 1986). However, improved varieties are often developed without considering their ability to grow under limited soil nutrients (Wissum *et al.*, 2009). According to Feli (1992), varieties that accumulate large amount of biomass seem to have more nitrogen uptake efficiency (NUPEff) which could decrease nitrogen utilization efficiency (NUTEff) and consequently lead to reduction in NUE. No conclusive findings had been published on NUE on local sorghum varieties, it is therefore crucial for more research to be carried out in the selection of varieties which are well responsive to low, medium or high nitrogen supply. Varietal difference in NUE of many crops including sorghum and their strategy of adaptation not extensively investigated in Botswana.

2.9 Interactions between RWUE/WUE and NUE

Availability of adequate soil moisture at crucial growth stages is not only to enhance the metabolic process in the plant cell but also to improve the effectiveness of the mineral nutrients applied to the plant. According to Gebreyesus (2012), soil moisture without soil fertility or fertility without soil moisture is less effective for production increment in the semi-arid areas. Yared *et al.* (2010) documented that reduction in low soil moisture can reduce nutrient uptake by roots and prompt nutrient deficiency by lessening the flow of nutrients from soil to root, creating restrained transpiration rates and impairing active transport and membrane permeability. Therefore considering soil moisture or rainfall distribution of an area is very important to limit the amount of fertilizer to be applied.

Accordingly any degree of water stress or lack of nitrogen in plants may have tremendous impact on growth and yield of the crop (Decheneg, 2002). Low soil moisture tension will enhance the capability of the crop to absorb nutrients from the soil and therefore nutrient availability would be at its optimum level (Singh and Kumar, 2009). Nitrogen and water are directly related as nitrogen needs water to be fully dissolved in the soil for easy uptake by the plant roots. But high application of water to the soil will lead to leaching of the fertilizer thus contaminating the underground surface therefore water and nitrogen have to be managed accordingly for their better interaction hence superior crop yield. Water and nitrogen use efficiency differ greatly between crop production systems, region and management. In most arid and semi-arid region of under developed countries, RWUE and NUE are often low due to low crop yields, degraded soil fertility and water scarcity (Rockstrom and Falkenmark, 2015; Rockstrom *et al.*, 2013; Sanchez, 2010). Previous studies show that an increase in N supply accompanies an increase in water uptake and WUE in wheat (Heitholt, 1988) tomato (Kutuk et al., 2004) tobacco (Brueck and Senbayram, 2009) and grassland ecosystem (Lu et al., 2014). However, limited literatures on the relationship between RWUE and NUE of sorghum, related species and other dry land crops have been documented so this study will help to establish information on how the two concepts are influenced by each other in the crop and related species.

CHAPTER THREE

MATERIALS AND METHOD

3.1 Description of experimental site

A field experiment was conducted during the 2015-16 cropping season at the Botswana University of Agriculture and Natural Resources (BUAN) located at latitude 24.34'25'S and longitude 25 50 00'E and 993 m above sea level. The site is located in the South Eastern part of Botswana, which is a semi-arid climatic zone with a mean annual temperature of 26.4 ^{0}C and annual precipitation of 538 mm (1981-2015) (Legwaila et al., 2014). Most of the rain starts in early November extending to March. In this study, soil physico-chemical properties, rainfall and temperature were determined in Table 4.1 and figure 4.1; 4.2. Soil texture was characterized as sandy loam, with low organic carbon (2.1%) and CEC (4.33 cmol/kg) and acidic pH of 4.7. Due to its sandy texture it is predicted to have low water holding capacity as demonstrated by Salter *et al.* (1966). Except for the month of March 2016, the site experienced low rainfall throughout the experimental period, which averaged about 20 mm monthly. The site experienced high temperature of 30-34^{o}C which were recorded from January to March with February experiencing the maximum temperature of 34^{o}C and minimum temperature of 22^{o}C.

3.2 Experimental field operations

3.2.1 Land preparation

The field was ploughed using a tractor mounted to a moldboard to prepare the seedbed. A further preparation of the soil to attain a fine tilth was done using hand rakes; that was meant to improve the aeration, infiltration and to prevent air logging during crop growth. The area of 86.3 by

12 6m was demarcated and divided into two equal halves to be used for the two planting dates of the experiment.

3.2.2 Experimental design and treatments

A 2*4*3 factorial experiment was conducted in a split-split randomized block design with three factors (2 planting dates, 4 plant population and 3 sorghum varieties) replicated four times. The treatments were as follows; the main plots were assigned to planting dates which were January and February each measuring 43.15m by 12.6m. In the past, the recommended planting dates in Botswana were between October and November, but due to the climatic change effect, rainfall has rendered to come late than expected which led to shifting of planting dates. Due to the shifting of planting dates this study focused on planting on January and February to find the appropriate planting date for farmers with better utilization of nitrogen and water where January was the recommended planting date.

Sub-plots were assigned to four plant populations (60 000plants/ha, 40 000plants/ha, 30 000plants/ha and 20 000plants/ha each measuring 5.6m by 5.15m. The 40 000plants/ha has been the recommended plant population in Botswana (DSFRS, 1985; Jones, 1987). Due to limited rainfall and shifted planting date, different plant populations was used to find out which plant population will do well in the new planting date and if they will maintain high performance in terms of yield, nitrogen use efficiency and water use efficiency. Given the limited rainfall and shifted planting date the populations were varied downward to find which least plant population can fit in the low water availability of Botswana and the new planting date. The spacing between the rows was kept constant at 0.75m while the spacing between the rows varied as follows; 0.2m, 0.3m, 0.4m and 0.5m depending on populations. Sub-sub plots were assigned to the varieties each measuring 5.6 by 2.2 m plots. A path of 2m was left to separate the planting dates, while 1 m path was left to separate replications and 0.75m path was also left between varieties.

3.2.3 Plant materials and planting

Three sorghum varieties, Segaolane (locally released variety), PSL985050 and PSL985028 (newly released varieties) were obtained from the National Plant Genetic Resource Center (NPGRC) at the Department of Agricultural Research in Sebele. Segaolane is an older locally recommended variety which was released by the Ministry of Agriculture, Government of Botswana in 1994 (Setimela *et al.*, 1997). PSL985050 and PSL985028 are new released open pollinated varieties by the Department of Agricultural Research. They were released to outperform Segaolane such as resistance to qualia birds as they possessed some spikes on their panicles and high yield potential. So this study aims at finding which variety will perform well in terms of Nitrogen Use Efficiency (NUE) and Rain water Use Efficiency (RWUE) in which planting date and plant population. A total of 3-5 seeds were planted per hill at a depth of approximately 2.5cm. The population of 0.3 by 0.75m, January planting and Segaolane variety were the control for the experiment.

Table 1.1 Variety's characteristics of interests to the study

Variety	Characteristics	Reference
Segaolane	Locally developed released variety with Medium maturity with high tillering ability, drought tolerant semi- dwarf plant stature, good grain yield potential (1.0-3.5t/ha).	Munamava and Riddoch, 2001, Gowda et al., 2009
PSL985050	Newly released variety. It is drought tolerant, semi-dwarf plant stature, drought tolerance, good grain yield potential (average 2.5-3.0t/ha)	Department of Agricultural Research (2014)
PSL985028	New released variety. It is drought tolerance, semi-dwarf plant stature, drought tolerance, good grain yield potential (average 2.5-3.0t/ha)	Department of Agricultural Research (2014)

3.3 Soil sampling and fertilizer application

Soil was sampled for analysis of physical and chemical properties before planting. Sampling was done from each sub- sub plot using an auger to a depth of 60 cm. Limestone ammonium nitrate (LAN) containing 20% N was applied by broadcasting at the vegetative (establishment) stage, which coincided with 5 weeks after emergence. The application rate was 0.3kg/ha of LAN applied to each sub- sub plot, to balance N to the equivalence of 50 kg N per ha.

3.4 Agronomic management

3.4.1 Weeding and thinning

Five weeks after emergence, the seedlings were thinned to one plant per hill. Only strong and healthy seedlings were left. Weeding was done regularly by pulling by hand and using a hand-held hoe to avoid competition for water, nutrients and other plant growth resources.

3.4.2 Pest control

At the beginning of boot stage, there was an outbreak of sugarcane aphid *(Melanaphis sacchari)* and stem borer *(Chilo partellus)* in the first planting date treatment. 12ml of cypermethrin chemical was diluted in 10 to 15L of water for the control of stem borer while 12ml of dectome was diluted in 10L of water for controlling sugarcane aphids.

3.4.3 Rainfall measurements

Rainfall was measured with a rain gauge that was 9 cm in diameter and 20cm height. The rain gauge was placed in an open field 5 m to the experimental field. Water in the gauge was measured manually using a graduated cylinder to an accuracy of 1 ml. The accumulated monthly rainfall for the whole growing season was recorded.

3.5 Data collection and measurements

Eight randomly plants from the middle of the plots were selected to determine plant growth parameters listed 3.5.1;

3.5.1 Plant growth parameters

3.5.1.1. Days to 50% emergence. Was recorded as the number of days from planting to when more than 50% seedlings started to emerge from the soil surface.

3.5.1.2. Number of leaves. Only healthy and fully matured leaves were counted from the three selected plants at flowering stage.

3.5.1.3 Plant height (cm). The height was measured with a measuring tape to the nearest 1 cm from the soil surface to the top of end of the flag at the beginning of booting.

3.5.1.4 Stem diameter (cm). This was measured as the thickness of the stem using a caliper to the nearest 1 mm. The measurements were taken from the lower part of the main stem.

3.5.1.5 Number of tillers- The number of productive tillers produced per each sampled plant was counted till the flowering stage.

3.5.1.6 Days to 50% booting stage. This was recorded as the number of days plants had taken for the flag leaf collar to start appears.

3.5.1.7 Days to 50% Panicle emergence. This was taken as the number of days from seedling emergence to when 50% of the plants show panicle exertion.

3.5.1.8 Days to 50% maturity. This was recorded as the number of days taken where 50% of the plants have a black layer appearing near the point of the seed attachment in the floret.

3.5.2 Data on yield and yield components

The following components were measured from three randomly tagged plants from each sub-sub plot.

3.5.2.1 Panicle size (cm). This was determined by measuring the thickness of the panicle using a string and a ruler.

3.5.2.2 Length of the panicle (cm). This was measured from where the panicle is attached to the stock to the tip of the panicle using a ruler.

3.5.2.3 Weight per panicle (g). This was computed as the average weight from the randomly sampled plants using the top pan balance.

3.5.2.4 Weight of 1000 seeds (g). The 1000 seeds were counted using the electronic seed counter and then weighed to the nearest 1 mg.

3.5.2.5 Above ground biomass (AGB) (kg) - biomass was harvested from each sub-sub plot at vegetative, boot, flowering stages. The biomass was cut at above ground level and then oven dry for 72^{0}C for two days and then weighed using Top Pan Balance to determine the mean dry biomass in kilograms.

3.5.2.6 Harvesting and grain yield (Gy) (kg/ha). Harvesting was done when the plants had reached physiological maturity where a black layer is visible at the base of the kernel. Harvesting was done using hand and a knife. Only middle rows were harvested from each sub-sub plot in an area of 11.33m^2 while boarder plants were left out. The area harvested was based on sub-sub plot which was 5.6 by 2.2 m. The harvested panicles were hand threshed and the obtained grain were used to determine grain yield for each varieties in each plant population from the two planting date. The measured grains were converted to kilograms per hectare (kg/ha).

3.5.2.7 Harvest index (HI) . This was calculated as the ratio of the total grain yield to the total plant above ground biomass yield (Donald 1962)

$$HI = GY\ (kg/ha)/AGB \qquad (3)$$

Where HI= Harvest Index

GY= Grain yield

AGB= above ground biomass (Stover + grain yield

3.6 Determination of Rainwater Use Efficiency (RWUE)

Rain water use efficiency was calculated as the measure of above ground net primary production (ANPP) and grain yield (Gy) produced per total precipitation (TP) using the accumulated rainfall from emergence to the end of the growing season and biomass harvested at each growth stage (Chen *et al.*, 2003). The formula was as follows;

Calculation was based on ground biomass and total accumulated rainfall during the cropping season at different growth period.

$$RWUEanpp=ANPP\ (kg/ha)\ /TP\ (mm) \quad (4)$$

Calculation was based on final grain yield and the total accumulated rainfall during the cropping season.

$$RWUEgy= GY\ (kg/ha)/\ TP\ (mm) \quad (5)$$

3.7 Determination of Nitrogen Use Efficiency (NUE)

The Micro Kjeldahl method (AOAC, 1975) was used for determination of nitrogen (N) concentration and the calculation of nitrogen use efficiency (NUE) and its components were done following the formula by Moll *et al.* (1982).

3.7.1 Soil and plant analysis

3.7.1.1 Grinding of plants materials

The dried biomass at harvest was grounded into powder using a grinder. The samples were placed into the smallest sip locks according to the replications and treatments.

3.7.1.2 Digestion process

The sampled soil was passed through the sieve to remove foreign materials. The samples were processed for determination of physical and chemical properties. For digestion of both soil and plant samples in determination of NUE using the Kjeldahl procedure, the digestion was done with concentrated Sulphuric acid (H_2SO_4). Samples of 1.25g were measured into digestion tubes along with 20ml of selenium solution. Few drops of hydrogen peroxide were added to the digestive tube. The digestive flasks were then placed on the digestion block at a temperature of 342°C for three hours. The mixtures were heated until white fumes can be seen. Then the tubes were allowed to cool for 30-60 minutes. After cooling, the digestive solutions were transferred into 250ml volumetric flasks and then filled to the mark using deionized water. The same procedure was repeated for all samples both soil and plant materials.

3.7.1.3 Distillation process

After digestion, the sample solutions were distilled using 32% sodium hydroxide (NaOH). 25ml of the digestive solution and 20ml of NaOH (32%) were measured in the digestion tube and 50ml of indicating boric acid were measured into conical flask and placed under the receiving station. The tube with a mixture of sample and NaOH was then placed under the receiving station to be distilled to 150ml volume attaining a color change from gray to green due to emission of NH3 by the sample. The same procedure was repeated in all samples for both soil and plants.

3.7.1.4 Titration process

The receiver solutions from the distillation process went through the titration process using 0.1% hydrochloric acid (HCl). The titration was done by releasing several drops of HCl into the receiver solution until a color from green to moderate pink appeared. The ml of the titrants used was recorded.

3.7.1.5 Calculations

N calculation for soil analysis, using the following formula;

$$N\% = [(Vs - Vo)^* N^* 1.4007] Ws \quad (6)$$

Where Vs (ml) = volume of the acid used in the titration of the sample

Vo (ml) = volume of the acid used to titrate the sample

N = molarity 0.01for HCl

1.4007 (mg) = constant related to the molecular weight of the N

Ws (g) = weight of sample

The calculated N was converted from percentage to decimals and then converted to kilograms which will be used as total plant N at maturity (Nt).

N calculation for plants analysis, using the following formula;

$$N\% = [D^* 1.4007 * (Va - Vb) * N] Ws \quad (7)$$

Where D = dilution factor

1.4007 (mg) = constant related to the molecular weight of N

Va (ml) = volume of the acid used in the titration of the sample

Vb = (ml) volume of the acid used to titrate the sample

N = molarity, 0.01for HCL

Ws (g) = weight of sample

The calculated N was converted from percentage to decimals and then converted to kilograms (kg) which will be used as Nsoil

Determination of NUE and its components [nitrogen uptake efficiency (NUPEff) & nitrogen utilization efficiency (NUTEff)] were done according to Moll *et al.* (1982)

$$NUPEff\ (kg/kg) = Nt / Nsoil \qquad (8)$$

$$NUTEff\ (kg/kg) = Gw / Nt \qquad (9)$$

$$NUE\ (kg/kg) = \frac{Nt}{Nsoil} \times \frac{Gw}{Nt} \qquad (10)$$

Where Nsoil = N supply from the soil plus the added N

Nt = total plant N at maturity

Gw = grain weight at harvest

3.8 Data Analysis

Analysis of variance (ANOVA) was done using the SAS 9.2 statistical software (SAS Institute, 2004) using the PROC GLM procedures. Treatment means were compared using Least Significant Difference (LSD) at risk level of 5% ($P \leq 0.05$). For correlation analysis, the Pearson correlation tests to determine the R or P value of linear correlations between variables were conducted in Microsoft Excel. The $P \leq 0.05$ was used to derive the significant difference unless stated otherwise.

CHAPTER FOUR

RESULTS

4.1 Soil properties of the BUAN Sebele experimental site

Results presented in Table 4.1 show selected physico-chemical soil properties of the experimental site in BUAN. As shown in the table, the soil is characterized as a sandy loam. Sandy soils are associated with low cation exchange capacity (CEC) thus cannot retain, hold and exchange nutrients efficiently. Generally they have low CEC 4.33cmol/kg and hold fewer nutrients, and likely to be subject to leaching of mobile "anion" nutrients. Low CEC soils also have low pH, organic carbon and total N with the pH of 4.7 indicating that the soil is acidic which agrees with the laboratory test.

4.2 Weather conditions at BUAN Sebele Experimental site

Botswana is generally known to experience convectional rainfall which occur heavily within a short period of time accompanied by thunder and lighting. The rainfall is normally expected to start in late October or early November. The 2015/2016 growing season was a very dry one with no rain experienced in December 2015. Figure 4.1 shows the accumulated rainfall recorded for the growing season. Little showers were experienced in January 2016 when the first planting date was done. The rainfall extended to June with March experiencing the highest accumulated level while little showers were experienced in May and June. The second planting which was done on the 4^{th} of February had the highest accumulated rainfall as compared to the first planting which was on the 4^{th} of January.

Figure 4.2 shows the monthly maximum and minimum temperature recording from January to June 2016. The season was also characterized by high temperatures with some dry spells in between the months. Both the highest maximum and minimum temperatures were recorded in February whereas the lowest were recorded in June. During the second planting date plants coincide with period of colds in the last week of April during flowering as temperatures were starting to drop as the winter season approaches.

Table 4.1: Selected physico chemical soil properties at BUAN Sebele Campus.

