Planting date, water availability and plant density effects on dry bean production (*Phaseolus, vulgaris* L.)

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Crop Science, School of Agricultural, Earth and Environmental Sciences, in the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the Water Research Commission (WRC) of South Africa through WRC Project No. K5/2272//4 ‘Determining water use of indigenous grain and legume food crops’.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: Professor Albert T. Modi

Date: 13 March 2017

DECLARATION

I, Nokuthula Cherry Hlanga, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed: Nokuthula Hlanga

Date: 13 March 2017

ABSTRACT

Dry beans (*Phaseolus vulgaris* L.) form an important part of the agricultural system in southern Africa. Small scale farmers use the crop in crop rotation or intercropping with another staple crop, maize. Although commercial seeds are not retained for use from one season to another, small-scale farmers do keep grain seed for reasons of germplasm preservation and economic reasons. It is important to understand the effect of some of the major agronomic factors on seed quality and crop performance in a situation where farmers retain seed from one season to another without using special seed storage methods. The objective of this study was to determine the effect of planting date, water availability and plant density on dry bean growth and yield using seed lots from subsequent generations of three dry bean varieties (Mtata, Malelane and Gadra). Dry beans subsequent seed quality varied significantly ($P<0.05$) among varieties, with Mtata, Malelane and Gadra having varied responses when subjected to varied agronomic conditions. All of the seed quality test indices varied significantly ($P<0.05$) among seed varieties, plant density, and water availability. Seed germination, germination velocity index (GVI), and mean germination time (MGT) were higher under rain-fed relative to irrigated conditions. This showed that dry bean varieties could be produced under water-limited conditions and produce relatively good seed quality. Field growth parameters were highly influenced and varied among agronomic management practices (dry bean varieties, plant density, season, and water availability). The three dry bean varieties Mtata, Malelane and Gadra had varied responses when subjected to varied agronomic conditions. Growth and yield parameters differed significantly ($P<0.05$) with planting date and water availability. Planting date (season), and water regime had considerable impact on growth and yield parameters. The highlight of the study was that the agronomic management practices have an important influence on crop growth and yield of dry bean crop. Although seed quality was statistically similar for the initial and post-harvest seed lots. Crop performance was better in the summer early season (January to April) when compared with the late season (May to August). Therefore, this study recommends that seed can be retained from previous harvest without significant loss of quality; however, careful selection of planting date is necessary to get optimum crop performance.

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CHAPTER 1

INTRODUCTION

1.1 Rationale for the Research

South Africa is a semi-arid country with an average rainfall of 450 mm per annum that is lower than the world's average of about 860 mm per annum (Department of Agriculture, 2010). In addition, much of this rainfall is unevenly distributed across the country and highly variable during the season. This often exposes crops to water stress at various plant growth stages often resulting in low yields or crop failure. Climate change projections do not show an improvement in the status quo; climate change predictions indicate that the country will experience physical water scarcity with an annual freshwater availability of less than 1000 m^3 per capita (an index for water scarcity) by 2025 (Rosegrant *et al.*, 2014). Rainfall patterns have changed to being more frequent, extreme and unpredictable (Thornton *et al.*, 2009). Climate change has influenced distribution rainfall pattern they have become spatially and complex, with some areas exhibiting wetter and others drier conditions since 1950 (Thornton *et al.*, 2009).

Disasters associated with climate change are likely to impact the low and middle income countries, especially the vulnerable with poor nutrition, especially women and children, leading to increased food and nutrition insecurity (Papsch *et al.*, 2016). Already there has been an increase in undernutrition, food availability disruptions, decrease in food access, and high occurrence of disease associated with imbalanced diets. The reduced food availability as a result of reduced yields due to low and increasingly erratic rainfall has a negative impact on food availability and affordability (Rosegrant *et al.*, 2014). There is a need to improve productivity of cropping systems under rain-fed conditions to ensure adequate food supply. In South Africa, increasing productivity should also ensure that crops grown are nutritious and can address the dietary requirements of poor rural people.

In this regard, agriculture plays an important role in food security and provides employment opportunities for a large percentage of the population. The trends of decreasing rainfall and increasing frequency and severity of droughts has increased the vulnerability of smallholder farmers who predominantly practice rain-fed farming. Smallholder farmers lack the adaptive capacity to respond to the effects of increasing water scarcity and droughts. Summer crops such as dry bean that depend on summer rainfall are unfavourably affected (Rosegrant *et al.*, 2014). Dry bean is one of the world's main staple crop and an important legume worldwide for direct human consumption (Miklas *et al.*, 2001). It is extensively produced worldwide, chiefly in Latin America and eastern and southern Africa as a food security crop (Miklas *et al.*, 2001). Dry bean is the most important protein source. Its seeds contain 22% protein, 2% fat, 61% carbohydrate (including 5% fibre) as well as adequate levels of all vitamins and minerals (DAFF, 2010).

Prolonged dry spells and erratic rainfall patterns are major limiting factors to dry bean production among smallholder farmers. Prolonged dry spells occur as a result of low and erratic rainfall distribution. This causes soil to dry up, leading to limited water availability for plant growth and development, which can result in physiological stress, including stunted plant growth and low yields (Smith et al., 2010). Mitigating strategies by smallholder farmers under such water limiting conditions include, introducing the production of legumes with good management strategies (Smith et al., 2010) and cultivation of improved high yielding modern varieties adapted to dry areas. These varieties possess morphological, agronomic and physiological attributes that enable them to use the limited water more efficiently (Shiferaw *et al.*, 2014). These varieties have high harvest index, which allows for improved crop productivity under drought stress (Shiferaw *et al.*, 2014).

Agronomic practices such as planting date selection can also assist farmers to manage water stress by ensuring that critical growth stages do not coincide with mid-season dry spells (Mirzaienasab and Mojaddam, 2014). Planting dry bean early is reported to be able to set and fill grain before the start of later season chilling. With early planting, the crop can develop a large canopy cover early in the growing season, thus maximising on transpiration, solar radiation interception, and hence high biomass accumulation (Esmaeilzadeh and Aminpanah, 2015). In addition, optimum plant density is a prerequisite for effective solar radiation capture and utilisation (Joshi and Rahevar, 2014). Nagle and Schneiter, (2009) reported that higher plant densities often translated to high dry bean yields. However, it is always important to determine the point of diminishing marginal returns with regards to increasing plant density in crops. Also, optimum plant densities may vary under different environments as often lower plant densities are recommended for water limited environments.

The yield gaps that exist in dry bean production can be improved firstly by adopting improved agronomic practices. This includes (i) proper variety selection, (ii) selection of appropriate planting dates, and (iii) use of optimum plant densities matched to the growing environment, among others. It is therefore important to develop such agronomic practices and using them to develop best management practices for advising farmers. For the current study, variety selection, planting date selection and plant density were considered as key practices that could be used to improve productivity of dry beans.

1.2 Aims and Objectives

It was hypothesized that planting date selection, water availability and plant density have no effect on growth and yield of selected dry bean varieties. A secondary hypothesis was that management practices have no effect on subsequent seed quality and dry bean performance. The secondary hypothesis was informed by the fact that poor rural farmers often retain seed from previous harvests for planting in subsequent seasons as they cannot afford to purchase seed every season. Therefore, the primary aim of this study was to determine the agronomic performance of three dry bean varieties in response to planting date and water stress under different plant populations.

1.2.1 Specific Objectives

The specific objectives were:

1. To determine the effect of planting date, plant density and water availability on growth, development and yield of dry beans; and
2. To determine the effect of production environment on subsequent seed quality.

References

Department of Agriculture. 2010. Dry beans production guidlines. Department of Agriculture, Forestry and Fisheries (Republic of South Africa)

Esmaeilzadeh, S. and Aminpanah, H. 2015. Effects of planting date and spatial arrangement on common bean *(Phaseolus vulgaris*) yield under weeed-free and weedy conditions. *Planta Daninha*, 33**,** 425-432.

Joshi, S. and Rahevar, H. 2014. Effect of dates of sowing, row spacings and varieties on growth attributing characters of rabi Indian Bean (*Dolichos lablab* L.). *Trends in Biosciences*, 7, 3717-3721.

Miklas, P. N., Johnson, W. C., Delorme, R. and Gepts, P. 2001. QTL conditioning physiological resistance and avoidance to white mold in dry bean. *Crop Science*, 41**,** 309-315.

Mirzaienasab, M. and Mojaddam, M. 2014. The effect of planting date on yield and yield components of two red bean cutivars in azna weather conditions *Indian Journal of Fundamental and Applied Life Sciences*, 4**,** 2231-3345.

Nagle, B. and Schneiter, A. 2009. Effects of seeding rate and row spacing on dry bean production. *Journal of Plant science*, 115, 98-120.

Papsch, R., Howe, T. and Vrabcheva, T. 2016. Comparison of the relationship between socio-economic status and health-related quality of life amongst atopic dermatitis patients across different healthcare systems. *Value in Health*, 19**,** A453.

Rosegrant, M. W., Koo, J., Cenacchi, N., Ringler, C., Robertson, R. D., Fisher, M., Cox, C. M., Garrett, K., Perez, N. D. and Sabbagh, P. 2014. *Food security in a world of natural resource scarcity: The role of agricultural technologies*, Intl Food Policy Res Inst.

Shiferaw, B., Tesfaye, K., Kassie, M., Abate, T., Prasanna, B. and Menkir, A. 2014. Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather and Climate Extremes*, 3, 67-79.

Smith, S. E., Facelli, E., Pope, S. and Smith, F. A. 2010. Plant performance in stressful environments: interpreting new and established knowledge of the roles of arbuscular mycorrhizas. *Plant and Soil*, 326**,** 3-20.

Thornton, P., Van De Steeg, J., Notenbaert, A. and Herrero, M. 2009. The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems*, 101**,** 113-127.

CHAPTER 2

LITERATURE REVIEW

2.1. Importance of dry beans

Dry bean (*Phaseolus, vulgaris* L.) originated from Latin America. *Phaseolus vulgaris* var. Mexicans and var. Aborigines and is distributed from northern Mexico to north-western Argentina. The crop belongs to the genus Pharsalus, family Leguminosae, subfamily Papilionoideae, tribe Phaseoleae, and subtribe Phaseolinae. The genus contains five domesticated species with dry bean being the most important one (*Phaseolus, vulgaris* L.) (Gepts, 2001). Dry bean production differs among the different producing countries. Annual production is about 15 million tonnes with an average yield of 700 kg/ha, with some countries reaching 2000±3000 kg/ha. The largest producers of dry beans is Brazil, Mexico, China and the United States of America (Gepts, 2001). For the year 2010, Latin America and the Caribbean (LAC) and Africa contributed 17.7% of the world dry bean production.

Dry bean is one of the world's main staple crop and an important legume worldwide for direct human consumption (Department of Agriculture, 2010). It is extensively produced worldwide chiefly in Latin America and eastern and Southern Africa (DAFF, 2010). Dry bean is widely produced mostly in developing countries such as east and southern Africa in order to improve food security (DAFF, 2010). Dry bean is an important source of proteins for nearly five hundred million people in Africa and LAC (DAFF, 2010). The seeds contain 22% protein, 2% fat, 61% carbohydrate (including 5% fibre) as well as adequate levels of vitamins and minerals (DAFF, 2010). There are several ways in which this crop can be utilised. This includes consumption as stew, soup, baked beans refried bean paste, fresh salad, dry and cooked products. Dry bean can also be used as animal feed (DAFF, 2010).