Soil properties	**Value**
pH ($CaCl_2$)	4.7
Organic carbon (%)	2.1
Total N (%)	0.43
CEC (cmol/kg)	4.33
EC (cmol/kg)	2.5
Soil particle distribution %	
Clay	13.8
Silt	13.4
Sand	72.8
Soil class	Sandy loam

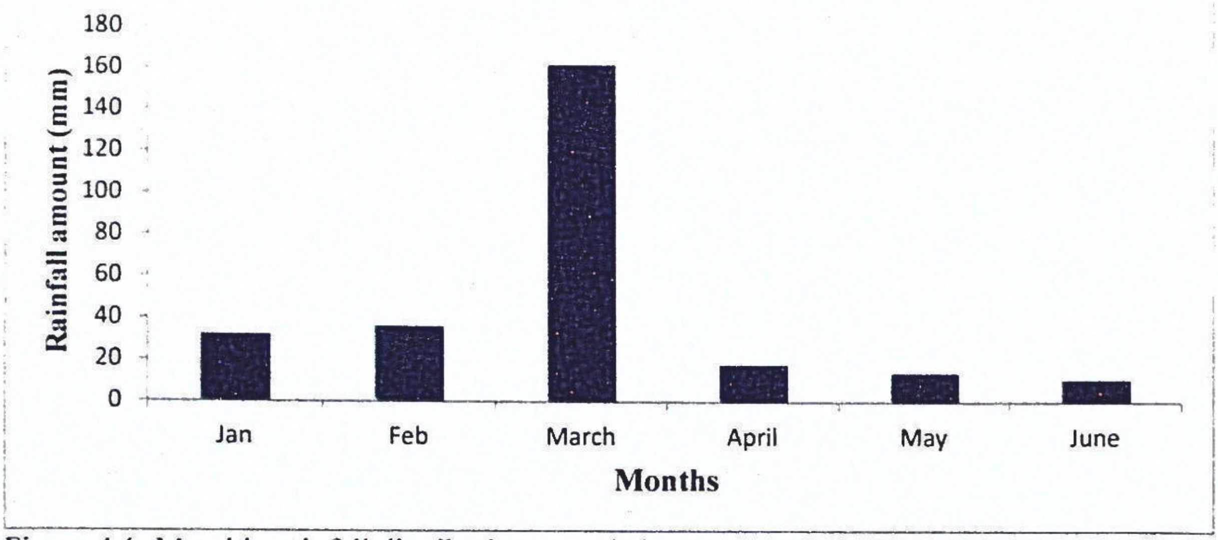


Figure 4.1: Monthly rainfall distribution recorded at Sebele BUAN campus during the 2015/2016 growing season

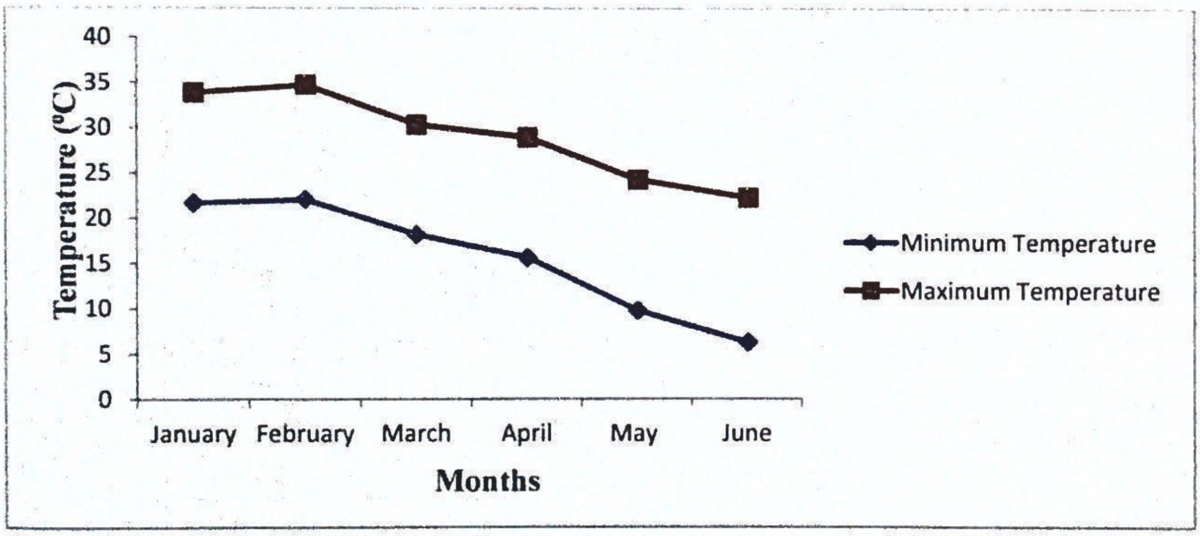


Figure 4.2: Monthly maximum and minimum temperatures recorded at Sebele BUAN campus during 2015/2016 growing season.

4.3 Morphological characteristics of sorghum as influenced by planting date, population and variety.

4.3.1 Plant height

The interactions (date*variety, date*population and date*variety*population) were not significantly different, while planting date ($P<0.0001$) and variety ($P<0.05$) significantly affected plant height (Table 4.2). The tallest plants were observed in the first planting date as opposed to the second planting date. Plant population also had significant influence on plant height where high densely population produced the tallest plants while low densely population produced the shortest height. The tallest plants among varieties were recorded for Segaolane under the high population while PSL985050 had the shortest height at low density (Figure 4.3a).

4.3.2 Stem diameter

Planting date and variety interacted significantly ($P<0.05$) on stem diameter while non-significant interaction was observed between date*pop and date*pop*var. Planting date and variety significantly affect stem diameter ($P<0.0001$, $P<0.05$) (Table 4.2).The thickest stem diameter was observed in the first planting. Figure 4.3b shows that population also varied significantly in stem thickness. Generally, as the plant density gets reduced, the stem grew thicker. Among varieties, Segaolane had the thinnest stem followed by PSL985028 and PSL985050 having the thickest stem diameter.

4.3.3 Number of leaves

Number of leaves were significantly ($P<0.05$) influenced by the interaction of date*pop*var while the interaction of date*pop showed a highly significant ($P<0.0001$) effect on number of leaves. Planting date and varieties also significantly ($P<0.0001$) influenced number of leaves

(Table 4.2). In regard to plant population, number of leaves differed significantly Figure 4.3c. Reduction in number of leaves was observed with an increase in plant population and Segaolane recorded more leaves as compared to the other two varieties.

4.3.4 Number of tillers

The interaction of planting date and variety significantly (P<0.0001) influence number of tillers meanwhile, while no significant interaction of date*pop and date*pop*var was observed. The results showed that, tiller number was significantly affected by both planting date and varieties at P<0.0001 (Table 4.2). A significant difference was also observed among the population. High population resulted in reduction in production of tillers while the lowest population enhances tiller production. Segaolane, among the three varieties produced more tillers while the other varieties, PSL985050 and PSL985028, produced almost similar number of tillers. No tillers were produced in the second planting and while a highly significant interaction was observed between date*var (Figure 4.4a).

4.3.5 Days to 50% flowering

Days to 50% flowering was significantly (P<0.05) affected by the interaction of planting date, plant population and varieties (Table 4.2). The interaction of date and variety was also effected days to 50% flowering (P<0.0001). Planting date and varieties also significantly (P<0.0001) affected the number of days to 50% flowering. Densely populated plants took long to reach flowering but were not significant from other populations. A significant difference in days to flowering between the varieties was observed. Among the varieties, Segaolane reached flowering stage earlier followed by PSL985028 and PSL985050 which took long to reach the flowering but it was not significant from PSL985028 (Figure 4.4b).

4.3.6 Days to 50% maturity

The results on days to 50% maturity are presented in Table (4.2). The results showed a significant ($P<0.05$) interaction of date*pop*var on days 50% to maturity. A significant interaction of $P<0.01$ was also observed between date*var and date*pop. On the other hand, planting dates were significantly different at $P<0.0001$. Plants planted on the second planting reached maturity earlier than those in the first planting. Varieties differed significantly ($P<0.05$) on 50% days to maturity where PSL985028 matured early followed by Segaolane and PSL985050. Population had a slight significant influence on days to 50% maturity with Segaolane taking long to mature in high densely population (Figure 4.4c).

Table 4.2: Effect of planting date and sorghum varieties on morphological characteristics of sorghum

Variety	Days to 50% flowering		Number of leaves		Days to 50% maturity		Plant height (cm)		Main stem diameter (cm)		Number of tillers	
	D1	D2	D1	D2	D1	D2	D1	D2	D1	D2	D1	D2
Segaolane	64.56c	52.63a	8a	5b	99.38a	77.63a	119.58a	98.34a	6.76c	4.52c	2.00a	nt
PSL985028	74.25b	60.25b	6a	4b	98.75a	64.25b	107.36b	92.99a	7.36b	5.41b	0.56b	nt
PSL985050	76.44a	61.06b	5a	4b	99.44a	66.63b	105.94b	94.27a	8.21a	6.32a	0.82b	nt
F-Statistics	20.52	1.13	8.3	6.8	0.39	10.27	1.14	0.64	4.70	7.63	7.68	0
Mean	71.75	59.98	6.3	4.3	99.19	69.50	110.96	92.21	7.44	5.42	1.13	0
Date	***		***		***		***		***		***	
Var	***		***		*		*		*		***	
Date*Var	***		ns		**		ns		*		***	
Date *pop	ns		ns		**		ns		ns		ns	
Date*pop*var	*		*		*		ns		ns		ns	

Means followed by the same letters in the same column are not significantly different at P<0.05. ***, **, * indicate significant differences at P<0.0001, P<0.01 and P<0.05 respectively; and ns - none significant difference at P>0.05 while nt indicate no tillers. D1 – First planting date (04 January 2016), D2 - Second planting date (04 February 2016).

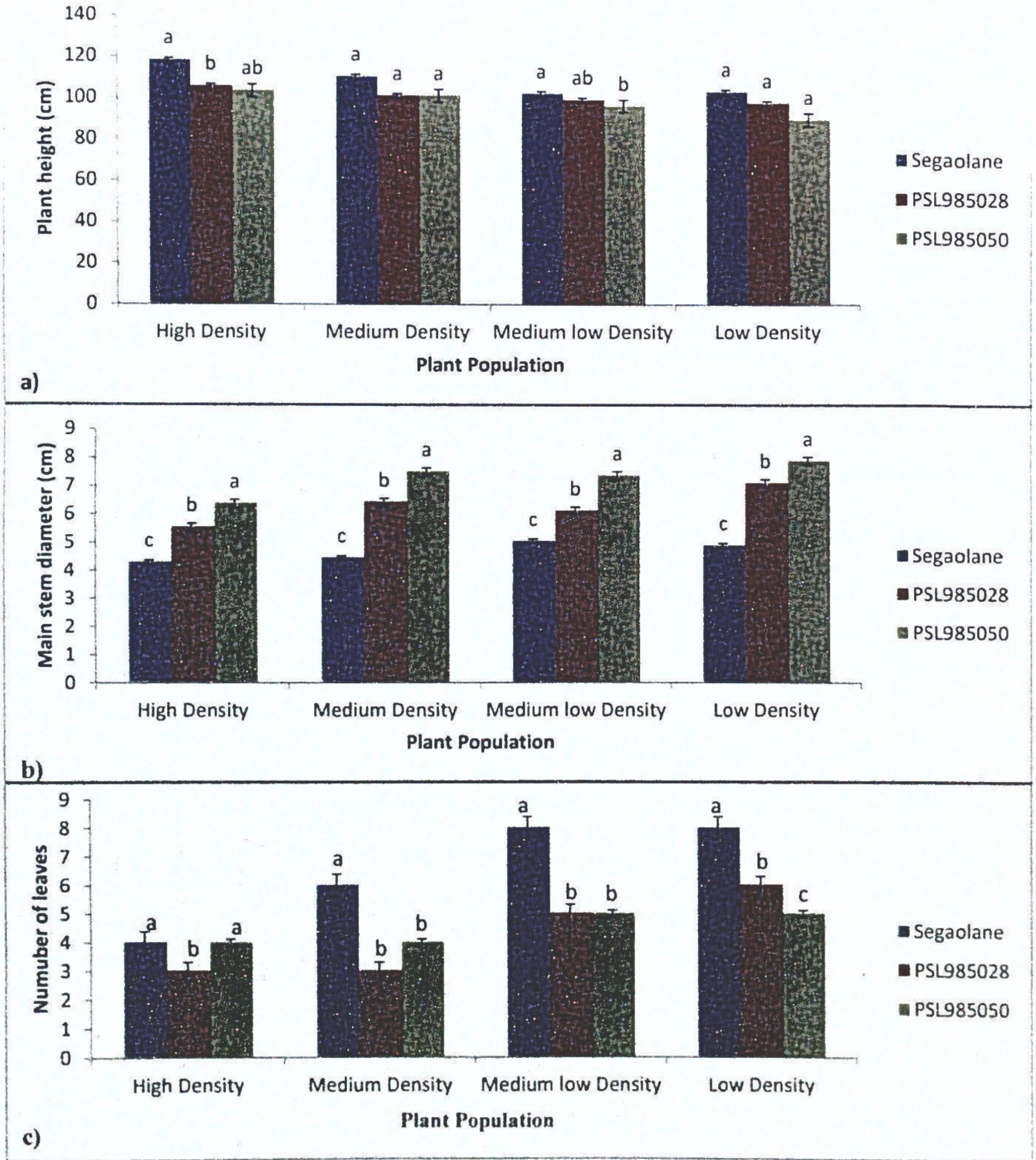


Figure 4.3: Effect of plant population and sorghum varieties on plant height (a), main stem diameter (b) and number of leaves (c). Different letters within a population indicate not significantly difference at P<0.05. Error bars indicate standard error of the means.

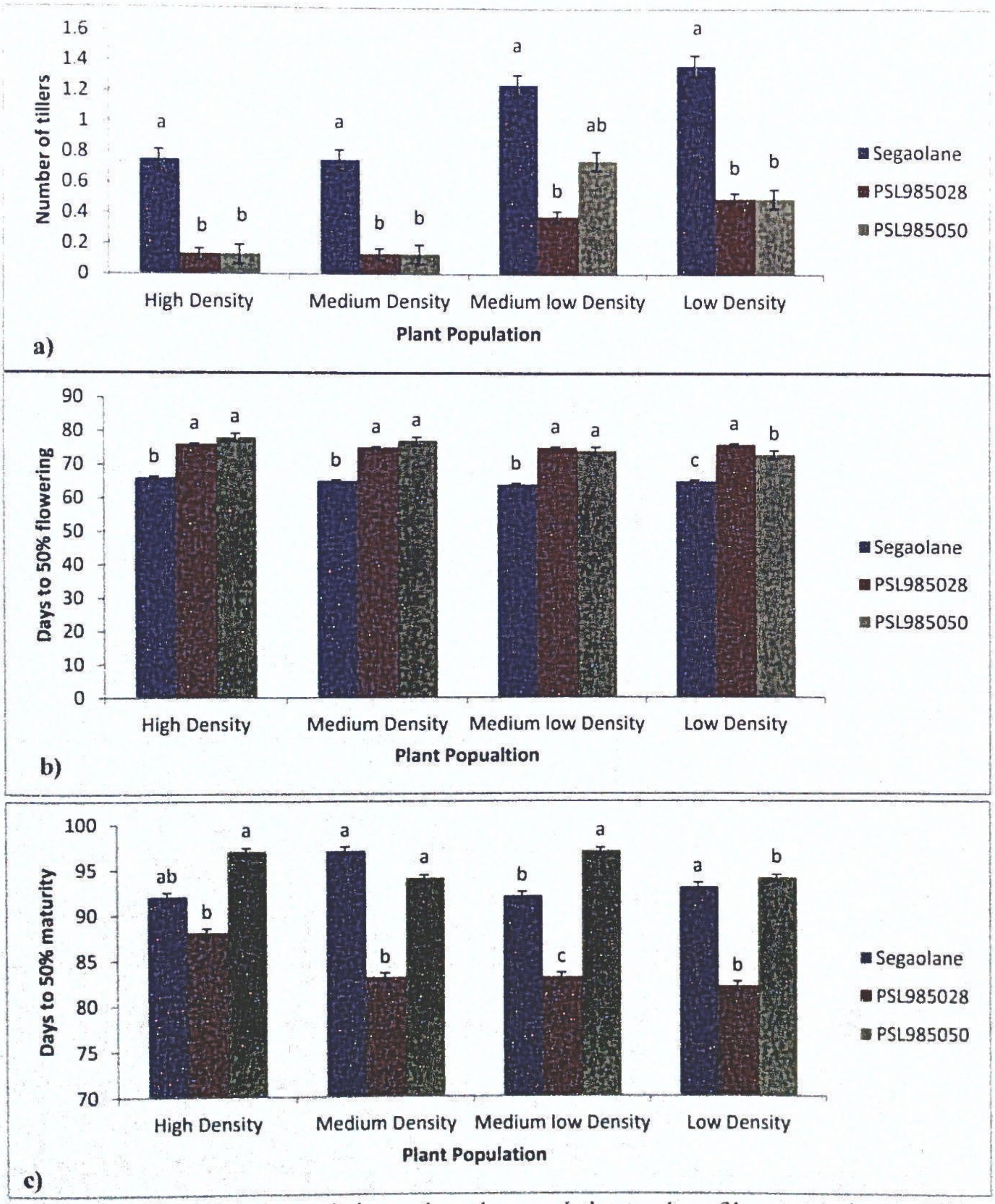


Figure 4.4: Effect of plant population and sorghum varieties number of leaves (a), days to 50% flowering (b) and maturity (c). Different letters within a population indicate not significantly difference at $P<0.05$. Error bars indicate standard error of the means.

4.4 Biomass production at different growth stages as influenced by planting date, plant population and varieties

4.4.1 Biomass at vegetative stage (BVg)

Results from sampled plants harvested at the vegetative stage showed a non- significant interaction of date*pop*var and pop*var however date*var interacted significantly (0.01) on biomass at vegetative stage. The two planting dates significantly ($P<0.0001$) influenced biomass accumulation. The varieties also differed significantly ($P<0.01$) in terms of biomass production with Segaolane producing the highest biomass as compared to other varieties (Table 4.3). Population also had a significant influence on BVg. Low densely population was significantly difference from other populations as increase in biomass was recorded as population decreases (Figure 4.5a).

4.4.2 Biomass at booting stage (Bbt)

The interaction of date*pop*var, pop*var and date* var had no significant effect on production of biomass at booting stage. Though, planting date and varieties had significant ($P<0.0001$, $P<0.01$) effect on biomass at booting stage (Table 4.3). PSL985050 produced the highest biomass followed by Segaolane with PSL985028 having the least biomass. Population also had an influence on BBt. The highest biomass was produced in the medium low population while biomass produced in high and medium densely population was not significantly different between the two populations (Figure 4.5b).

4.4.3 Biomass at flowering (BFl)

Results showed that all the interactions did not significantly affect biomass at flowering were presented in Table 4.3. However, a significant difference between planting dates ($P<0.0001$) was observed. There was also a significant difference ($P<0.01$) between varieties. Segaolane produced the highest biomass followed by PSL985050 while PSL985028 produced the least biomass. Plant population also affected biomass production as the least amount of biomass was produced in the lowest population with medium low population having the highest biomass (Figure 4.6a).

4.4.4 Biomass at physiological maturity (BPm)

Biomass at physiological maturity was also determined and the results revealed a significant interaction of date*var while pop*var and date*pop*var had no significant effect on the biomass production. The two planting date were significantly different at $P<0.0001$ (Table 4.3). A non-significant difference was also observed between the varieties where Segaolane had an outstanding biomass production as compared to other varieties. Plant population effect was also indicated by the results. An inverse relationship was observed between BPm and plant population where the results showed that as population decrease from highly densely population to medium low population, biomass production increases (Figure 4.6b).

4.4.5 Grain yield (Gy)

The results in Table 4.3 showed that date*pop*var interacted significantly $P<0.05$) to influence grain yield. The interaction of date*var also significantly ($P<0.01$) influenced grain yield. A significant ($P<0.0001$) difference of planting date and varieties on grain yield was also observed Figure 4.6c indicates a significant difference between populations. The results also showed that, as population decreases, grain yield also decreases. Among the varieties, Segaolane yielded best followed by PSL985050 with PSL985028 producing the lowest yield.

Table 4.3: Effect of planting date and sorghum varieties on biomass production and grain yield at different growth stages.

Variety	BVg (kg/ha)		BBt (kg/ha)		BFl (kg/ha)		BPm (kg/ha)		Gy (kg/ha)	
	D1	D2	D1	D2	D1	D2	D1	D2	D1	D2
Segaolane	33.64a	7.91b	79.88a	44.99ab	149.95a	80.51b	783.63a	123.64b	373.48a	62.51a
PSL985028	23.17a	7.66b	70.65a	36.06b	109.44a	52.83b	676.25a	129.37b	269.87b	52.60a
PSL985050	25.25b	8.11a	98.34a	49.08b	149.45a	67.54b	742.06a	142.55b	281.51b	63.80a
F-Statistics	1.54	1.25	1.98	0.75	1.45	2.56	1.25	1.04	4.59	1.16
Mean	27.35	7.89	82.95	43.35	136.28	66.96	733.65	131.78	308.28	59.63
Date	***		***		***		***		***	
Var	**		**		**		ns		***	
Date*Var	**		ns		ns		*		**	
Pop*Var	ns		ns		ns		ns		ns	
Date*pop*Var	ns		ns		ns		ns		*	

Means followed by the same letters in the same column are not significant difference at P<0.05.; ***, **, * Indicate significantly different at P<0.0001, P<0.01 and P<0.05 respectively; and ns – not significant at P>0.05. Where BVg – biomass at vegetative stage, BBt – biomass at booting stage, BFl – biomass at flowering, BPm – biomass at physiological maturity and Gy – grain yield, D1 – First planting date (04 January 2016) and D2 – Second planting date (04 February 2016).