2.2 Phenology

Dry bean is an annual warm season crop. There are two commonly known types of growth habits that are observed from the legume, namely: (i) Type I – Determinate growth habit (flowers at end of branches and stem elongation ceases after flowering), and (ii) Type II – Indeterminate growth habit (few short and upright branches, and stem elongation continues after flowering) (Fourie, 2014). The growing period is said to be from 90 to 120 days for dry bean (Food and Agriculture Organization, 2015). Dry bean is a dicotyledonous plant with an apogeal germination whereby the cotyledons are pushed above the ground due to the elongation of hypocotyl (DAFF, 2010). The first true leaf that is formed after the cotyledons emerge from the soil and is a simple or unifoliate and all succeeding leaves are compound (with three leaflets) (Gross and Kigel, 1994).

Dry bean is a self-pollinating plant with clustered white or lavender flowers at different nodes on same plant. Pod and seed colour and seed size and seed, differ according to the market class or variety (DAFF, 2010). Vine type of beans have an overlap of vegetative and reproductive periods due to the continued vegetative growth after flowering (Hill *et al.*, 2016). The crop flowers after two to three weeks with new pods that will be half or fully matured (Kim *et al.*, 2014). Pod development starts off by being green and change to light brown/ tan during maturity. Depending on the variety, each pod has about two to four seeds at full maturity (DAFF, 2010). The crop has two distinct developmental stages, namely, vegetative (v) and reproductive stages (R). Vegetative stages are determined by counting the number of trifoliate leaves (V_1 - V_n) on the main stem commencement above the unifoliate leaf. Reproductive stages are described with flower, pod, and seed characters. Emergence (crook stage) dented as V_E -V_C occurs 7-8 days from planting and this is the stage when the hypocotyl emerges and the cotyledons and unifoliate leaves becomes visible. Early vegetative growth V1 - V3 begins when the third trifoliate leaf is unfolded 10-19 days from planting. Branching and rapid vegetative growth stages starts from V4 -Vn which is from the fourth trifoliate leaf to the n^{th} trifoliate leaf unfolding at 19-40 days from planting. The reproductive stages is represented by flowering and pod formation from R1 which is one open flower per plant which is equal to 100% bloom to R4 at 50% will be at maximum length (mid pod set) 50-59 days from planting. Pod filling and maturity occurs at stage R5 to R8 where R5 is the stage when one pod has fully developed seeds (early seed fill) to 80% of pods having attained mature colour for harvesting (64-94 days from planting) (Prasad and Djanaguiraman, 2014).

Attributed to the fact that the crop has a high variety of seed colours and sizes, seed improvement and variety selection may be based on these traits. In terms of seed colour, red speckled beans are mostly desired by the consumers. Hence, plant breeders and the seed industry should select in favour of these seeds. Large seed size is also desired and should be favoured in seed selection practices. In addition, improved varieties are also characterized by high yield, long season, yield reliability, good seed quality and disease resistance, among other factors (Fourie, 2014).

2.3 Climatic Requirements

2.3.1 Temperatures

Dry beans are an annual crop and thrive under warm conditions. The optimal temperatures are 18 to 24°C. Growth is retarded at temperatures below 20°C while temperatures above 30°C can be detrimental to reproductive growth. Temperatures below 20°C can lead to delayed maturity and cause development of empty mature pods. Above threshold temperatures during flowering can lead to flower abscission and low pod set, therefore, low yield (Smith, 2006).

2.3.2 Rainfall

Dry beans planted under rain-fed conditions require about 400 to 500 mm minimum rainfall for the growing season although an annual total of 600 to 650 mm is highly ideal (Smith, 2006). Dry bean grows well in areas with moderate rainfall; however, the crop does not tolerate humid environments due to pod drop and high diseases incidence (FAO, 2015).

2.3.3 Planting date

Planting date is considered as one of the major agronomic factors in crop production as it influences the balance between vegetative and reproductive growth period (Dube *et al.*, 2014). In order to obtain maximum yield in crop production, it is important to establish the optimum planting date. Planting date also influence other factors such as harvest quality, and eventually crop yield and quality (Joshi and Rahevar, 2014). It has been observed that planting at an appropriate planting date has an advantage over climatic conditions temperatures, humidity and day length (Mirzaienasab and Mojaddam, 2014).

There are different factors affecting planting date selection such as, soil temperature, heavy rains chance that will lead to soil encrustation and restrict seedling emergence. Late season high temperatures during reproductive stage the will cause possible blossom drop. Growing season length affects temperature range during the flowering stage and high temperatures are not suitable. Less rain during harvest and frost damage are not good for the plant. How the bean is rotated in the field in terms of what crop is planted after, may it be cereal crop or legume crop. Rainy weather during harvesting affects dry bean quality (Dube *et al.*, 2014). The optimum planting dates for South African conditions range from November to mid-January in areas where frost occurs, and March and April in frost-free areas (Smith, 2006, DAFF, 2010)

It has been suggested that manipulating agronomic practices such as planting date may also increase crop competitiveness against weeds (Acosta-Gallegos *et al.*, 1996). Early planted dry bean is reported to be able to set and fill grain before the onset of chilling later in the season. In addition, the early planted crop can achieve optimum canopy cover, thus, maximising on transpiration and solar radiation interception which translates to increased biomass accumulation (Esmaeilzadeh and Aminpanah, 2015). However, early planting often expose seeds to a dry seed bed, thus, compromising early establishment (Esmaeilzadeh and Aminpanah, 2015). Thus, proper planting date selection should ensure that the crop avoid stresses at all critical crop growth stages in order to maximize on crop yield (Acosta-Gallegos *et al.*, 1996).