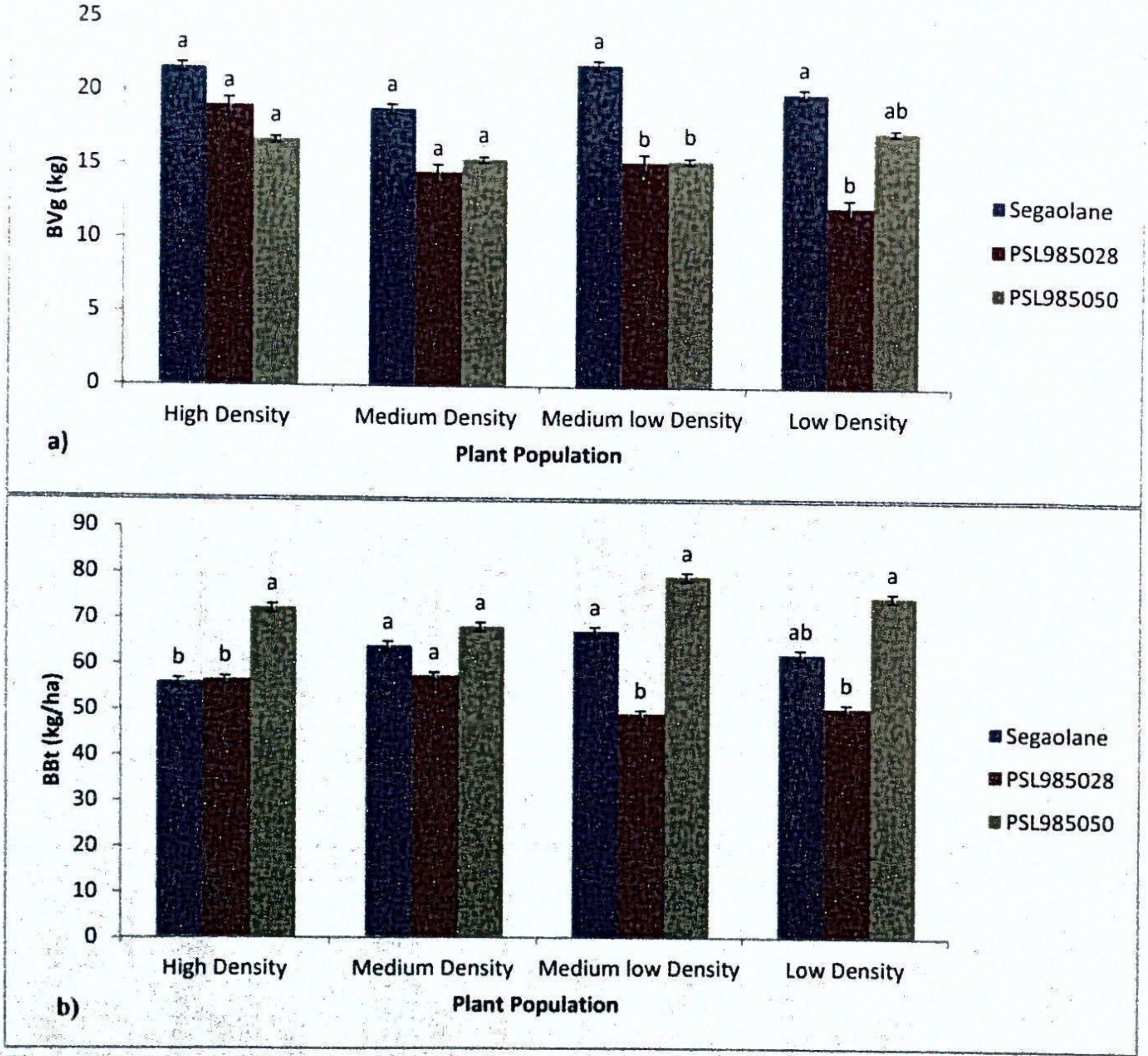


Figure 4.5: Effect of plant population and sorghum varieties on biomass at vegetative (a) and booting stage (b). Different letters within a population indicate significant difference at P<0.05. Error bars indicate standard error of the means

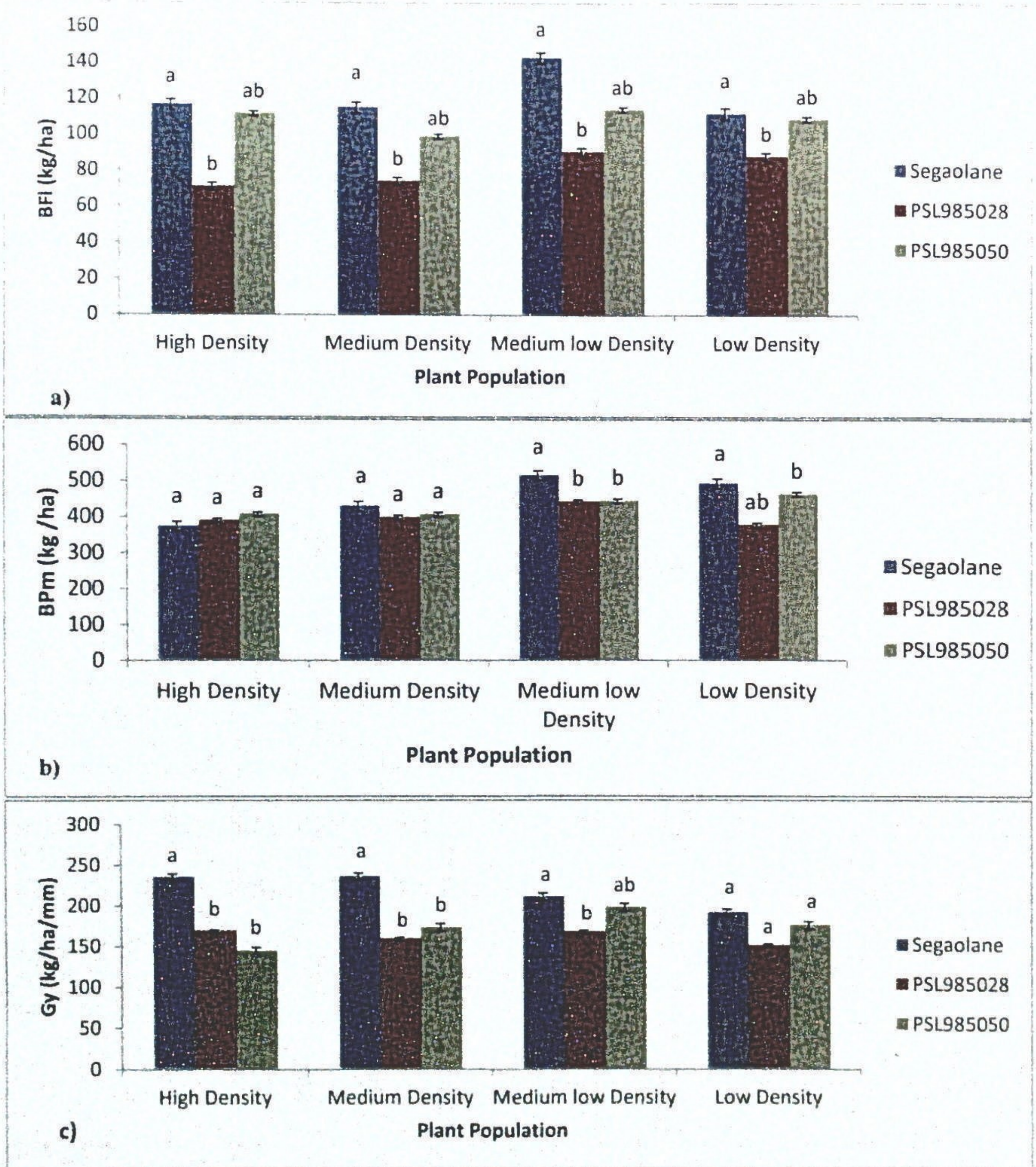


Figure 4.6: Effect of plant population and sorghum varieties on biomass production at flowering (BFI) (a) and physiological maturity (BPm) (b) and grain yield (Gy) (c. Different letters within a population indicate significant difference at $P<0.05$. Error bars indicate standard error of the means.

4.5 Plant population and variety effect on RWUE at different growth stages

4.5.1 Rainwater use efficiency at vegetative stage (RWUEVg)

Plant population showed significant effects on RWUE at different growth stages of sorghum. The mean average RWUEVg was higher at highest density and then dropped in the medium density. A slight constant increase in RWUEVg was observed between medium low and low densely population. Among varieties Segaolane had the highest RWUEVg as compared to other varieties. The same trend of constant increase in RWUEVg for Segaolane was also observed in medium low and low densely populated plants. PSL985028 experienced the highest RWUEVg at medium low population while PSL985050 had the lowest RWUEVg in all population except high densely population (Figure 4.7a).

4.5.2 Rainwater use efficiency at booting stage (RWUEBt)

The results in Figure 4.7b showed that, the mean average RWUEBt and RWUEBt among varieties varied accordingly among the population. A constant slight increase of average RWUEBt was observed as plant populations get reduced. A varietal variation was also observed as PSL985028 had the highest RWUE in medium low and low densities with PSL985050 had the lowest RWUE in all population. Segaolane had a slightly higher RWUE than other varieties at medium density.

4.5.3 Rainwater use efficiency at flowering stage (RWUEFl) and physiological maturity (RWUEPm)

As summarized in Figure 4.8a and 4.8b, plant population had an effect on RWUEFl and RWUEPm. The same trend was observed in both stages where RWUE was high at high population then dropped in the medium density. A constant increase was then observed in medium low and low population densities. Between the three varieties, Segaolane had the highest RWUEFI as compared to other varieties in medium low density but then dropped in low density. RWUEFI for PSL985050 was increasing as the population reduce from high densely plants to medium low population and then experienced a slight drop in low densely population. PSL985028 had the lowest RWUEFI in all populations with a constant increase in medium low and low density. At maturity RWUE for Segaolane was increasing with decreasing population from high to medium low density. As for PSL985028, the highest RWUEPm was observed at high density and get reduced in the medium low density and then increase again in the medium low to low density. The lowest RWUEPm was observed in the lowest population for PSL985050.

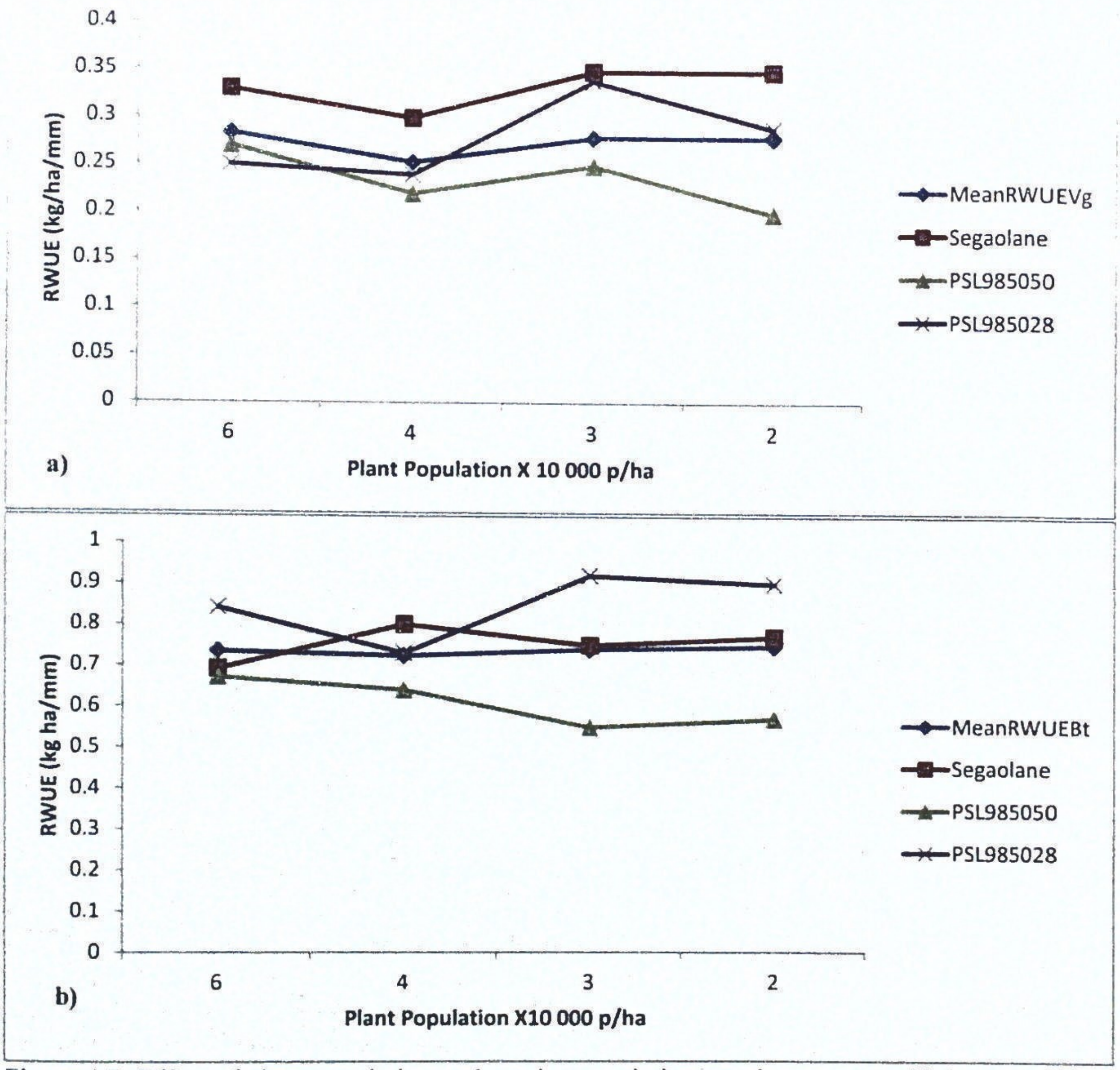
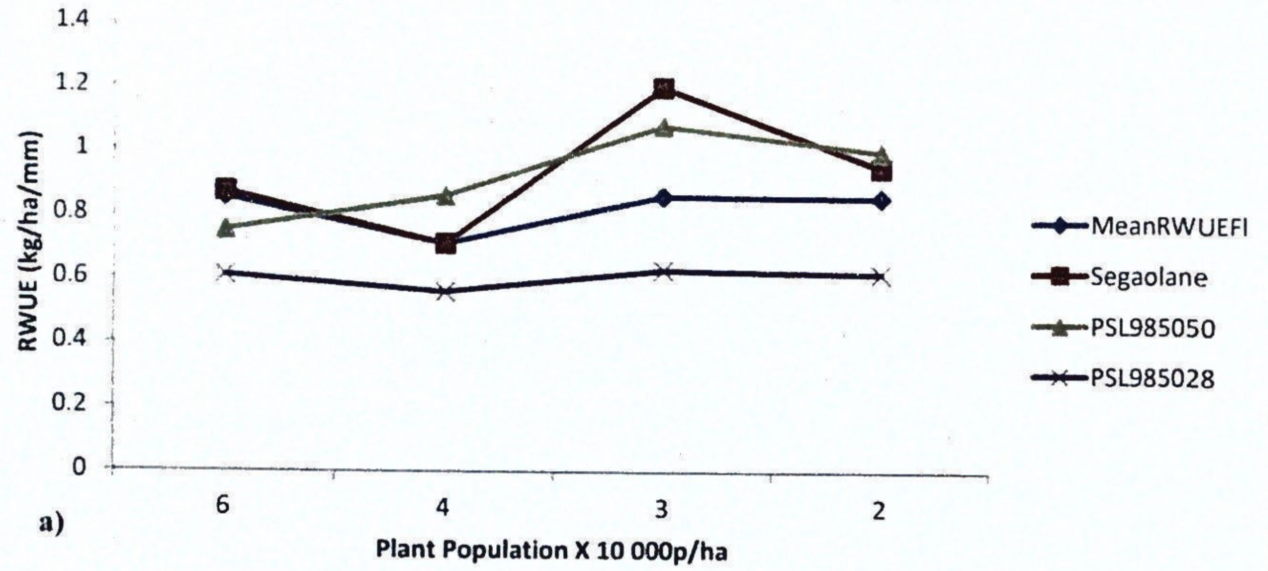
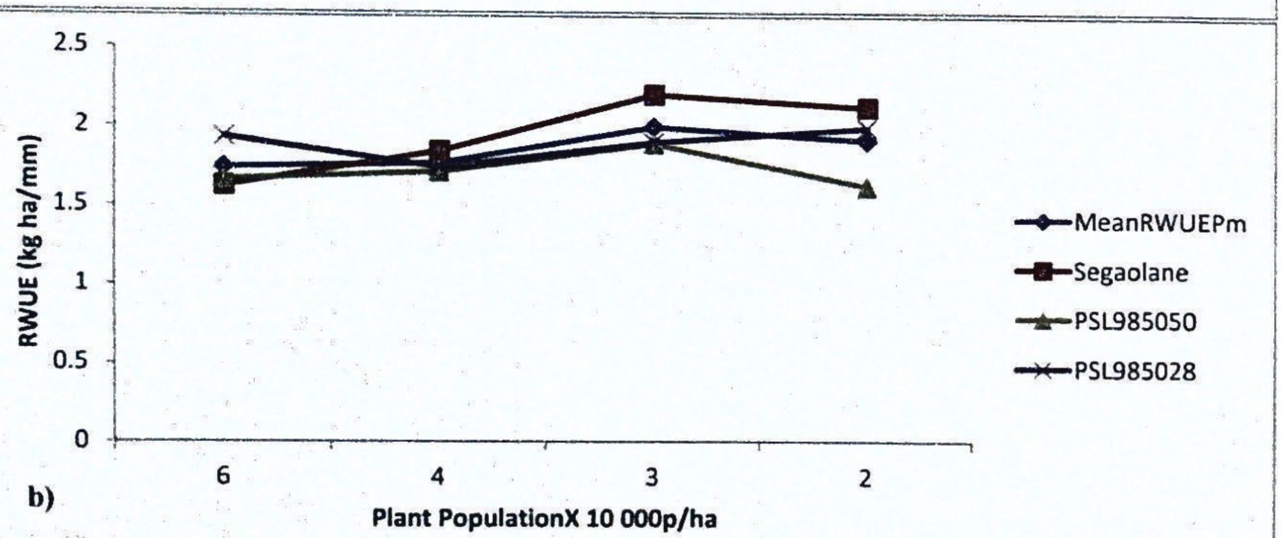


Figure 4.7: Effect of plant population and sorghum varieties on rainwater use efficiency at vegetative stage (RWUEVg) (a) and rainwater use efficiency at booting stage (RWUEBt) (b).



a)



b)

Figure 4.8: Effect of plant population and sorghum varieties on rainwater use efficiency at flowering stage (RWUEFl) (a) and rainwater use efficiency at physiological maturity (RWUEPm) (b).