2.4 Agronomy

2.4.1 Soil

Dry beans grow well under warm climatic conditions therefore, require to be planted in warm soils with a minimum temperatures above 13°C with no frost. The depth of the soil should be at least 0.9 m, fertile and well drained. Sandy loam, sandy clay loam or clay loam with a clay content of between 15 and 35% is suitable. Sandy soils are mostly inherently infertile and prone to nematode infestations. Dry beans require a soil pH of 5.8 to 6.5; as they are highly sensitive to acidic soils (pH < 5.2 and acid saturation higher than 10%). Soils should be also be less compacted for optimal growth and not alkaline or poorly drained (Smith, 2006).

2.4.2 Fertilizer requirements

Although dry beans are a legume, it is essential to plant dry beans on previously fertilized soil. Nitrogen application should be 70% during planting and 30% applied as side dressing four weeks after planting. According to Smith, (2006), nitrogen application on dry beans is associated with high seed yield.

Biological nitrogen fixation is the process whereby nitrogen (N_2) from the atmosphere is converted into ammonia (NH_3) in the presence of nitrogenase. Nitrogenase, a biological catalyst found in specific micro-organisms like rhizobium in legumes (Mulongoy and Gueye, 1992). Dry beans have a symbiotic relationship with root rhizobia bacteria inside nodules (Smith, 2006). The bacteria infect the root hairs of bean plant and produce nodules, thereafter, become the host of the bacteria as they get energy from their host plant (Mulongoy and Gueye, 1992). They also take free nitrogen from the soil air and process it into combined nitrogen. With that, the plant gets the fixed nitrogen from the nodules, therefore can synthesize and forage protein. Following senescence or harvest, the fixed nitrogen in the crop residues is then released back into the ground to be taken up by the other crops for their survival, hence providing the soil with nitrogen. For many organic and traditional farmers, dry bean crop rotation with a wide range of crops, referred to as green manure (Mulongoy and Gueye, 1992). Rotating legumes with non-legumes has been shown to have a double advantage of growing the crop with less or no additional nitrogen fertilizer, plus a nitrogen credit for the following non-legume crop. In developing countries where nitrogen is not readily available, this benefit is even more important (Mulongoy and Gueye, 1992).

Biological nitrogen fixation is affected by excessive moisture and waterlogging. These soils reduced root hairs growth of and, site nodulation, and therefore, interfere with normal O_2 diffusion of into the root system of plants. Furthermore, dry soils tend to lower the number of and inhibit nodulation and N_2 fixation. Prolonged exposure to dry soil conditions will result in nodules decay. However, deep rooted legume nodules are able to access soil water from deeper layers of the profile (FAO, 2015).

During extreme temperatures, N_2 fixation is affected in different ways due to the enzymatic processes (Rogers *et al.*, 2009). However, the difference comes in between symbiotic systems and their ability to tolerate high (> 35°C) and low (< 25°C) temperatures (Rogers *et al.*, 2009). Biological nitrogen fixation is dependent on photosynthesis. Very few plants will be able to grow or even fix N_2 under shade conditions. Therefore, dry bean grown under shaded conditions show retarded growth (Mulongoy and Gueye, 1992).

2.4.3 Plant density

Suitable plant spacing is required for high solar radiation interception at different dry bean canopy layers. Thereby increasing photosynthesis rate, and consequently, dry matter production of dry bean (Joshi and Rahevar, 2014)**.** Under commercial production, dry bean plant density is usually 150 000 plants per hectare (Table 2.1). However, for determinate and early maturing varieties, a plant density of 177 000 plants per hectare is recommended when using mechanical harvesting (DAFF, 2010). There was not much information describing optimum planting populations under low input dryland cropping systems. Nagle and Schneiter, (2009) reported that planting dry beans in more closely spaced rows increased yields. However, yield stability was negatively affected. Determinate and indeterminate plants do not respond similarly to the different plant populations (Nagle and Schneiter, 2009).

Table 2.1: Spacing and population of dry beans in South Africa (Adapted from DAFF, 2010).

Type	**Spacing within rows (mm)**	**Spacing between rows (mm)**	**Plant population**
Early maturing determinate	75	750	177 000
Medium and late maturing	75	900	150 000

2.4.4 Irrigation

Irrigation offers the potential for increasing yields and enabling production in otherwise unsuitable soils (DAFF, 2010). In areas where water is unrestricted (not merely supplementary irrigation), the soil should be wetted to field capacity before planting for dry bean production. Under dry bean production soon as the soil is sufficiently dry, seedbed should be prepared planted, and thereafter, the field should not be irrigated until the seedlings have emerged (FAO, 2015). Irrigation scheduling is essential for optimum water use efficiency. For dry beans critical water stress sensitive growth stages are flowering and early pod set (FAO, 2015). Proper irrigation scheduling is essential to avoid over-irrigating and waterlogging as dry beans are sensitive to aeration stress. High soil moisture content can aggravate (Fusarium wilt (*Fusarium oxysporum*).

2.4.5 Crop protection

Crop protection is known as the science and practice of managing plant diseases, weeds and other pests that damage agricultural crops. In which includes dry beans (DAFF, 2010).

2.4.5.1 Weed control

Dry beans competes poorly with weeds due to growing closer to the ground and do not easily overshadow weeds (DAFF, 2010). Efficient weed control is a prerequisite for high dry bean yields. Weed control should start early, soon after seedling establishment to avoid weed roots impeding dry bean root growth and nodulation (DAFF, 2010). During later growth stages, the presence of weeds in the field can hamper mechanical harvesting and also reduce yield quality due to high impurity percentage (DAFF, 2010).