4.6 Effect of plant population and variety on Grain rainwater use efficiency (RWUEGy) and Grain yield (Gy).

Grain RWUE and grain yield were also affected by plant population and varieties as shown in Figure 4.9a and 4.9b. The same trend was observed in both RWUEGy and Gy. Average mean for RWUEGy and Gy was constant from high population to medium density but then experienced a slight drop in low density. Varietal variation was also observed among the varieties. Segaolane had superiority in terms of RWUEGy and Gy over other varieties. It had a decreasing RWUE with decreasing plant population. An increasing RWUE for PSL985028 was showed in medium low density with a slight fall in low population. Low RWUEGy and Gy were recorded for PSL985050 in the lowest population.

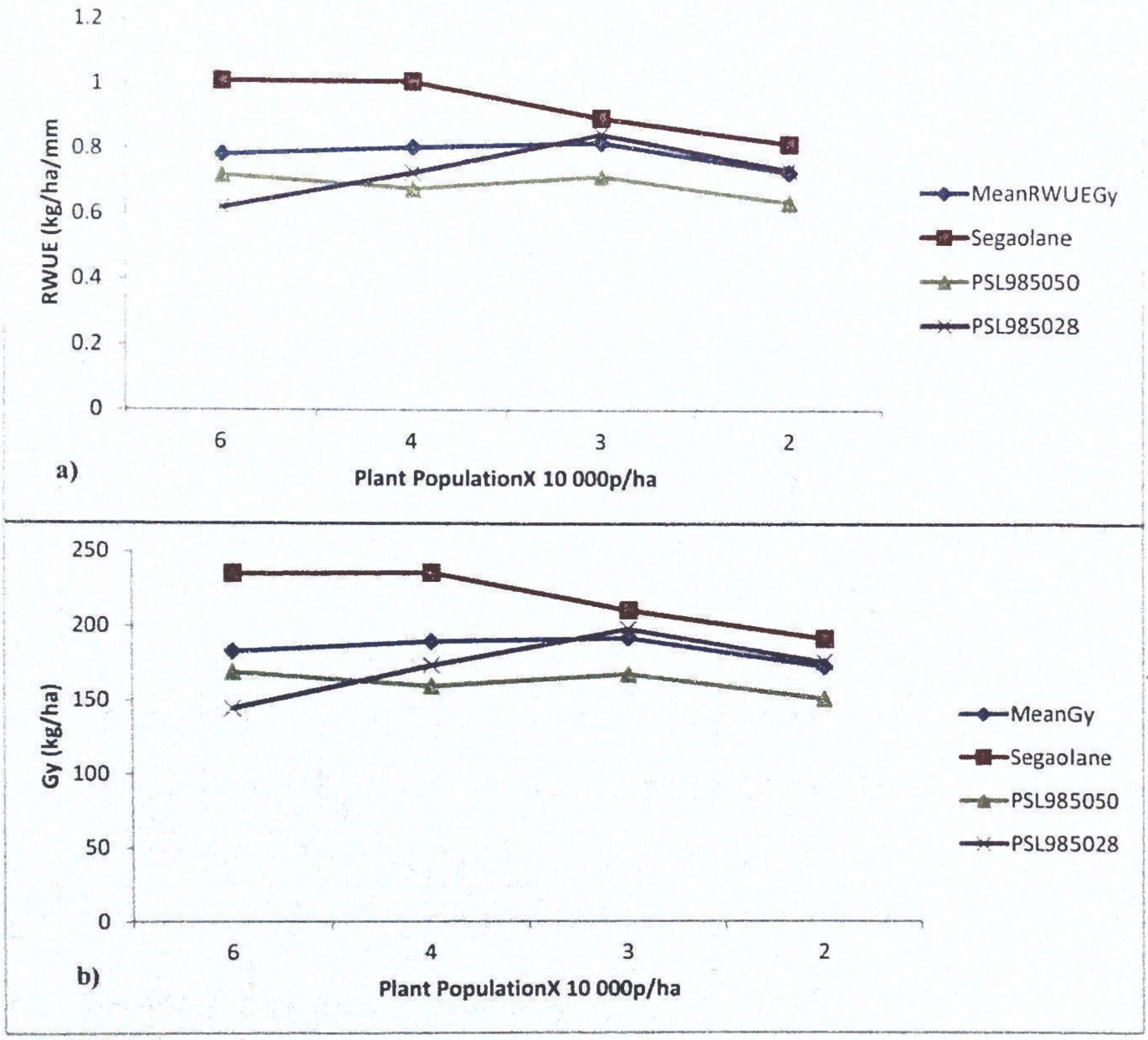


Figure 4.9: Effect of plant population and sorghum varieties on grain rainwater use efficiency (RWUEGy) (a) and grain yield (Gy) (b).

4.7 Rainwater Use Efficiency as influenced by planting date, population and varieties at different growth stages.

4.7.1 Rainwater Use Efficiency at Vegetative stage (RWUEVg)

As summarized in Table 4.5, no significant interactions of date*pop*var and pop*date were shown on RWUEVg but the interaction of date*var had significant (P<0.01) impact on RWUEVg. A significant difference (P<0.0001) was observed on RWUEVg during the two planting dates. Varieties were also significantly different at P<0.01. The results in Figure 4.10a showed that Segaolane was more efficient in water use than the other varieties.

4.7.2 Rain Water Use Efficiency at Booting (RWUEBt)

There was no significant interaction of date*pop*var and pop*var on RWUEBt while the interaction of date*var was significant (P<0.05) on RWUEBt. On the other hand RWUEBt decrease significantly (P<0.0001) as planting date is delayed. A significant difference between varieties was also observed (P< 0.01). As highlighted in Figure 4.10b, PSL985050 was more efficient at booting followed by Segaolane while PSL985028 had the least RWUE.

4.7.3 Rain Water Use Efficiency at Flowering stage (RWUEFl)

The results showed no significant interaction of date*pop*var and pop*var on RWUEFl. However, date*var was found to be significantly P<0.01 interacted well on influencing RWUEFl. A significant difference was also observed between planting date (P<0.0001) and varieties at P<0.01 (Table 4.5). Varieties were also significantly different (P<0.01) as PSL985028 was efficient in terms of rain water use followed by Segaolane while PSL985050 had the least RWUE (Figure 4.11a).

4.7.4 Rain Water Use Efficiency at Physiological maturity (RWUEPm)

There was no significant interaction of date*pop*var and pop*var while a significant interaction ($P<0.05$) was noted for date*var on RWUEPm. RWUEPm was significantly affected by planting date at $P<0.0001$. The results also revealed a significant difference ($P<0.05$) between the varieties (Table 4.4). As summarized in figure 4.11b, varietal variation was observed within population. Segaolane was more efficient at maturity in the medium low density followed by PSL985050 in low density while PSL985028 had the least RWUE in the lower density.

4.7.5 Grain Rain Water Use Efficiency (RWUEGy)

The interaction of date*pop*var had a significant ($P<0.05$) effect on RWUEGy while the interactions of date*var was highly significant at $P<0.0001$). It was also shown that planting dates were significantly difference at $P<0.0001$. More RWUEgy was recorded in the first planting as compared to second planting. Varieties also varied significantly at $P<0.0001$ (Table 4.4). Figure 4.11c showed that the highest RWUEgy was experienced by Segaolane followed by PSL985028 with PSL985050 having the least RWUEgy in almost all populations.

Table 4.4: Effect of planting date and sorghum varieties on rainwater use efficiency at different growth stage.

Variety	RWUEVg (kg/ha/mm)		RWUEBt (kg/ha/mm)		RWUEFl (kg /ha/mm)		RWUEPm (kg/ha/mm)		RWUEGy (kg/ha/mm)	
	D1	D2	D1	D2	D1	D2	D1	D2	D1	D2
Segaolane	0.63a	0.04b	1.28ab	0.23b	1.5a	0.37b	3.39a	0.48b	1.62b	0.25a
PSL985028	0.43b	0.04a	1.04b	0.18b	1.61a	0.24b	2.92a	0.51b	1.17b	0.21a
PSL985050	0.47b	0.04a	1.44a	0.25b	0.9b	0.31a	3.21a	0.57b	1.22b	0.26a
F-Statistics	1.54	1.52	1.47	0.75	2.37	2.53	1.25	1.03	4.63	1.17
Mean	0.51	0.04	1.25	0.22	1.33	0.31	3.18	0.52	1.33	0.24
Date	***		***		***		***		***	
Var	**		**		**		*		***	
Date*Var	**		*		**		*		***	
Pop*Var	ns		ns		ns		ns		ns	
Date*Pop*Var	ns		ns		ns		ns		*	

Means followed by the same letters in the same column are not significant at $P<0.05$.; ***, **, * Indicate significant differences at $P<0.0001$, $P<0.01$ and $P<0.05$ respectively; and ns – not significant difference at $P>0.05$. Where RWUEVg= rainwater use efficiency at vegetative stage, RWUEBt = rainwater use efficiency at booting, RWUEFl= rainwater use efficiency at flowering stage, RWUEPm = rainwater use efficiency at physiological maturity, RWUEGy = Grain rainwater use efficiency, D1 – First planting date (04 January 2016), D2 – Second planting date (04 February 2016)

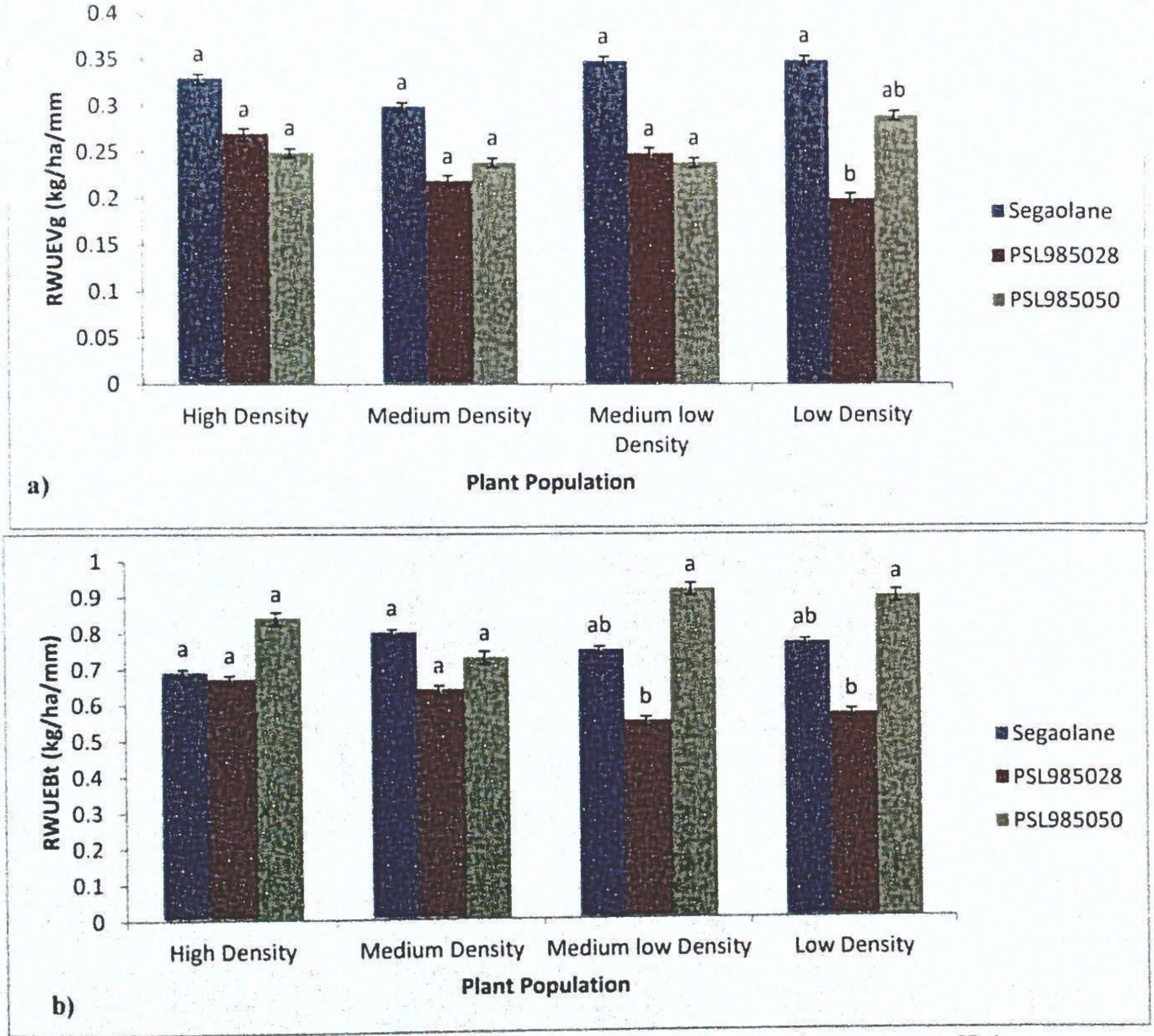


Figure 4.10: Effect of plant population and sorghum varieties on rainwater use efficiency at vegetative stage (RWUEVg) (a) and rainwater use efficiency at booting stage (RWUEBt) (b). Different letters within a population indicate not significant difference at $P<0.05$. Error bars indicate standard error of the means.

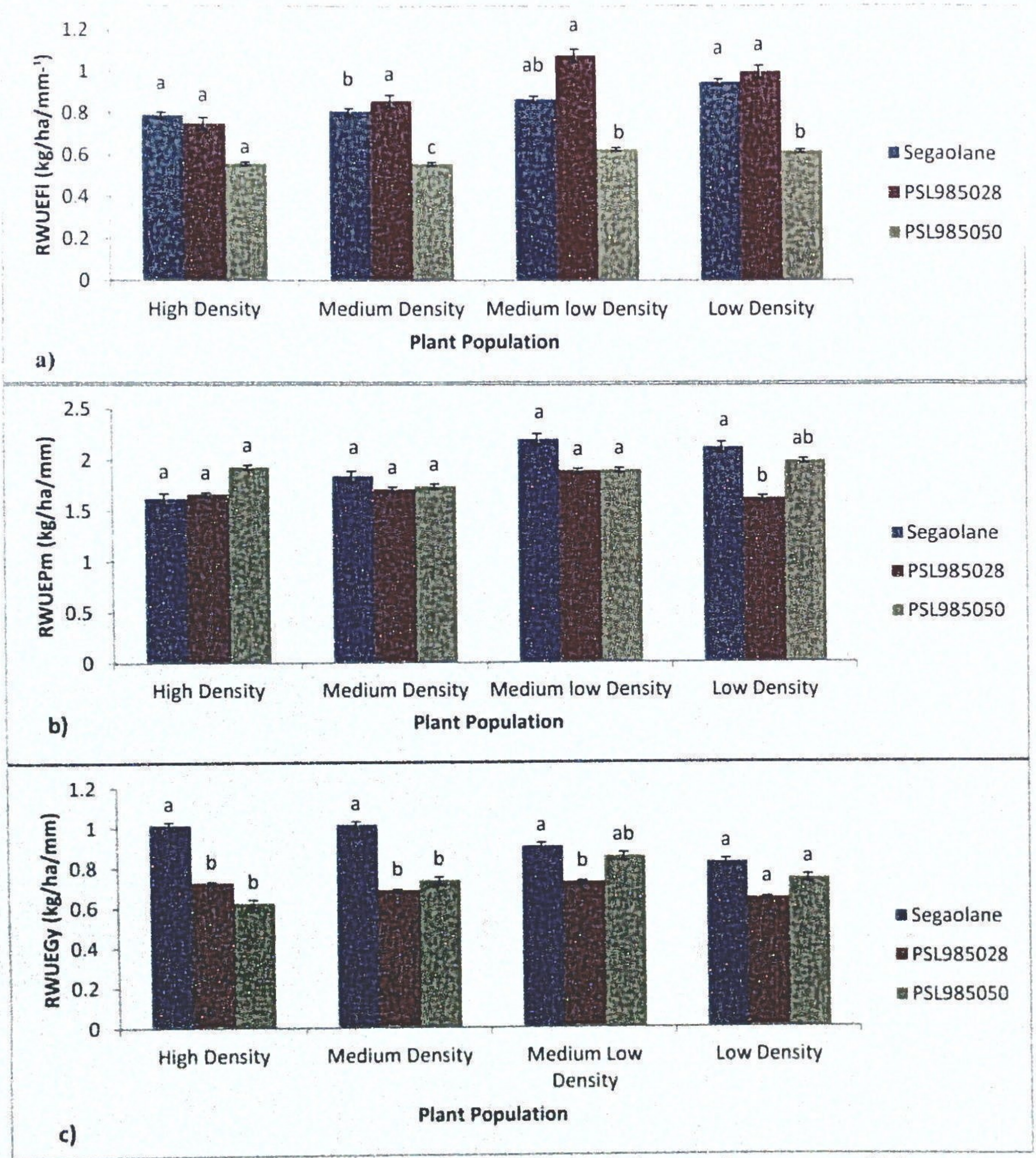


Figure 4.11: Effects of plant population and sorghum varieties on rainwater use efficiency at flowering stage (RWUEFl) (a), rainwater use efficiency at physiology maturity (RWUEPm) (b) and grain rainwater use efficiency (RWUEGy) (c). Different letters within a population indicate not significant difference at P<0.05. Error bars indicate standard error of the means

4.8 Effects of planting date, populations and varieties on yield components

Results on yield components (panicle length, panicle thickness, panicle weight, and 1000 seed weight and harvest index) are presented on Table 4.5. The results showed non- significant interaction of date*var, pop*var as well as date*pop*var on all yield components. However a significant differences (P<0.0001) between the planting dates was shown on all the yield components except harvest index (HI). A significant difference was observed between the populations with an increase on panicle length (PL) as population decreases. A descending trend was observed on panicle thickness (PT), panicle weight (PW) 1000 seed weight (1000SW) and harvest index (HI) as population decreased. There was no significant difference between varieties on PT, 1000SW and HI while significant differences were observed between varieties for PL and PW (P<0.0001, P<0.01) respectively. In this case Segaolane had the highest PW, PL, 1000SW followed by PSL985028. On the other hand PSL985050 had thickest panicles followed by PSL985028 with Segaolane producing thinnest panicles.

Table 4.5: Effect of plant date, plant population and sorghum varieties on yield components of sorghum.

Date	PL(cm)	PT (cm)	PW (g)	1000SW (g)	HI
Jan	24.74±0.48a	11.36±0.22a	40.85±3.79a	32.81±3.56a	0.44±0.12a
Feb	17.68±0.48b	7.86±0.22b	14.11±3.79b	16.66±3.56b	0.54±0.12a
Population					
High Density	19.07±0.68b	8.71±0.31b	20.25±3.79c	18.33±3.56b	0.38±0.12c
Medium Density	20.17±0.68b	8.89±0.31b	25.44±3.79b	26.10±3.56a	0.55±0.12ab
Medium low Density	22.60±0.68a	10.36±0.31a	31.41±3.79a	26.24±3.56a	0.43±0.12bc
Low Density	22.80±0.68a	10.47±0.31a	32.85±3.79a	28.26±3.56a	0.59±0.12a
Variety					
Segaolane	23.48±0.59a	9.26±0.27a	29.47±3.79a	26.67±3.56a	0.51±0.12a
PSL985050	19.64±0.59b	10.00±0.27a	25.40±3.79ab	23.11±3.56a	0.49±0.12a
PSL985028	20.51±0.59b	9.56±0.27a	27.59±3.79b	24.42±3.56a	0.47±0.12a
F-statistics	6.17	5.93	8.71	5.04	2.89
Mean	21.209	9.608	27.486	24.732	0.489
Date	***	***	***	***	ns
Population	**	***	***	***	**
Date*pop	**	**	ns	ns	***
Var	***	ns	**	ns	ns
Date*var	ns	ns	ns	ns	ns
Pop*Var	ns	ns	ns	ns	ns
Date*pop*Var	ns	ns	ns	ns	ns

Means followed by the same letters in the same column are not significant at $P<0.05$ using the Least Significant Difference (LSD). ***, **, * Indicate significantly different at $P<0.0001$, $P<0.01$ and $P<0.05$ respectively; and ns – not significantly different at $P>0.05$. Where: PL – panicle length, PT – panicle thickness, PW – panicle weight, 1000 SW – thousand seed weight, and HI – harvest index

4.9 Effect plant population and variety on uptake, utilization and efficient use nitrogen

4.9.1 Nitrogen Uptake efficiency (NUPEff)

Figure 4.12a shows uptake efficiency as influenced by plant population and varieties. The highest nitrogen uptake efficiency (NUPEff) was noted in the medium low density with lowest population having the lowest NUPEff. Among the varieties Segaolane had the highest UPEff in comparison to other varieties. The highest NUPEff was obtained at medium low density and experienced a sudden drop in low density. The lowest NUPEff was recorded for PSL985028 in medium density and Segaolane in low density.