2.4.5.2 Plant diseases control

Pest and disease incidence are a function of seasons, environment and management practices (Muedi *et al.*, 2015). Integrated pest and disease management has been suggested as a strategy for controlling pests and diseases (Muedi *et al.*, 2015). Root and stem diseases often affect crop growth causing yield losses such as Fusarium, Pythium, Rhizoctonia, charcoal rot and Sclerotium root rot (Southern blight). The latter four can also cause seed rotting and damping-off. Root rot can be prevented to a certain degree, but not treated. Fungicides can only be applied to seed as a preventative measure against the diseases (DAFF, 2010). Bacterial brown spot (*Pseudomonas* *syringae* pv. Syringae) is known to be an economically important disease and cause small oval necrotic lesions on leaves (DAFF, 2010). The lesions will have a narrow yellow green zone of the tissue. This disease is transmitted through weed hosts, as it can survive in plant dead matter for one year. The pathogen are spread through wind, rain, and or overhead sprinkler irrigation. Other bacterial diseases are Bacterial wilt (*Corynebacterium flaccumfaciens*)**,** a moderate disease in terms of occurrence, plants cause to wilt, through seeds spread and able to live in the seeds for many years (Figure 2.1). There are some resistant varieties to bacteria brown spot known and the only way to prevent infections is through using disease free seeds and practicing crop rotation with a non-legume crop. Common blight (*Xanthomonas campestris* pv.), Halo blight (*Pseudomonas syringae* pv.) are other known bacterial diseases for dry beans (Hagedorn and Inglis, 1968).

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Figure 2.1: Dry bean plant leaves with bacterial brown spot *(Pseudomonas syringae pv. Syringae)* *(*www.barmac.com).

Angular leaf spot (*Isariopsis griseola*) is a fungus incited foliage disease that cause angular shaped spots on leaves, thereafter, become dark brown or black (Figure 2.1) (Muedi *et al.*, 2015). The fungus Angular leaf spot decreases crop yield. The fungi in infected bean debris mostly seeds is windblown and can overwinter. The fungus thrives in humid conditions but can be controlled with the use of cultural practices such as crop rotation, using pathogen free plant material when planting.

Other fungal diseases are Anthracnose (*Colletotrichum lindemunthianum*), Ascochyta leaf and pod spot (*Ascochyta boltshauseri* Sacc), Powdery mildew (*Erysiphe polygoni*), Rust (*Uromyces phaseoli*), and White mould (*Sclerotia sclerotiorum*) (Hagedorn and Inglis, 1968).

Figure 2.2: Angular leaf spot (*Isariopsis griseola*) (www.barmac.com).

Viral diseases which are known include curly top causing leaves pucker, turn downwards, curly leaves that are yellow. Other viruses are Golden mosaic and Yellow mosaic.

2.4.5.3 Pest and insect control

Pests and insects target different parts of the crop structure (Parrella *et al.*, 2013). There are insects that make holes in the foliage bean leaf beetle, reddish to yellowish-brown beetles and bean leaf beetles consume mostly young leaves (Hagedorn and Inglis, 1968).

2.4.6 Harvesting

Dry beans are harvested when all pods have turned yellow but before becoming dry and pods begin to shatter (DAFF, 2010). When dry beans reach physiological maturity moisture content 50%, but the beans are only harvested at 16% moisture content. However, ideally 15% moisture content is more suitable for harvesting (DAFF, 2010). When the moisture content drops to 12%, seeds may split during threshing. Such seeds are rejected by canners and seed companies as they are difficult to clean without further seed split (DAFF, 2010).

2.5 Seed Quality

Seed quality play a vital role in agricultural production, as poor seed quality limit yield potential and reduces farmers' productivity. Seed quality is a collection of different parameters, namely, genetic quality, physical purity, germination, vigour, uniformity in size, and freedom from seed-borne diseases (Chibarabada *et al.*, 2015). High viability, storability and vigour are important characteristics of seeds (Chibarabada *et al.*, 2015). The two main components of seed quality are seed viability and vigour. Seed viability refers to the potential of a seed to germinate under optimum conditions (Bewley and Black, 2012). While it is useful indicator, especially for seed certification purposes, it does not provide an indication of the field planting value of a seedlot. Seed vigour is defined as the ability of seed to have potential for rapid, uniform emergence and development of normal seedlings under a wide range of field conditions (Bewley and Black, 2012). It thus provides information on the field planting value of a seedlot. Seed viability and vigour tests are done in the laboratory by doing standard seed germination test to predict seed performance under practical conditions and field test of seedling establishment. Factors such as seed age, maturity level at harvest, mechanical injuries, disease infection, and storage environment can influence seed quality (Bewley and Black, 2012).

Seed quality is also affected by agronomic management practices such as planting date, water availability and planting density. This is especially important for smallholder farmers who retain seed for planting in the next season. Limited water conditions have resulted in poor seed set, seed mass and size and shrivelled seed in turn affecting seed quality in rapeseed (*Brassica napus L. var. oleifera*) (Champolivier and Merrien, 1996). Planting during an appropriate planting season and planning density crops are able to utilize the optimum growing conditions for production of good quality seed (Champolivier and Merrien, 1996). Chibarabada *et al*. (2015) reported that water stress on the maternal plant had an effect on seed quality of the progeny thereby, recommended that seed production should be done under optimum stress, stress free conditions.

2.6 Crop Water Use Efficiency (WUE)

According to Condon *et al.* (2004), ``Water use efficiency (WUE) is the measure of cropping system's capacity to convert water into plant biomass or grain``. Water use efficiency relies on the soil's capacity to capture and store water, the crop's capacity to access stored water in the soil during the season, the crop's capacity to convert water into biomass, and the crops ability to convert biomass into economic yield (harvest index). Furthermore, water use efficiency can be enhanced by appropriate agronomic management practices and crop adaptability traits under water deficit. Studies have been conducted on the effects of row spacing, planting date and water deficit on water use efficiency.