4.9.2 Nitrogen Utilization efficiency (NUTEff)

Figure 4.12b shows plant population and variety effect on nitrogen utilization efficiency (NUTEff). The mean average NUTEff was influenced by population where the highest NUTEff was recorded at medium density while the lowest was recorded at high densely population. A varietal difference was also observed where the highest and the lowest NUTEff were obtained by PSL985028 in medium density and highly populated density respectively. Segaolane had the highest and the lowest NUTEff at low and high densely population while PSL985050 had the least NUTEff in medium low densities.

4.9.3 Nitrogen use efficiency (NUE)

NUE was also influenced by plant population and variety. The mean average NUE was increased with an increasing population but declined in the lowest population. Segaolane had the highest NUE as compared to other varieties. The highest NUE was noted in the medium low density for Segaolane but the efficiency went down in low population. There was no difference between PSL985050and PSL985028 in terms of the efficient use of nitrogen (Figure 4.12c).

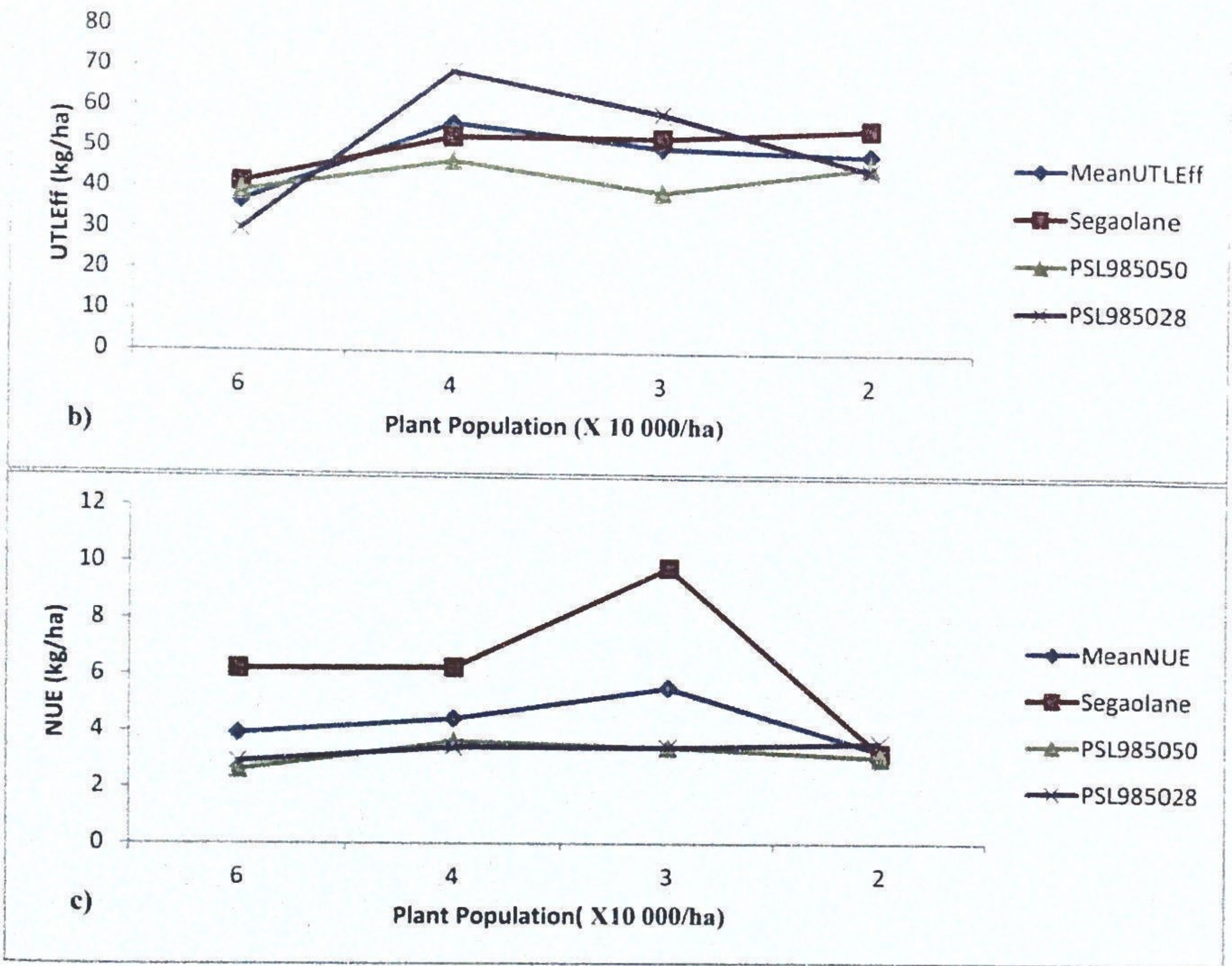


Figure 4.12: Effect of plant population and sorghum varieties on nitrogen uptake efficiency (NUPEff) (a) and nitrogen utilization efficiency (NUTEff) (b) and nitrogen use efficiency (NUE) (c).

4.10 Nitrogen Use Efficiency and its components as influenced by planting date, plant population and variety.

Results represented in Table 4.6 show a summary of NUE and its components for the sorghum varieties investigated. There was a significant interaction of P<0.05 between date*var and pop*date on NUPEff and NUE while significant difference of P<0.01 was observed on NUTLEff between date*var. No significant interaction was observed between date*pop*var and pop*var for NUPEff. On the other hand, date*pop*var was also not significant for both NUPEff and NUE. The results also revealed that planting date had a significant effect (P<0.0001) on both NUE and its components (uptake efficiency and utilization efficiency). The first planting date has the highest nitrogen uptake and utilization efficiency hence the highest NUE. A significant difference was observed between the varieties for nitrogen uptake efficiency (NUPEff) and utilization efficiency (NUTLEff) (P<0.05) while NUE was significant (P<0.0001) between the three varieties with Segaolane having the highest NUPEff and NUE. Figure 4.13 shows that varieties differed significantly within population for NUPEff, NUTEff and NUE.

Table 4.6: Effect of planting date and sorghum varieties on NUE and its components.

Variety	UPEff (kg/kg)		UTEff (kg/kg)		NUE (kg/kg)	
	D1	D2	D1	D2	D1	D2
Segaolane	0.14a	0.02b	53.44b	48.18a	10.52a	2.23a
PSL985028	0.12ab	0.03ab	53.30b	33.02ab	5.36b	1.29a
PSL985050	0.08b	0.04a	70.95a	30.98b	3.36b	1.05a
F-Statistics	2.14	0.94	4.07	1.52	3.71	1.57
Mean	0.12	0.03	59.23	37.39	7.08	1.51
Date	***		***		***	
Var	*		*		***	
Date*Var	*		**		*	
Pop*Var	*		ns		*	
Date*Pop*Var	ns		ns		ns	

Means followed by the same letters in the same column are not significant at P<0.05; ***, **, * Indicate significantly different at P<0.0001, P<0.01 and P<0.05 respectively; and ns – not significantly different at P<0.05. Where, NUPEff- nitrogen uptake efficiency, NUTEff- nitrogen utilization efficiency, NUE- nitrogen use efficiency, D1 – First planting date (04 January 2016), D2 – Second planting date (04 February 2016).

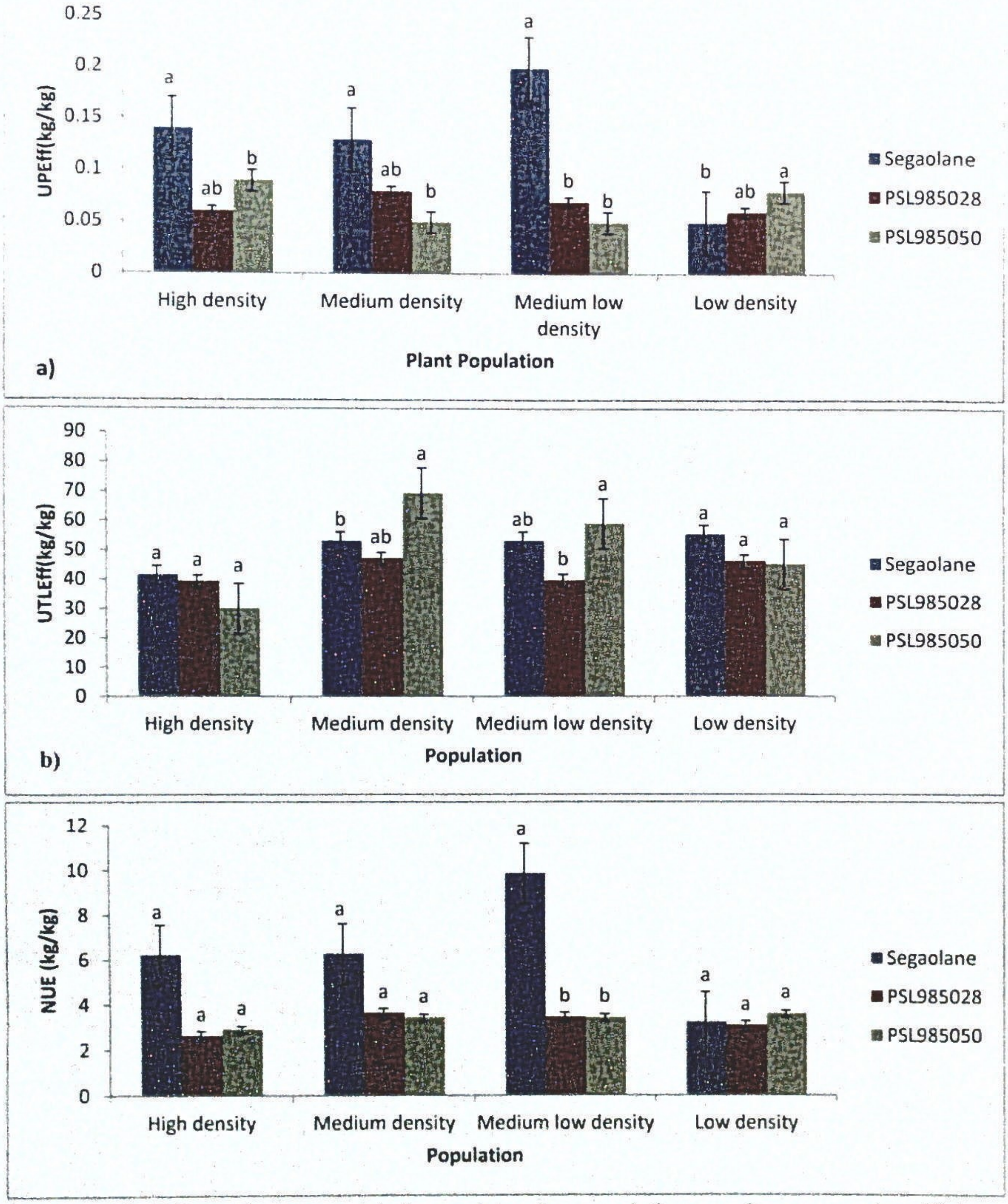


Figure 4.13: Effect of plant population and sorghum varieties on nitrogen uptake efficiency (UPEff) (a), nitrogen utilization efficiency (UTLEff) (b) and nitrogen use efficiency (NUE) (c). Different letters within a population indicate significant difference at P<0.05. Error bars indicate standard error of the mean.

4.11 Correlation and regression analysis

The relationship between RWUE and Gy during the two planting dates is shown in Figure 4.14. A significant strong linear relationship was found between rainwater use efficiency (RWUE) and grain yield (Gy) on the first and the second planting date with coefficients of R^2=0.99, (P<0.0001) and R^2=1.00, (P<0.0001) respectively. The results in Figure 4.15 show a relationship between RWUE and biomass for the two planting dates. A non-significant relationship was also observed between RWUE and biomass with coefficients of R^2=0.01, (P>0.43) for the first planting and R^2=0.06, (P< 0.1) for the second planting. Relationship between harvest index (HI) and Gy was presented in Figure 4.16. The results revealed a significant positive linear relationships in the first planting (R^2= 0.67, P<0.0001) and second planting date (R^2 = 0.38, P<0.0001). With respect to harvest index and biomass at physiological maturity, a negative and a non-significant relationship was observed between the two parameters in the first planting (R^2 = 0.40, P<0.0001) and (R^2=0.18, P>0.24) in the second planting (Figure 4.17).

Results presented in Figure 4.18 show the relationship effects between RWUE and nitrogen use efficiency (NUE). A linear positive and significant relationship was observed in the first planting date (R^2=0.32, P<0.0001) and second planting (R^2=0.56, P<0.0001). The relationship between grain yield (Gy) and nitrogen use efficiency (NUE) was presented in Figure 4.19. There was a positive and significant linear relationship that was observed between Gy and NUE (R^2= 0.32, P<0.0001) for the first and (R^2 = 0.56, P<0.0001) for the second planting date. A non- significant relationship was observed between NUE and biomass during the first planting date (R^2 = 0.01, P>0.47) and ($R^2$0.04, P>0.12) in the second planting date (Figure 4.20).

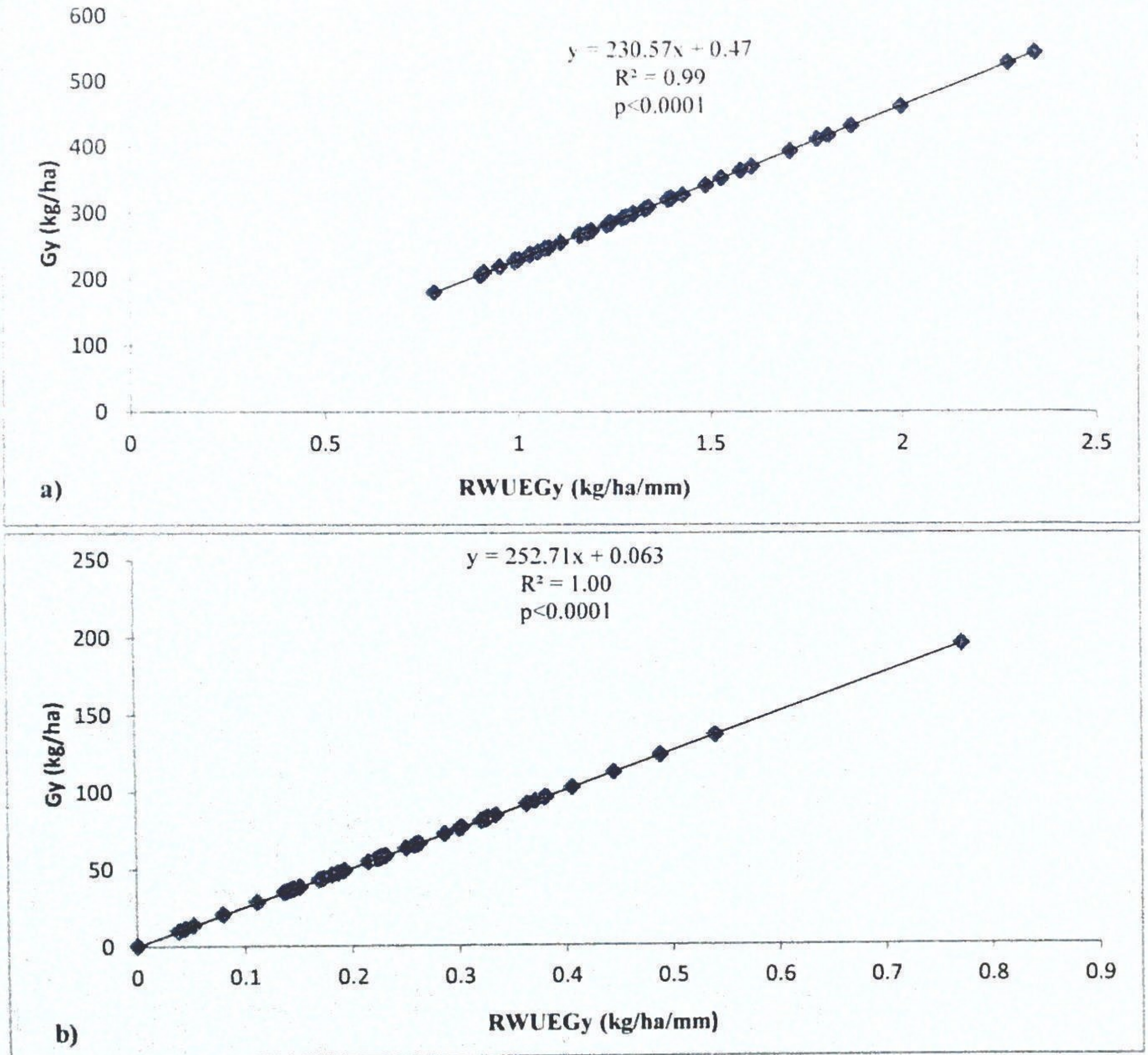
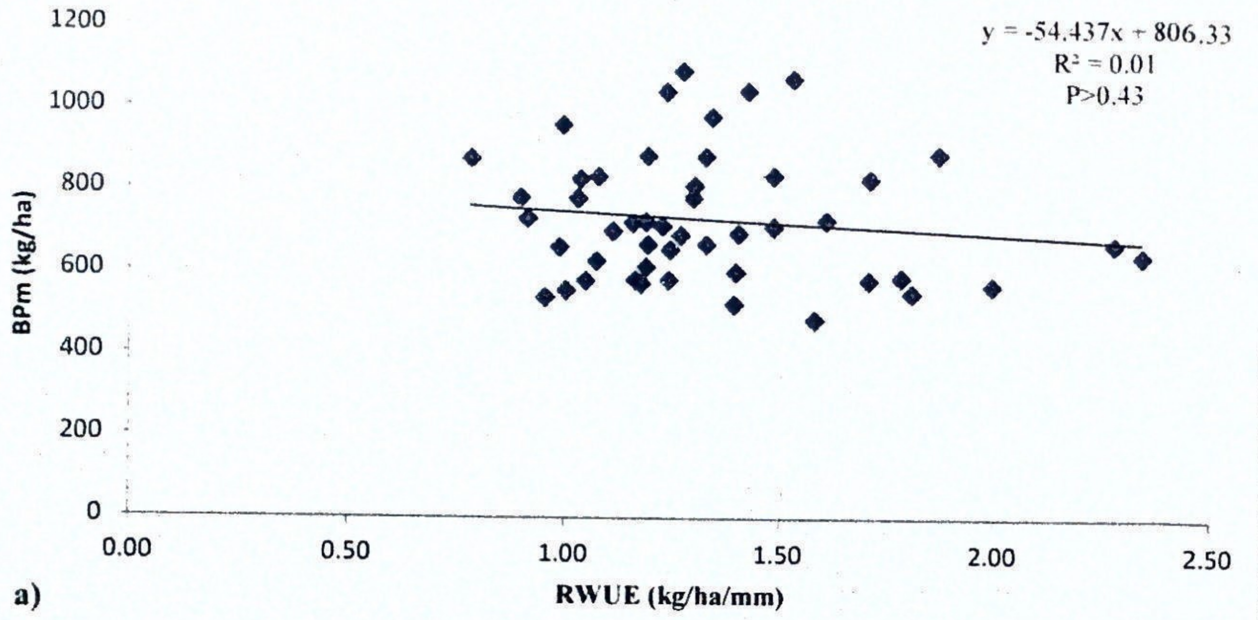


Figure 4.14: Relationship between grain yield (Gy) with rain water use efficiency (RWUE) during the first (a) and second planting date (b). Where: First planting date – 04 January 2016, second planting date – 04 February 2016.