According to Yi *et al.* (2010), low water availability had an effect on vegetative growth but accelerated deeper rooting system and promoted reproductive growth with an increase in water use efficiency of maize. A study done by Xue *et al.* (2006) showed that limited water conditions between jointing and anthesis, significantly increased wheat yield and water use efficiency by increasing photosynthesis and the remobilization of pre-anthesis carbon reserves. A field study conducted by Chen *et al.* (2010) concluded that winter wheat production under narrow row spacing reduced soil evaporation, and low improvements on grain production but increased WUE. In a separate study done by Wakrim *et al.* (2005), they reported that dry bean had optimum performance under narrow spacing, had high grain yield and water use efficiency. Recently, Barbieri *et al.* (2012) reported similar results for maize grown under narrow spacing and water limited conditions.

2.7 Conclusions

Dry bean is one of the world's main staple crop and an important legume for direct human consumption. The crop has high nutritional value (protein source), drought tolerant characteristics and N-fixation properties therefore, dry bean therefore has potential to contribute to food and nutritional security in Africa, especially amongst smallholder farmers. However, smallholder farmers face challenges in achieving high yields for dry bean. Mostly challenges are associated with lack of proper agronomic practices under rain-fed conditions. In order to improve productivity of dry beans under smallholder farming, there is a need to develop best management practices that can be used to inform farmers' decisions. Chief among these, are cultivar selection, planting date selection and plant density.

References

Acosta-Gallegos, J. A., Vargas-Vazquez, P. and White, J. W. 1996. Effect of sowing date on the growth and seed yield of common bean (*Phaseolus vulgaris* L.) in highland environments. *Field Crops Research*, 49, 1-10.

Barbieri, P., Echarte, L., Della Maggiora, A., Sadras, V., Echeverria, H. and Andrade, F. 2012. Maize evapotranspiration and water-use efficiency in response to row spacing. *Agronomy journal*, 104**,** 939-944.

Barnes, G. and, McGrath, L. 2016. Angular leaf spot on beans. http://barmac.com.au Accessed (18/08/2016).

Bewley, J. D. and Black, M. 2012. Physiology and biochemistry of seeds in selation to germination: Volume 2: viability, dormancy, and environmental control, Springer science & business media.

Bhandari, S. 2016. Growing plants from seed. Available from http://bagbani.yolasite.com. Accessed (18/08/2016).

Champolivier, L. and Merrien, A. 1996. Effects of water stress applied at different growth stages to *Brassica napus L. var. oleifera* on yield, yield components and seed quality. *European Journal of Agronomy,* 5**,** 153-160.

Chen, S., Zhang, X., Sun, H., Ren, T. and Wang, Y. 2010. Effects of winter wheat row spacing on evapotranpsiration, grain yield and water use efficiency. *Agricultural Water Management,* 97**,** 1126-1132.

Chibarabada, T. P., Modi, A. T. and Mabhaudhi, T. 2015. Water use characteristics of a bambara groundnut (*Vigna subterranea L. Verdc*) landrace during seedling establishment. *Water South Africa,* 41**,** 472-482.

Condon, A. G., Richards, R., Rebetzke, G. and Farquhar, G. 2004. Breeding for high water-use efficiency. *Journal of experimental botany,* 55**,** 2447-2460.

Department of Agriculture. 2010. Dry beans production guideline. Department of Agriculture, Forestry and Fisheries: Directorate Plant Production in collaboration with the ARC.

Dube, E., Sibiya, J. and Fanadzo, M. 2014. Early planting and hand sorting effectively controls seed-borne fungi in farm-retained bean seed. *South African Journal of Science,* 110**,** 01-06.

Esmaeilzadeh, S. and Aminpanah, H. 2015. Effects of planting date and spatial arrangement on common bean (*Phaseolus vulgaris*) yield under weed-free and weedy conditions *Planta Daninha*, 33**,** 425-432.

Food and Organization, A. 2015. Crop Water Information: Bean. Food and Agriculture Organization of the United Nations.

Fourie, D. 2014. Dry bean cultivar recommendations. ARC-Grain Crops Institute: Agriculture Research Council.

Gepts, P. 2001. *Phaseolus vulgaris* (Beans). *Encyclopaedia of Genetics***,** 1444-1445.

Gross, Y. and Kigel, J. 1994. Differential sensitivity to high temperature of stages in the reproductive development of common bean (*Phaseolus vulgaris* L.). *Field Crops Research,* 36, 201-212.

Hagedorn, D. J. and Inglis, D. A. 1968. Hand book of bean diseases, Cooperative Extension Publications Murray St., Madison, Wisconsin. Cooperative Extension Publications.

Hill, E. C., Renner, K. A., Sprague, C. L. and Davis, A. S. 2016. Cover crop impact on weed dynamics in an organic dry bean system. *Weed Science*, 64**,** 261-275.

Joshi, S. and Rahevar, H. 2014. Effect of dates of sowing, row spacings and varieties on growth attributing characters of rabi Indian bean (*Dolichos lablab* L.). *Trends in Biosciences*, 7, 3717-3721.

Kim, H., Koo, S., Kang, B., Lee, Y., Kim, H., Yun, H., Baek, I., Jeong, H. and Choi, M. 2014. Growth characteristics of sprouts and changes of antioxidant activities in common bean (*Phaseolus vulgaris* L.) with cultivated temperature. *Korean Journal of Crop Science / Hanguk Jakmul Hakhoe Chi*, 59, 201-207.

Loo, Y. Y., Billa, Singh, A. 2015. Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geoscience Frontiers*, 6, 817–823.

Mirzaienasab, M. and Mojaddam, M. 2014. The effect of planting date on yield and yield components of two red bean cutivars in Azna weather conditions. *Indian Journal of Fundamental and Applied Life Sciences*, 4, 2231-3345.