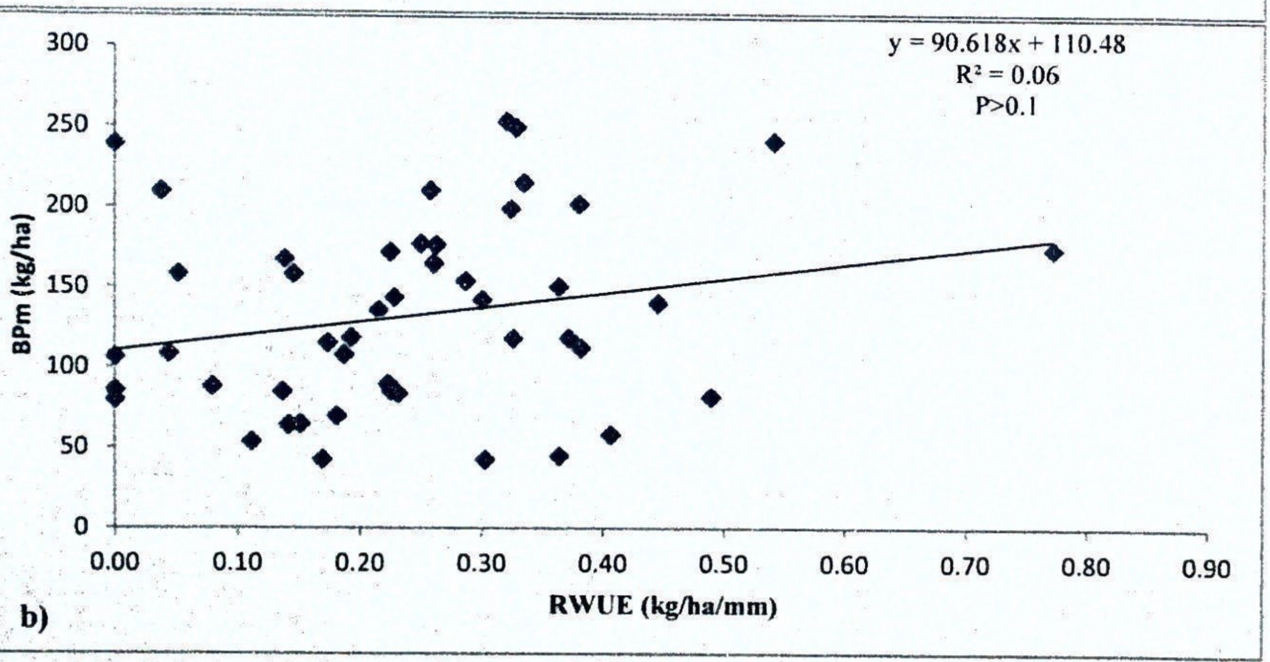


Figure 4.15: Relationship between biomass yield (BPm) and rainwater use efficiency (RWUE) during the first (a) and second planting date (b). Where: First planting date – 04 January 2016, second planting date – 04 February 2016.

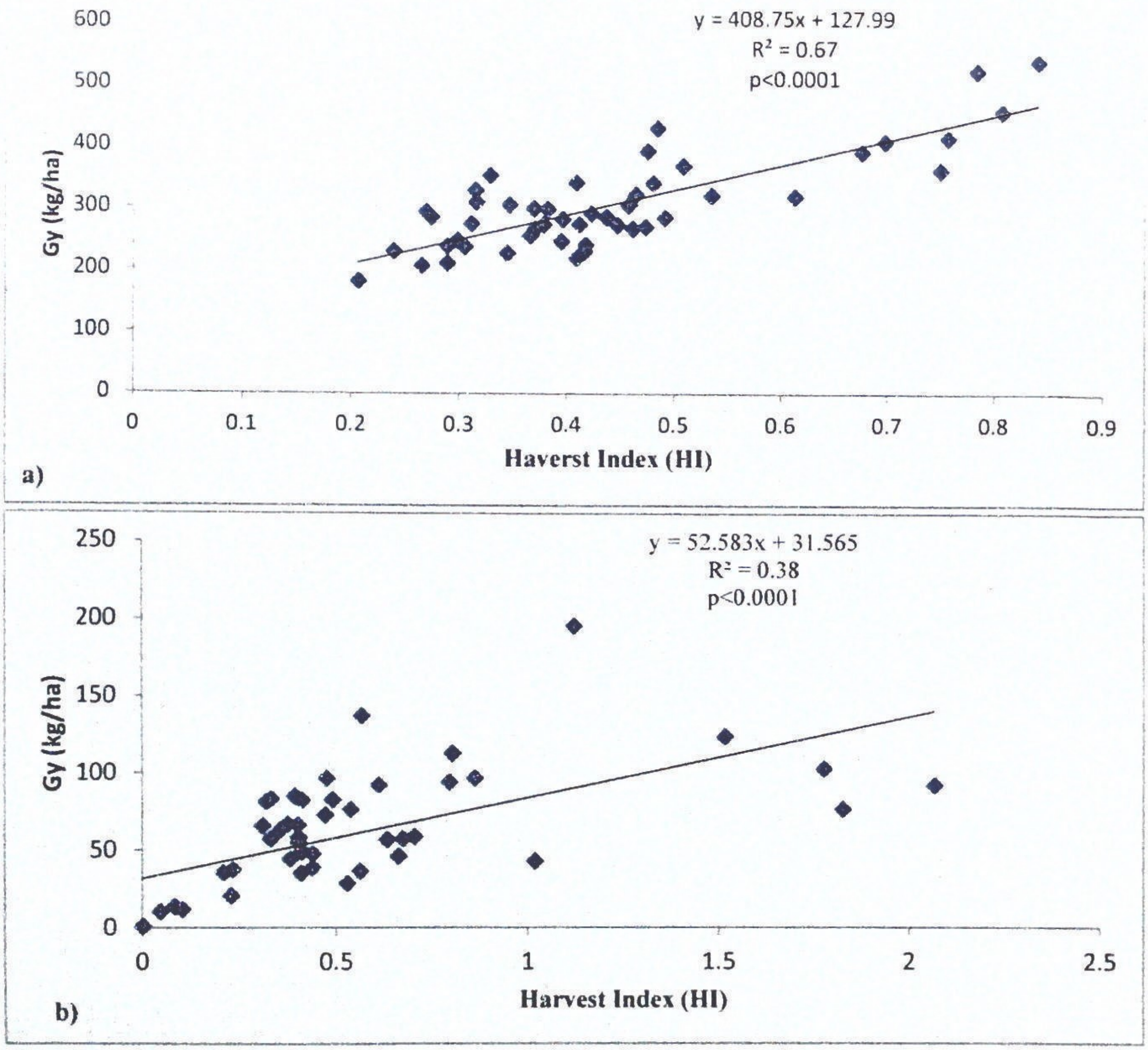


Figure 4.16: Relationship between grain yield (Gy) and harvest index (HI) during the first (a) and second planting date (b). Where: First planting date – 04 January 2016, second planting date – 04 February 2016.

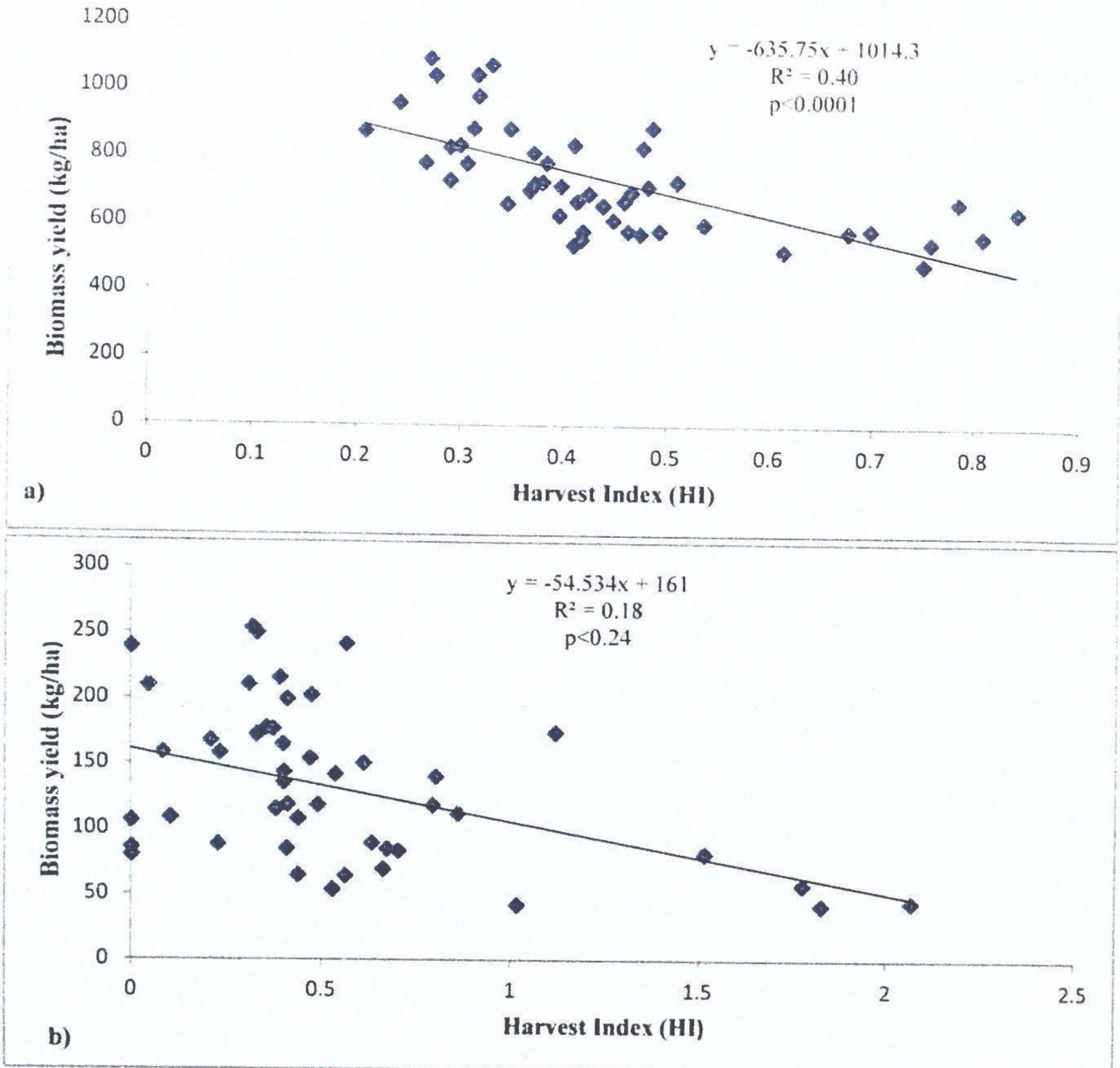


Figure 4.17: Relationship between biomass yield at physiological maturity (BPm) and harvest index (HI) during the first (a) and second (b) planting date. Where: First planting date – 04 January 2016, second planting date – 04 February 2016.

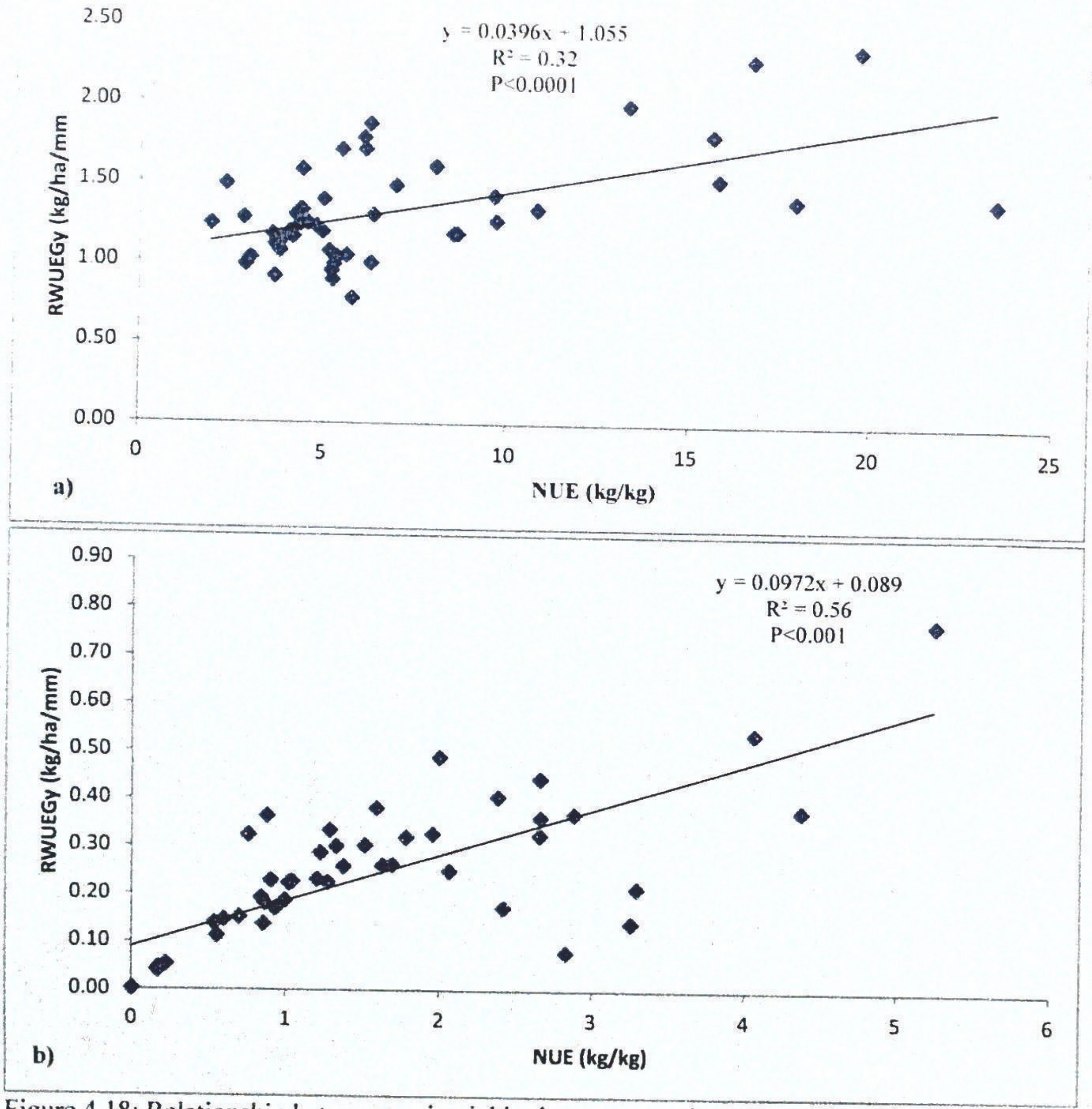
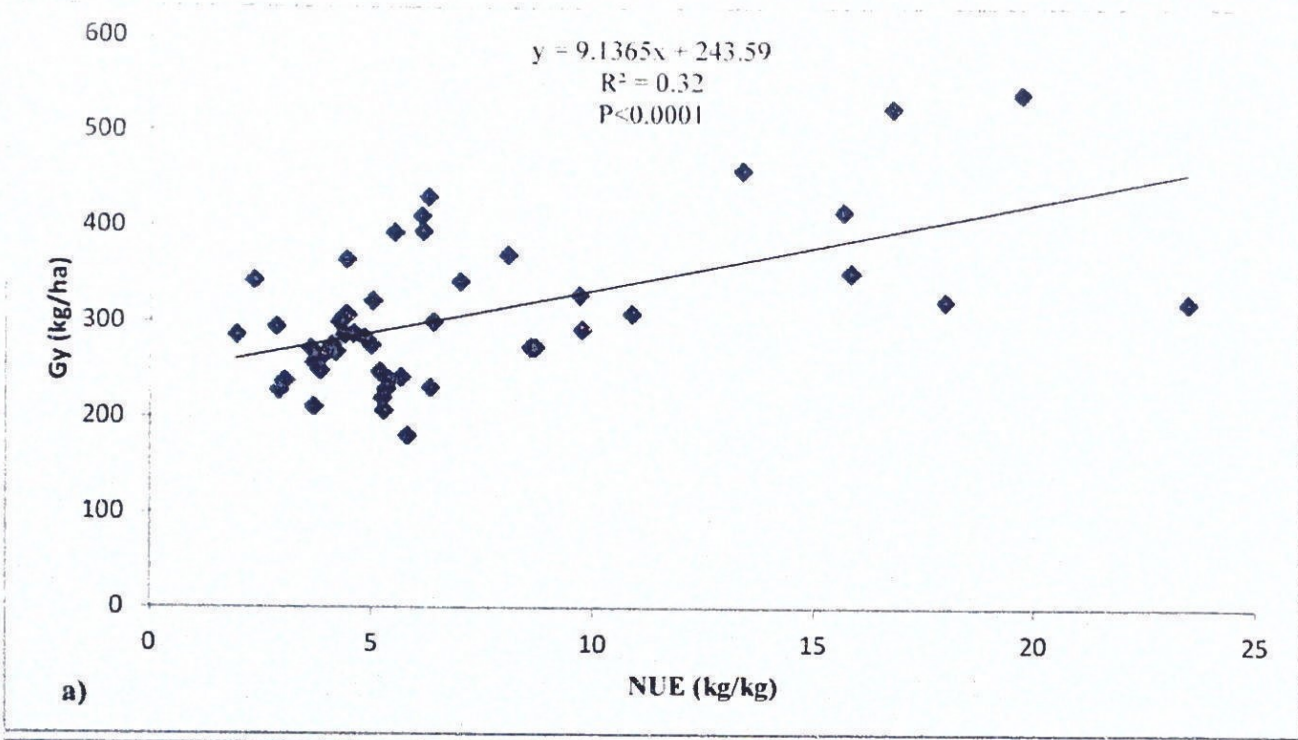


Figure 4.18: Relationship between grain yield rainwater use efficiency (RWUEgy) and nitrogen use efficiency (NUE) during the first planting (a) and the second planting date (b). Where: First planting date – January planting 2016, second planting date – February planting 2016.



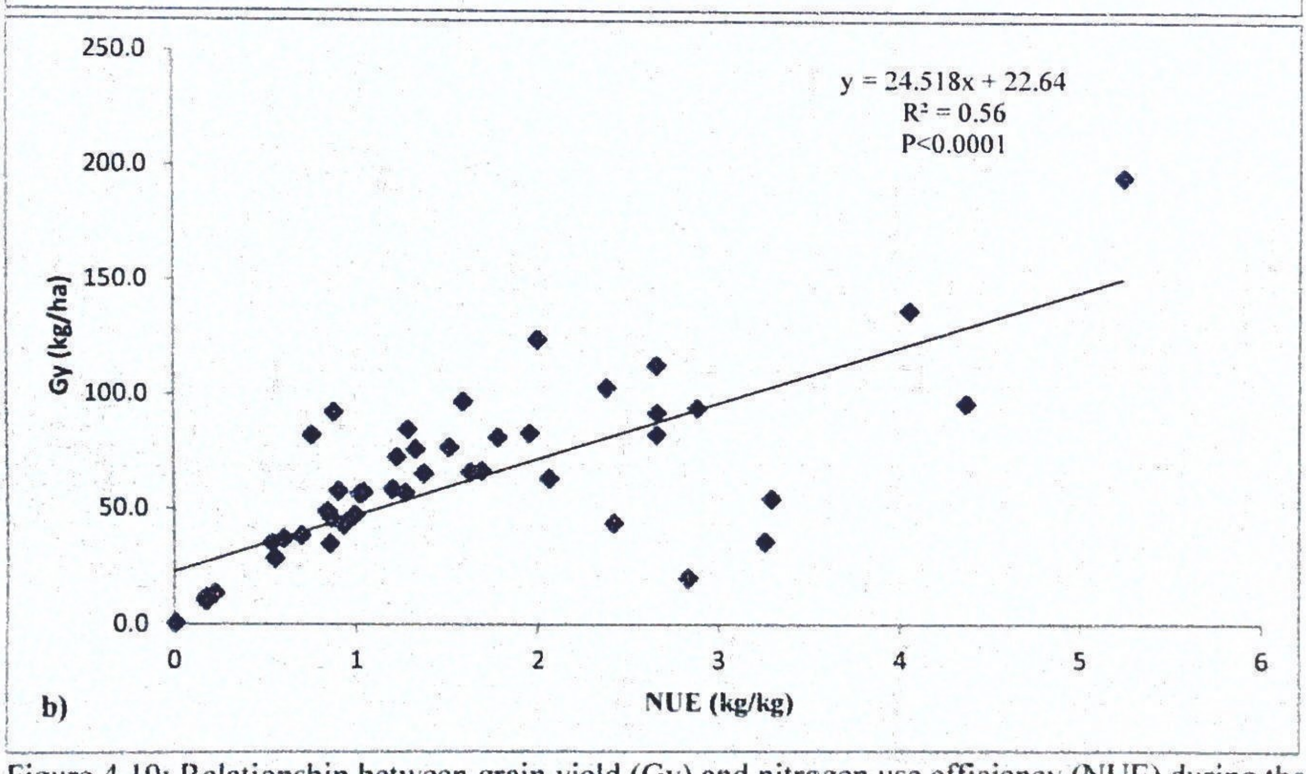


Figure 4.19: Relationship between grain yield (Gy) and nitrogen use efficiency (NUE) during the first planting and second planting date (a) and (b). Where: First planting date – 04 January 2016, second planting date – 04 February 2016.

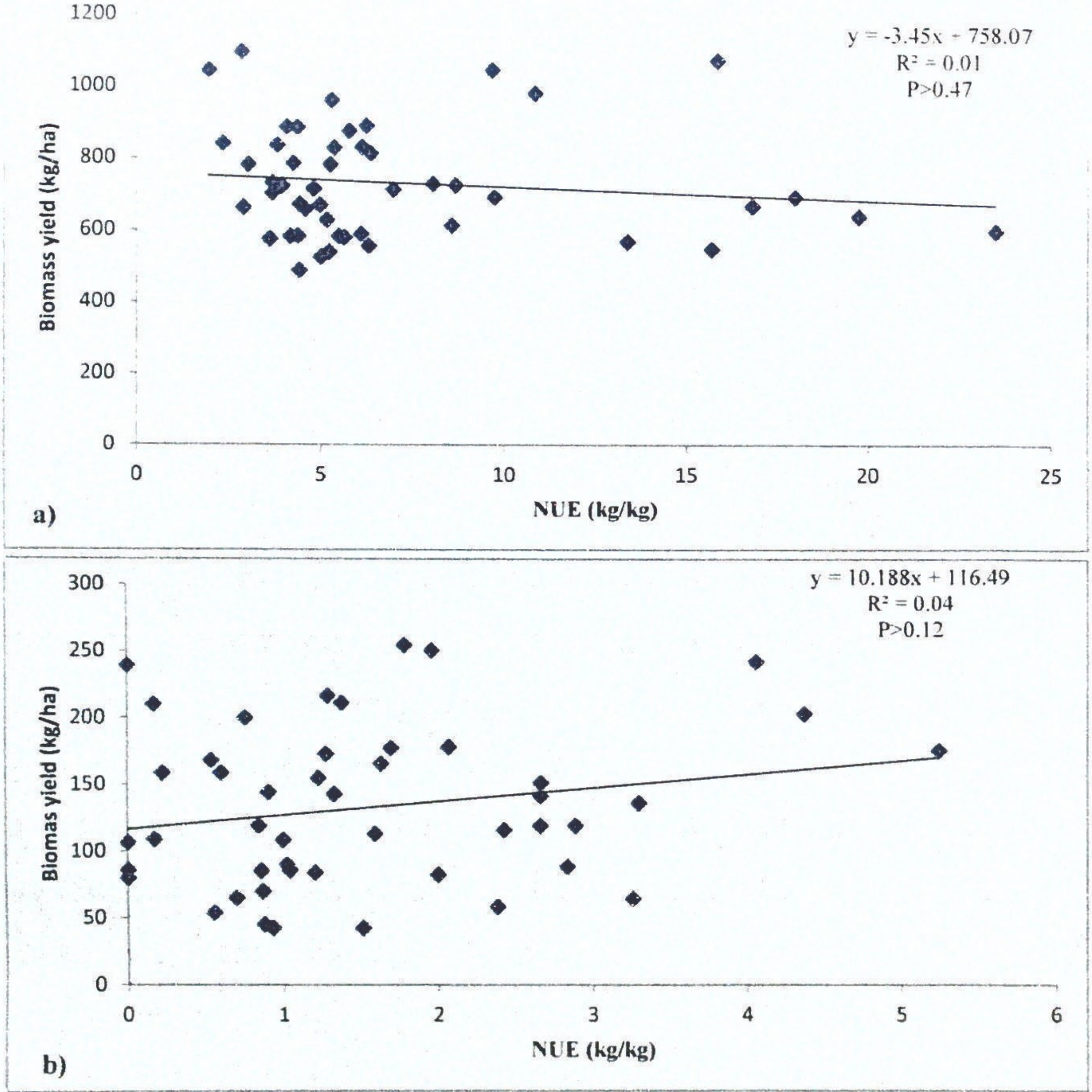


Figure 4.20: Relationship between biomass yield at maturity (BPm) and nitrogen use efficiency (NUE) during the first (a) and second planting dates (b) respectively. Where: First planting date – 04 January 2016, second planting date – 04 February 2016.

CHAPTER FIVE

DISCUSSI ON

5.1 Effect of planting date, plant population and varieties on morphological characteristics of sorghum.

5.1.1 Plant height

Plant height was significantly affected by planting dates, plant population and varieties. Early planted plants grew taller with thicker stem diameters while late planted ones showed stunted growth with thin stems. The results may be attributed to growing conditions like day length and also management condition like early planting and abundance of resources. Thus the conditions were favorable to early planted crops and unfavorable to late planted crops resulting in stunted and thinner crops. Reduction in plant height exhibited by late planted crops can be associated with unfavorable weather conditions such as low temperatures towards the end of the growing season and during crop maturity. As adaptation strategy, when the growing period is limited plants assimilate and mature faster in order to avoid unfavorable conditions resulting in stunted and thinner plants (Ismail & Ali, 1996; Moosavi *et al.*, 2012;). Jafari (2010) also showed that late planting led to a decrease in plant height as well as stem diameter in millet. However, Hadebe (2017) carried a study in South African climatic conditions found that; late planted sorghum varieties tend to grow taller. Longer and thinner shoots were associated with lower biomass accumulation under severe water stress for the late planting date. The difference in the results may be due to the type of the climate experienced in those two locations and the different type of varieties of sorghum used.

With respect to plant population, sorghum planted at higher population tends to grow taller than when planted at the lowest population. The tall plants observed under high plant population may be the results of inter plants competition for sunlight hence the plants try to outcompete each other by growing taller to reach for maximum light. Several studies (Miko and Manga, 2004; Kiniry, 1988) observed similar tendency of plants growing taller under high plant population with lower light level and greater inter plant competition for light resulting in taller and tender plants. Imam and Ranjbar (2000) suggested that the increase in plant height as plant population increases was associated with increase in inter- plant completion over radiation and disruption of growth regulator balance. Reduction in light dispersion into the middle and lower strata of the canopy due to high plant population decreases auxin decomposition and consequently plant height.

The three varieties used in this study (Segaolane, PSL985028 and PSL98505) presented a varying range of morphological characteristics. This shows that the varieties used in this study could be distant relatives as they showed no similarities in morphology during growth as the effect on plant height was significant. Variation in plant height among the varieties may be associated with different genetic make-up of the plant species. Ayub *et al.* (1999) observed difference in plant height among varieties and attributed the differences to genetic make- up of the crop. Similar results were also obtained by Bahar *et al.* (2015) who carried a study on sorghum and reported different plant height among the varieties which could be the results of genetic factors within the varieties.

5.1.2 Stem diameter

Early planted sorghum varieties tend to have thicker stem diameter as compared to those planted late; thicker stems during the early planting date maybe due to favorable growing conditions, adequate amount of water and maximum day length during the full growing cycle. Moosavi *et al.*

(2012) concluded that reduction in stem diameter exhibited by late planted crops can be associated with low temperatures which are experienced when the crops were reaching their maturity thus leading to early assimilation and quick maturity of the plants in-order to escape the cold period.

The results revealed that, the effect variety had significant differences in stem thickness for both planting dates as PSL985050 had the thickest stem followed by PSL985028 and then Segaolane with the thinnest stem. This may be related to genetics of the varieties as some are fleshy hence thick stems; among the planted varieties PSL985050 was fleshier than Segaolane and PSL985028. Considerable variation among the varieties was observed on stem diameter by Konuskan (2000) and also found out that even under the same environmental and management condition the varieties recorded varying stem thickness.

However, a decrease in stem diameter as population increases was revealed on this study, which could mean that the plant population had a negative effect on all planted varieties. The highest stem diameter was observed at the lowest planting population of 20 plants per m^2. The decrease may be associated with inter specific competition on resources and hence lessen photosynthetic capacity of the crop, assimilate production and its partitioning and thus cause a decline in stem diameter. Zand and Shakiba (2013) noted that reduction in stem diameter as plant population increased in sorghum can be linked to decline in assimilate allocation as well as inter-plant competition. Konuskan (2000) and Mobaser *et al.* (2007) also reported decrease in stem diameter with increasing population may be due to inter plant competition.

5.1.3 Number of tillers

The development of tillers is an essential characteristic that affect the accumulation of biomass and as well as grain yield in many cereal crops. The intensity of tillering is a varietal characteristic which can be caused by environmental factors, management practices or the crop genotype. Planting date and varieties had an effect on the number of tillers produced as varieties planted late produced no tillers as compared to those planted early. When sorghum is planted late, its growing period will be limited as the growing season shortened; this then means the plant does not reach a stage where it could produce tillers. In this study early planted Segaolane produced more tillers as it had the capability to compensate for yield especially at lower densities by producing tillers while the other varieties do not have the highest tillering mechanism.

Similar results were reported by Shamme et al. (2016) where number of tillers differs among sorghum varieties planted at different planting date which are also due different genetic makeup of the varieties. Bruns and Horrocks (1984) indicated that a varied range in tiller number exists in grain sorghum depending on varieties and growing conditions; therefore it means that number of tillers is highly affected by the genotypic effect. Ishaq (1996) also observed significant differences on tillers produced when different varieties were managed under same conditions and also noted tillers are initiated at leaf stage and variety differ in their tillering ability.

Like most crops in the Gramineae family, sorghum has the ability to grow tillers that can also be productive under a suitable environment. Tillers development depends mostly on the availability of water supply, planting season and plant population. The results of this study revealed that an increase in plant population resulted in fewer tillers. The highest average number of tillers of about 1.3 was obtained at the lowest plant population while the lowest average number was 0.5

at the highest plant population. The high number of tillers in the lowest plant population may be due to enough space between the plants in such that the tiller experience minimum competition for resources as compared to high population where there is high competition for resources hence reducing the stimulation of tillers. The results are line with those of Zand & Shakiba (2013) who reported the highest number of tiller of 3.18 with low density. Mosavi *et al.* (2009) also reported that an increase in plant population results in a decrease in number of tillers due to insufficient penetration of light through canopy. Other studies in sorghum by Dijanaguiraman and Ramesh (2013); Mahmoud *et al.* (2013); Snider *et al.* (2012); Mosavi *et al.* (2009) reported similar results where increase in density per unit area reduced tiller number.

5.1.4 Number of leaves

One of the most important plant growth parameter is the leaf which is the primary part of photosynthesis in plants; therefore it is assumed that a plant with more number of leaves would perform better in photosynthesis subsequently having a higher yield. The number of leaves between the varieties planted at different dates and plant populations was significantly different. Early planting resulted in more leaves produced while late planting resulted in reduction in number of leaves. The reduction in number of leaves in the late planting may due to inappropriate planting date which caused the plants to produce fewer leaves as growth and development of the plant is inhibited by poor growing conditions. Similar observation on sorghum were made by Azrag and Dagash (2015) who reported that, planting date had a significant effect on number of leaves which may be activated by favorable conditions during the vegetative growth. Hadebe (2017) reported lower average leaf number when sorghum is planted late under climatic conditions of Pietermaritzburg, South Africa due to irregular rainfall during the late planting season.

Plant population had a negative effect on the number of leaves; with an increase in plant population resulting in lower number of leaves and vice versa. Competition for nutrient, water and sunlight could be attributed to the decrease in plant leaf as plant population increases in the late planting. This may be due to the fact that high population resulted in fast leaf senescence, increased leaf shading and decline in net assimilation of the crop. The results confirmed the findings by Miko and Manga (2008) in which highest leaf number was obtained from the lowest plant population. Segaolane had more leaves as compared to PSL985050 and PSL985028. PSL985050 and PSL985028 varieties had the lowest number of leaves because they experienced low leaf development and retention during the hot days of the growing season as compared to Segaolane which seemed to withstand the hot period better. Similar results were found by Hadebe (2017) who reported variation on number of leaves among sorghum varieties which was attributed by genotypic differences.

5.1.5 Days to 50% flowering and maturity

Planting date, plant population and varieties influenced the number of days to 50% flowering and maturity. During the early planting date the day length was very long and the observation showed that flowering was highly influenced by day length. That was because during the first planting date flowering was at its maximum and in the second planting date, flowering was at its lowest due declining in day length as the winter season approach. Most cereal start flowering when the day length shortens; thus in this study the crops planted early took long to initiate flowering as compared to those planted late. Reduction in number of days to flowering and maturity as planting date was delayed may be attributed by shorter day length which caused the plants to grow faster in-order to escape the cold season. The results are consistent with those of Conley and Wiebold (2003) who explained that the decrease in number of days to flowering which lead to early maturing as planting date was delayed was due to slow emergence and less rapid accumulation of heat units as compared to early planting dates. Similar results were also observed on sorghum by Bhosale (2012) who reported a decrease on number of days to flowering with late planting date. Decline in temperature during flowering and grain development as well as shorter day length as the winter season approaches during the late planting date resulted in plants flowering early and maturing faster to escape harsh conditions. Pauli *et al.* (1964) also reported similar results with decrease in number of days to maturity as planting date was delayed.

The results showed that, at high plant population number of days taken by the plants to flower increases. That may have been linked with limited resources due to inter-plant competition as high plant population encourages inter-plant competition. However the results were not significantly different. In contrary Zand and Shakiba (2013) reported that high plant population reduce days to 50% flowering of sorghum which was more likely to be caused by inter-plant completion for resources hence early flowering to avoid plant resources starvation. Regarding days to maturity, the influence of plant densities was not significantly different though plants in the lower density matured a bit earlier than those in the dense and medium population. Delayed maturity in the lower densely population was associated with low inter-plant competition as compared to high population as such plants planted at lower plant population. In contrary, Tabo *et al.* (2002) reported that densely planted sorghum matured faster than those widely spaced.

Days to 50% flowering and maturity hastened for all the varieties during late planting in order to escape both pre and post-anthesis water stress and the cold period. This resulted in early flowering, decrease grain and biomass yield. Segaolane reached flowering earlier than other varieties but reached maturity at almost the same time as PSL985050. The delay in maturity for

Segaolane may be due to slow seed filling and development of the variety. PSL985050 and PSL985028 reached 50% flowering almost at the same time but PSL985028 took longer period of time to reach 50% maturity. These differences are generally due to the genetic make- up of the individual variety because PSL985050 and PSL985028 are early maturing while Segaolane is a medium maturing variety. The results corroborate with results of previous study by Abdalla (1991) who observed varietal significant difference on number of days to reach 50% flowering and maturity.

5.2 Effect of planting date, plant population and varieties on biomass production at different growth stages of sorghum.

The potential yield of a crop is reliant on its biomass production, which is related to the total above ground biomass production. Planting date, plant population and varieties had both positive and negative impact on sorghum biomass production. The highest biomass was recorded on the plants planted early while the lowest biomass was recorded with late planted plants. The differences observed between the planting dates could be attributed to climatological contrasts such as temperature and day length. During the early days of planting, the temperatures were normally high and the day lengths were long as compared to the late planting whereby temperatures start to be cooler and day length was gradually reducing. Freeman *et al.* (1973) suggested that decline in biomass production in late plantings was due to the shortened growing season forcing plants to grow faster to escape unfavorable conditions such as decrease in mean temperatures as the next season approached. Several researchers (Broadhead, 1972; Gascho *et al.*, 1984; Ferraris and Charles- Edwards, 1986) reported consistent reductions in biomass yield of sorghum across an array of environments due to late planting. According to Hadebe (2017), late planted sorghum tends to grow tall with thinner shoots which were associated with lower biomass accumulation. Mossavi *et al.* (2012) reported similar results with decline in maize biomass as planting date is delayed due to temperature effect.

Biomass production is dependent on the radiation use efficiency and light interception and the latter is defined by the architecture of the canopy, as well as plant population (Byrt, 2011). An increase in biomass as plant population decreases to medium low density for Segaolane variety was pronounced in all growth stages except for vegetative stage where biomass production increase with the increasing plant population. The increase in biomass as plant population decrease may be due to the fact that the plant were well spaced and therefore had access to enough resources hence lead to well-developed plant with broad leaves and thick stems thus increase in biomass production.

The effect of plant population was significant yet not consistent on biomass at different growth stages. At the vegetative and physiological stage, biomass was increasing as plant population decreased. However biomass at booting and flowering was affected by increase in plant population. The non- consistent increase of biomass across plant population fell in line with the report by Wondimu (2004) that dry matter is directly reliant on the interception of occurrence radiation by the crop canopy and the competency with which is used to yield dry biomass. Buah and Mwinkaara (2009) and Tabo *et al.* (2002) argued that increase in plant population resulted in increased biomass production which was only consistent with the results obtained at vegetative and physiological maturity.

Variation in biomass was also affected by varieties as varieties of the same species may not grow to the same extent even though given in the same environment, population or planting date. The three varieties differ in biomass at different growth stage. Segaolane produced the highest biomass at the vegetative and flowering stages and PSL985050 produced the highest biomass at booting and physiological maturing while PSL985028 produced the least biomass in all growth stage. The low production of biomass by PSL985028 could have been caused by its reduced height and less leaf production. Increase in biomass for PSL985050 may be due to thick stems and fleshy broad leaves. The results agree with Tekle and Zemach (2014) in sorghum who reported that varieties had significant effect on biomass production.