Mulongoy, K. G., M Spencer, D., Von Carlowitz, P., Gritton, E., Ayala, B., Hernández-Bravo, G. R., Ramakrishna, B., Raven, J., Vanderleyden, J. and Fatecha, A. Biological nitrogen fixation and sustainability of tropical agriculture: proceedings. *Publicacoes Miscelaneas* A4/BR (Brasil), 1992. IITA, Ibadan (Nigeria).

Muedi, H. T., Fourie, D. and Mclaren, N. W. 2015. Distribution and severity of bacterial brown spot on dry beans in South Africa: an update. *South African Journal of Science,* 111**,** 1-6.

Nagle, B. and Schneiter, A. 2009. Effects of seeding rate and row spacing on dry bean production. *Journal of Plant science*, 115, 98-120.

Parrella, R. a. D. C., Santos, J. B. D. and Parrella, N. N. L. D. 2013. Evaluation efficiency of severity of angular leaf spot in common bean based on diseased and healthy leaf area. *Crop Breeding and Applied Biotechnology,* 13**,** 178-185.

Prasad, P. V. and Djanaguiraman, M. 2014. Response of floret fertility and individual grain weight of wheat to high temperature stress: sensitive stages and thresholds for temperature and duration. *Functional Plant Biology,* 41**,** 1261-1269.

Ramaekers, L., Galeano, C. H., Garzón, N., Vanderleyden, J. and Blair, M. W. 2013. Identifying quantitative trait loci for symbiotic nitrogen fixation capacity and related traits in common bean. *Molecular breeding*, 31, 163-180.

Rogers, A., Ainsworth, E. A. and Leakey, A. D. 2009. Will elevated carbon dioxide concentration amplify the benefits of nitrogen fixation in legumes? *Plant Physiology,* 151**,** 1009-1016.

Smith, B. 2006. The farming handbook, University of Natal Press.

Srivastava, V., Soni, A. and Sonam, K. 2015. Analysis on effect of cold stress in bean seeds (*Phaseolus vulgaris* L.). *American Journal of BioScience,* 3**,** 145-166.

Wakrim, R., Wahbi, S., Tahi, H., Aganchich, B. and Serraj, R. 2005. Comparative effects of partial root drying (PRD) and regulated deficit irrigation (RDI) on water relations and water use efficiency in common bean (*Phaseolus vulgaris L*.). *Agriculture, Ecosystems & Environment,* 106**,** 275-287.

Xue, Q., Zhu, Z., Musick, J. T., Stewart, B. and Dusek, D. A. 2006. Physiological mechanisms contributing to the increased water-use efficiency in winter wheat under deficit irrigation. *Journal of Plant Physiology,* 163**,** 154-164.

Yi, L., Shenjiao, Y., Shiqing, L., Xinping, C. and Fang, C. 2010. Growth and development of maize (*Zea mays L*.) in response to different field water management practices: Resource capture and use efficiency. *Agricultural and Forest Meteorology,* 150**,** 606-613.

CHAPTER 3

MATERIALS AND METHODS

Based on the objectives of the study, a series of laboratory and field experiments were conducted. The first experiment was designed to determine seed quality of the three dry bean varieties. Thereafter, a second experiment (field trial) was conducted to determine the agronomic and physiological performance of the three bean varieties under varying field conditions. Following completion of the field trials, progeny seed quality was assessed to determine the effect of different production environments on the maternal plants on progeny seed quality. Details of the experiments conducted are described below.

3.1 Plant Material

Three dry bean varieties, namely, Mtata, Malelane, and Gadra, were sourced from McDonald's Seeds (Pty) Ltd in Pietermaritzburg KwaZulu-Natal. Umtata is a determinate variety reported to be suitable for growing under conditions prevalent around Pietermaritzburg. Malelane is a fine bean for the pre-pack market bred to suit South African conditions. Malelane yields a very attractive straight bean, with a green colour, and with an excellent uniformity. The field holding ability of Malelane is good while seed development is slow. It has good disease resistance and vigorous growth. Gadra is well adapted to the lowveld and KwaZulu-Natal production areas and well adapted for late planting when compared with other varieties. It is early maturing, excellent disease resistance, upright, bush growth habit and large seed size.

3.2 Seed Quality Test

A series of seed quality tests were conducted for the original purchased seeds and the progeny at the University of KwaZulu-Natal's seed technology laboratory. For the progeny, seed quality tests also included water activity and seed moisture content.

3.2.1 Water activity and seed moisture content

The Decagon Model AquaLab Series 3 water activity meter (Decagon Devices, USA) was used to measure seed water activity. Three replications were done for each treatment. A grain moisture meter (Model am-5000, China) was used to measure seed moisture content of harvested seeds using settings (P8) for dry bean. Three replications were also done for each treatment.

3.2.2 Standard germination test

Seed germination capacity was determined using the standard germination test under laboratory conditions. Briefly, three replicates consisting of 25 seeds of each variety (Gadra, Mtata and Malelane) were germinated between double-layered moistened brown paper towels (ISTA, 2011). The paper towels were rolled and tied at either end with rubber bands before being placed in zip-lock bags to prevent moisture loss. The zip-lock bags were then placed in a germination chamber set at 25°C (Germination cabinets, Model PL2, England) were they were kept for 8 days. Seed germination was observed daily and germination was defined as radicle protrusion of 2 mm (ISTA, 2011).

3.2.2.1 Germination velocity index (GVI)

Seed vigour was measured using the germination velocity index (GVI) (germination speed) and calculated based on Maguire's (1962) formula:

$$GVI = G1/N1 + G2/N2 + \ldots + Gn/Nn \qquad \textbf{Equation 3.1}$$

where:

GVI = Germination Velocity Index,

G1, G2…Gn = number of germinated seeds in first, second… last count, and

N1, N2…Nn = number of sowing days at the first, second… last count.