5.3 Effect of planting date, plant population and varieties on yield components

Sorghum yield depends on several components such as panicle length, panicle thickness, panicle weight, 1000 seed weight and harvest index (HI). The results from the study showed that yield components were significantly reduced with delayed planting date. The 1000 seed weight, panicle length, panicle thickness and weight decreased with delayed planting. The exception was recorded on HI which increased with late planting which may be the result of relative decrease in biological yield to grain yield in late planting. The results concurred with those of Paul *et al.* (1964) who conducted a study in sorghum and found that, late planting resulted in reduced number of days to panicle initiation and flowering which may be due to the shortening of day length and decrease in temperature. Caddel and Weibel (1971) supported the results by stating that, as the duration to panicle development reduced, the panicle size, length and weight also declined.

The reduction in yield components when planting date is delayed may be due to early vegetative growth period, lower amount of carbohydrates and decline in translocation transmission to grain hence suppressing development of the crop. Consequently resulted in small sized panicle, decrease in length and thickness hence reduction in 1000 seed grain weight (Hua *et al.*, 2014). In this study the sorghum varieties recorded a higher HI when planted late and in contrast when planted early maize recorded higher HI (Maryam *et al.*, (2013). The effect may be due to different crop species, ecological area of study and plant population. Similar results were obtained in a study on sorghum by Bahar *et al.* (2015) showing a significant influence of planting date on yield components of sorghum where 1000 seed weight, panicle weight and size decreased with late planting. The results agree with those of Bandiougou (2012) who observed that yield components were influenced by planting, the effect of planting date on growth, development and yield of grain sorghum were found to be variable among hybrid maturity group and locations.

A significant effect of plant population on panicle length, panicle thickness and panicle weight was observed as shorter and small panicles were produced with densely populated plants while longer thick panicles were obtained in lower plant population. High competition for plant promoting resources among densely populated plants may have led to shorter small panicle size as compared to widely spaced plants with minimum competition hence longer thick panicles. Miko and Manga (2008) obtained similar results when they observed a reduction in panicle weight as plant population increased. Habyarimana *et al.* (2004) also obtained higher panicle weight in sorghum under low plant densities. Moosavi *et al.* (2013) reported that increase in plant population led to significant reduction in 1000 seed weight and harvest index. The findings are similar to those from our study as high population resulted in decline in harvest index and 1000 seed weight. The reduction may be attributed to inter plant competition for resources such as nitrogen and water. Zand *et al.* (2014) also reported decrease in 1000 seed weight, panicle weight and HI of sorghum with increasing plant population. Increase in panicle weight at lower densities may be due to adequate availability and efficient utilization of water and nitrogen for comparatively less number of plants (Abuzar *et al.*, 2011). Zamir *et al.* (2011) associated low panicle weight at high plant population with less availability of photosynthesis and high rate of respiration as a result of enhanced mutual shading.

Significant effect of varieties on some of the yield components was observed as this study showed that panicle length and panicle weight differed significantly among the varieties. The longest panicle and the highest panicle weight were recorded for Segaolane while PSL985050 and PSL985028 had the shortest panicle with the least panicle weight. The difference in panicle weight among varieties is associated with the difference in grain weight, dry mater accumulation and water use efficiency (Chohan *et al.*, 2003; 2006; Mehmud *et al.*, 2003). Panicle thickness, 1000 seed weight and harvest index (HI) were not significantly influenced by varieties. The results for HI and 1000 seed weight are in contrast with observations made by Tekle and Zermach (2014) who reported that 1000 seed weight and HI varied mainly due to different plant population and crop varieties used in the research. Studies by Koycu and Kurt (1997) and Keshin *et al.*, (2005) indicated that differences in 1000 seed weight among sorghum varieties were associated with differences in genetic traits which are also contrast with the results of our the study.

5.4 Effect of planting date, plant population and varieties on grain yield of sorghum.

Low grain yields were obtained with plants planted at low plant population in both planting dates, while delayed planting date greatly reduced grain yield. Low grain yield at low plant population was a result of few plants stand per unit area. The conditions during the second planting date was not conducive for optimum growth and development of sorghum because of short day length leading to shortening days to maturity and decline in temperatures hence reduction in grain yield. Sorghum like other cereals does not perform well when growing during the short day season as it needs maximum light for assimilation and partitioning of the assimilates. The results confirmed those of Bandiougou, (2012) who reported decrease in sorghum yield with later planting where effect of planting date on sorghum yield changed with locations based on environmental conditions prevailing during the crop growing period.

An average mean yield of 375.48kg/ha was obtained with early planting while an average of 62.51kg/ha was obtained with late planting. Similar trends of yield results were obtained by Bahar (2015) who found a significant influence of planting date on sorghum yield where a significantly higher yield was obtained with early planting as compared to a relatively lower yield recorded with late planting under the climatic condition of Darfur, Sudan. The differences in the yields could be associated with difference in rainfall distribution during the two planting dates, the different locations and the type of sorghum varieties used.

Previous studies indicated that late planting can result in reduction in yield of many crops (Egli & Comelius, 2009, Sindelar *et al.*, 2010) and significantly reduce growth and quality of most crops (Bauer *et al.*, 2000) while others found the effect not significant (Baumhardt and Howell, 2006). Delayed planting is associated with inadequate photo-assimilates production in plants that might influence the overall nutrients partitioning from the source (leaf, roots, stem) to the sink (seeds) (Schiltz *et al.*, 2005) thus resulting in remarkably reduced seed yield.

Plant population had negative effect with agronomic growth of crops, as sorghum plants planted at low plant population produced in low grain yield/hectare. The highest yield of 250kg/ha were recorded with high plant population of 50 plants/m² which translated into more head per unit area as compare to yield of 155kg/ha recorded in low plant population of 20plants/m² having lower total number of heads per unit area. The results concur with those of Moosavi *et al.* (2013) who reported the highest total grain yield from plant population of 50m² and lower total grain yield from population of 12plants/m^2 under climatic conditions of Sistas, Iran. Grain yield per unit area at 50plant/m^2 increase as a result of high biological yield per unit area as a consequence of more plants per unit area. Westage *et al.* (1989) added that such results may be caused by the delay in canopy closure which reduces interception of seasonal incident solar radiation. Similar results were also observed by Zand et al, (2014) who reported increased sorghum grain yield with high plant population of 20plants/m^2 as compared to a low population of 8plants/m^2 due to more panicles per unit area. In contrary Weidenfeld and Matocha (2010); Grimes and Musick, (1960); Stickler and Wearden, (1965); Staggenborg et al., (1999) carried studies under various climatic condition and found out that different plant population had no significant effect on grain yield.

Variation among the varieties on final grain yield was significant with Segaolane producing the highest average yield of 250kg/ha followed by average yield of 180kg/ha and155kg/ha for PSL985050 and PSL985028 respectively. The increment in yield recorded for Segaolane may be attributed by its ability to produce productive tillers that resulted in more heads per unit area hence increase in grain yield. Grain yield advantages for Segaolane may also be associated with increase in yield parameter such as panicle length (PL) and panicle weight (PW). Several studies reported similar results where there was a significant difference among sorghum varieties in grain weight (Chohan *et al.*, 2003; 2006; Mehmud *et al.*, 2003; Yousef *et al.*, 2009). Yield potential differ among varieties as research on local varieties reported Segaolane to have yield potential of 1-3tons/ha under adequate rainfall coupled with appropriate planting date and plant population while PSL985050 and PSL985028 reported to have yield potential of 2.5-3.0 tons/ha (Tsuaneng and Maphanyane, 2000). The huge difference in yields among the varieties could be the result of different growing mechanism among them.

5.5 Effect of planting date, plant population and varieties on RWUE

Planting date for sorghum in Botswana is contingent on when rainfall become well established and usually varies from year to year and from region to region. The results showed a decrease in RWUE during the late planting date while early planting resulted in increased RWUE. Reduction in RWUE in the late planting could be due to stunted and weak plants with weak roots architecture to be able to absorb water down the soil layer and as such lot of water were drained into the soil without been used. Early planted crops have an advantage of an extended productive period that translates into an increase in seed yield (Panda *et al.*, 2004; Awasthi *et al.*, 2007). Therefore, the decrease in RWUE as the planting date was delayed could be the reason of the high reduction in seed yield of the crop due to shortened productive phase compared to the consumptive water use.

The results from this study showed lower RWUE ranging from 2.9 to 3.4kg/ha/mm at physiological maturity and RWUEGy ranging from 1.2 to 1.6kg/ha/mm during the early planting while in the late planting, RWUE obtained at physiological maturity was 0.04kg/ha/mm and RWUEGy was 0.03kg/ha/mm. The RWUE values are lower than those found by Hadebe (2017) who conducted a study on sorghum under rainfed conditions in Pietermaritzburg, South Africa and reported RWUE of 25.2kg/ha/mm at physiological maturity with early planting while grain RWUE was 8.3kg/ha/mm. In the late planting Hadebe (2017) reported RWUE of 23.1 at physiological maturity and 8.7kg/ha/mm for RWUEGy. The difference between the RWUE values may be due different ecological and climatological characteristics of the locations and the varieties.

The amount of soil moisture stored in the soil profile is mostly influenced by the amount of rainfall during the growing season. Hence, according Mosavi *et al.* (2009) optimizing plant population according to the available soil moisture is a crucial aspect in crop production because increase in plant population can reduce water availability to individual plant leading to reduction in RWUE. In general soil water evaporation is reduced as plant density increases because the larger canopy acted as soil cover. That tends to increase water use efficiency as most of the water lost contributed to dry matter build by transpiration. The results in this study showed a negative effect of plant population on RWUE as an increase in plant population resulted in decrease of RWUE. This can be associated with inter-plant completion which resulted in high consumptive water use and hence decrease in RWUE. A similar observation was made by Karasahin *et al.* (2013) that high population reduces RWUE which was associated with the exhaustion of soil water causing terminal stress which resulted in reduced seed yield hence lower RWUE. Under lower densities, increment in RWUE maybe the results of more rational use of water throughout the growing season. Pandey *et al.* (1988) observed that when pearl millet is planted in high plant population (200 000plants/ha) under rain-fed conditions resulted in high consumptive use and water use efficiency as compared to lower plant density of 100 000plants/ha. These contradicting results may be attributed to different crop species and plant population adopted as well as ecological conditions of the location during the growing season.

The results in this study revealed significant influence of varieties in production of a unit of dry matter or yield per unit amount of water that resulted in widely varying values. Tabo *et al.* (2002) also reported varietal difference on RWUE of sorghum. Singh *et al.* (2008) associated variation between varieties with differentiation in their genetic build-up which affects both morphological traits controlling the rate of transpiration and water absorption by the root from the soil and the physiological functions responsible for photosynthesis to economically harvested plants. Traits that are reported to influence water use efficiency in sorghum include epicuticular wax (Saneoka and Ogata, 1987; Premachandra *et al.*, 1994), root system hydraulic conductivity (Li, *et al.*, 2011) and root vigor (Wasson, *et al.*, 2012). Perhaps varieties which displayed high water use efficiency had the above traits.

Generally in semi-arid conditions, RWUE is often low due to the erratic water supply and varietal variation and that match with the results from the study where varied RWUE was recorded among the varieties. During the vegetative growth, Segaolane used water efficiently as compared to the other varieties; this may be due to the ability of Segaolane to fold its leaves during hot period thus reducing transpiration rate and as such more water is used than been evaporated and this showed the capability of Segaolane to grow under dry conditions.

The trend changed in the booting stage as PSL985050 had the highest RWUE followed by Segaolane and PSL985028. PSL985028 showed high efficient use of water during flowering stage while PSL985050 had the least RWUE. During the physiological maturity, all the three varieties had almost similar RWUE but Segaolane was outstanding in its water efficiency. A significant variation was also noted among the varieties for RWUEgy with Segaolane showing superiority in RWUEgy followed by PSL985050 and PSL985028 respectively. These findings suggest that Segaolane variety could be highly suitable for production under minimum water availability as average yields per crop could be obtained with less rainfall. Chand & Bhan (2002) who reported similar results where different water use efficiency was observed among sorghum varieties. The difference in RWUE of sorghum at different growth stages was due to varying water consumption of water at different stages. The variation in RWUE of sorghum at different growth stages is supported by Porter *et al.* (1960) who stated; sorghum water consumption differ among the stages whereby it was at its lowest at seedling, tillering and ripening and reaches its peak at the booting and grain filling stages.

5.6. Effect of planting date, plant population and varieties on nitrogen use efficiency (NUE) and its components

Time of planting is the non-monetary input which is important not only on ensuring higher crop yields but also to optimize the utilization of applied resources such as nutrients especially nitrogen. Plants planted at different planting dates, plant population and varieties differ in utilizing resources (nitrogen). The results in our study showed that crops planted late had lower NUE as compared to those planted early. Those results are in agreement with Elasha (1997) who reported that the early planted sorghum have significant effect on NUE but the results are in contrast with those of Adam (2015) who found no significant effect of planting date on NUE. These contradicting results may be due to different planting date as well as different crop species. Both nitrogen uptake efficiency (NUPEff) and nitrogen utilization efficiency (NUTEff) decreased as planting date was delayed with similar results observed by Ehadaie and Wainess (2001) who reported that both early and late planted crops turned to extract more nitrogen from the soil but there is less partitioning of nitrogen to grain as compared to those planted at the most ideal date.

In this study a negative effect of plant population on NUE was observed as NUE decrease with an increasing sorghum population. This may be due to high competition between the plants as higher amount of applied nitrogen was up taken by plants per unit area that leads to decline in its efficiency. Reduction in uptake efficiency (NUPEff) was observed at the lowest population with less of total applied nitrogen up taken by plants. An observation was made in that an increase in plant population per unit area resulted in reduction in NUE, as there was an increase in nitrogen utilization (Koochaki *et al.* (1994) and as such plant population has to be adjusted according to the soil fertility potential to support plant growth. Low productivity of crops per area due to further increase in plant population in sorghum was reported by Tabo *et al.* (2002) with regard to competition among the individual plants for growth resources mainly soil nutrients. Zand and Shakiba (2013) also observed that sorghum plant population affect NUE resulting in NUE decreasing when plant population is increasing which may be due to high inter plant competition. At low plant population, NUE increases due to steady N intake and adsorption capacity of the plant.

Generally low NUE is experienced among cereal crops and NUE is normally triggered by nitrogen uptake and utilization. The study showed results where low NUE was recorded among sorghum varieties. NUE differ significantly between the varieties; Segaolane had NUE of 10kg/kg, while 2.5 kg/kg was observed in PSL985050 and PSL985028. Variation in NUPEff and NUTEff were also revealed by the result with Segaolane exhibiting the highest overall biomass which activated the high uptake of nitrogen but lowered its utilization. Feil (1992) also indicated that varieties producing large amounts of biomass seemed to have more NUPEff, which could decrease NUTEff. Despite the low NUTEff as compared to other varieties, Segaolane had the highest NUE. The enhanced NUE for Segaolane may be due to genetic variation such as deep and fibrous roots which were able to absorb N from the lower layer of the soil as stated by (Bohrani and Sarvestani, 2006). Bohrani and Sarvestani (2006) also observed that differences in plant nitrogen accumulation could be due to grain composition dilution effects which show that there is genetic variation in nitrogen uptake between crops and varieties. Most genetic variation in NUPEff are due to morphological differences in root system, root length and diameter as well as biomass accumulation. Cultivar variation in NUE is normally due to the differences in the absorption of nitrate and N remobilization (Van Sanford and MacKown, 1986; Rodgers and Barneix (1988).

5.7 Correlation analysis

In Botswana arable farming largely depends on rainfall as the major source of water in crop production under rain fed agriculture. In this era of climatic change, rainfall has been more erratic and unreliable than before. The changing rainfall pattern has forced farmers to change their planting date and positioning it with the onset of the first rains, which at times is delayed into the late cropping season forcing farmers to start planting late thus resulting in increased crop failure associated with decline in biomass accumulation, HI and grain yield. Given the use of fertilizer to improve crop yields, balancing such nutrient (nitrogen) with the purpose of increasing the proportion of water balance as productive transpiration is one of the best management approaches to increase yield returns and water productivity (Rockström *et al.*, 2010). Therefore correlation analysis was performed to determine simple correlation coefficient between some of the studied parameters during the two planting dates. Strong and significant relationship were observed whereas others showed non- significant positive and negative relationships.

Generally, NUE, RWUEgy, HI and BPm (at second planting) showed a strong highly significant relationship with Gy while a positively but weak correlation was noted between Gy and BPm in the first planting. These traits are important for selection and breeding criteria in improving Gy hence their relationship with Gy will be of paramount importance in crop production. The results on Gy and NUE showed a perfect positive relationship between the two components in both planting dates. The results were in agreement with Buah and Mwinkaara (2009) who reported positive correlation between Gy and NUE in sorghum. Positive relationship between Gy and BPm could be due to that, at the highest population, plant height, and BPm were high as was

Gy. On the other hand BPm was negatively and not significantly related to NUE on the first planting but positively and not significant to NUE in the second planting.

Given the relationship between RWUEgy and Gy, a strong perfect linearly relationship was observed between the two during the two planting date. The results showed that increase in Gy contributed much to RWUEgy as more water was efficiently used. The results also showed a positive but weak relationship between RWUE and biomass at harvest in both planting dates with the first planting date having a very weak relationship as compared to the second one. This weak relationship may be due to the fact that, high biomass was produced in the first planting which may had resulted in high consumption of water hence low RWUEgy. In the first planting date, temperature was high which may have accelerated transpiration as such lead to low RWUEGy.

Regarding the RWUEgy and NUE a positive significant relationship was observed between the two components. According to Mandic *et al.* (2015) NUE is dependent of water availability. In this experiment, water was a limiting factor during the cropping season 2015/2016 and that maybe the reason for lower values of RWUEGy and NUE obtained. The information on NUE and RWUE has not been extensively studied however there are available literatures on the interaction of nitrogen and water. According to Grant *et al.* (2002) and Moser *et al.* (2006) high doses of N coupled with water deficit can result in decrease in maize yield while low or optimum N application coupled with excessive water result in nitrogen leaching. Yared *et al.* (2010) further reported that reduction in low soil moisture can reduces nutrient uptake by roots and prompts nutrient deficiency by lessening the flow of nutrients from soil to root, creating restrained transpiration rates and impairing active transport and membrane permeability. Hence, a close relationship between soil moisture and N availability for plant uptake is observed and further studies required exploring more about the efficient use of the two concepts (Hussaini *et al.*, 2008; Aynehband *et al.*, 2011).

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

6.1.1 Planting date had a significant effect on all the measured parameters of sorghum in which late planting resulted in reduction grain yield (Gy), rain water use efficiency (RWUE), nitrogen use efficiency (NUE).

6.1.2 Among the three studied varieties, PSL985028 had higher reductions in most of the studied variables such as grain yield (Gy) whereas Segaolane was out- performed other genotypes in grain yield (Gy), rain water use efficiency (RWUE) and nitrogen use efficiency (NUE).

There was a linear relationship between rain water use efficiency (RWUE) and nitrogen use efficiency (NUE) even though lower values of NUE and RWUE was recorded. The model can be used in sorghum to predict nitrogen use under water limiting condition.

6.1.3 Plant population had a significant effect on grain yield (Gy), rain water use efficiency (RWUE), nitrogen use efficiency (NUE). Grain yield (Gy) was high at the highest plant population of 60 000plants/hectare while RWUE and NUE were high at medium low density (30 000plants/ha).

6.2 Recommendations

6.2.1 January planting is recommended for farmers as promising yields were obtained in January as compared to February planting

6.2.2 Based on relative performance of Segaolane on nitrogen, rain water use efficiency and grain yield it is therefore recommended for research by breeders aiming at improving these traits for the benefits of the farmers.

6.2.3 Plant population of 30 000 plants/hectare is the most appropriate population so it is recommended for farmers for better utilization of resources.

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