3.2.2.2 Mean germination time (MGT)

Mean germination time (MGT) was calculated according to Ellis and Roberts (1981) formula:

$$MGT = \mathbf{\Sigma\ Dn/\Sigma\ n} \qquad \textbf{Equation 3.2}$$

where;

n = number of seeds which were germinated per day D, and

D = number of days counted from the beginning of germination.

3.3 Field Trials

A set of trials were conducted to determine the effect of planting date, plant density and water availability on dry bean growth, development and yield over two seasons (early and late season).

3.3.1 Description of experimental site and management

Field trials were conducted at the University of KwaZulu-Natal's Ukulinga Research Farm in Pietermaritzburg (29° 37′ S; 30° 16′ E; 775 m a. s. l.). The planting dates for the early and late season were 12 January and 03 May 2016, respectively. The trials were harvested on 12 April and 13 September 2016, respectively.

Prior to planting, soil samples were taken from the field for soil fertility analyses. The sampling followed standard sampling procedure of taking three samples randomly in the field from upper, middle, and lower part of the field to represent the whole field. Soil samples were analysed for soil fertility at Cedara (29° 31' 59.99" S and Longitude: 30° 16' 60.00" E). The same procedure was repeated again after harvesting to determine soil fertility levels at the end of the season.

3.3.2 Experimental Design

The experimental design was a split-plot laid out in randomised complete blocks and replicated three times. There were three factors, namely, (i) varieties (Mtata, Malelane and Gadra), (ii) plant densities (high, medium and low), and (iii) water regime (rain-fed and irrigated). The field was 30 x 20 m. The three varieties were as described in Section 3.1. High plant density involved planting seeds at 0.5 x 0.2 m, low medium density at 0.5 x 0.3 m and high density at 0.5 x 0.5 m. The irrigated water regime included watering the crops at 30 mm per week for the duration of the trials. Rain-fed trials were established with irrigation to allow for maximum plant stand thereafter, irrigation was withdrawn after crop establishment.

3.3.4 Site description and crop management

Prior to land preparation, soil samples were taken to Cedara for analysis and fertility recommendations. Land preparation was done by disking and rotovating to achieve a fine tilth. The field trials were sprayed using Mancozeb (Dithane M45) at 45 g /15 L for cutworm. Weeding was done routinely by hand hoeing.

3.4 Data Collection

3.4.1 Plant growth and physiology

The plants were given up to emergence (VE) stage before the non-destructive evaluation of plant growth and physiology parameters. Four plants per plot were randomly measured for plant growth parameters (height, leaf number) and averages were recorded. Plant height was measured from the ground level to the tip of the fully matured leaf using a measuring tape (Stanley 3m Power lock steel tape measure). Leaf number was counted by counting the number of fully developed unifoliate to trifoliate leaf that were visible. Stomatal conductance was determined using the Model SC–1 steady state leaf porometer (Decagon Devices, Inc., USA). Leaf area index (LAI) and photosynthetically active radiation (PAR) were measured using the AccuPAR LP80 Ceptometer (Decagon Devices, USA). A portable chlorophyll meter, the SPAD-502 Plus (Konica Minolta, Japan) was used to measure chlorophyll content index (CCI) on the fully expanded trifoliate and solar radiation exposed leaves.

3.4.2 Yield parameters

After harvesting, fresh mass from the two middle experimental rows were weighed with a digital sensitive balance (Masskot, FX320, Switzerland) and average mass (g) per plot was recorded. After shelling the crop, seed mass per plant was weighed with a digital sensitive balance (Masskot, FX320, Switzerland). Thereafter, the seeds were categorised into damaged and non-damaged seeds from the pods.

3.4.3 Gravimetric soil water content

Soil samples were collected at the field for soil water measurements. The samples were taken every week at 30 cm depth using a soil auger. The samples were immediately put in sealable bags. The samples were weighed before being put into brown paper bags and dried in an oven at 105°C until constant mass was reached. This was done every week.

3.5 Statistical Analyses

Data collected were subjected to analyses of variance (ANOVA) using GenStat® Version 18 (VSN International, United Kingdom) at the 5% probability level. Duncan's test on GenStat® at the probability level of 5% was used to compare means.

References

Ellis, R. and Roberts, E. 1981. The quantification of ageing and survival in orthodox seeds. *Seed Science and Technology*.

ISTA (International Seed Testing Association). 2011. *International rules for seed testing*. Switzerland: ISTA Zurich.

Maguire, J. D. 1962. Speed of germination—aid in selection and evaluation for seedling emergence and vigor. *Crop science*, 2**,** 176-177.

CHAPTER 4

SEED QUALITY IN RESPONSE TO DIFFERENT AGRONOMIC PRACTICES

4.1 Introduction

Due to inadequate food intake and poor nutrition, the diets of many South Africans lacks essential vitamins, minerals; and most importantly, proteins (Kruger *et al.*, 2012). This has led to protein-deficient diseases such as muscle wasting, swelling due to water retention, low blood pressure and heart rate, anaemia and liver problems (Munro, 2012). Dry beans (*Phaseolus vulgaris*) are known to be a significant source of protein, fibre, vitamins, and minerals (Wani *et al.*, 2015). However, access to improved agricultural resources such as quality seeds and water stress has been observed to be a limiting factor to productivity in developing countries (Lee *et al.*, 2012).

Smallholder farmers have been observed to use retained dry bean seed harvested from previous seasons as they cannot afford to purchase improved seed varieties (Azadi *et al.*, 2016). Due to the self-pollinating nature of legumes, inbreeding depression often leads to decreased quality and vigour of subsequent seed (Ghassemi-Golezani and Mazloomi-Oskooyi, 2012). In addition, water stress conditions in which the maternal plant is exposed affects seed quality and vigour (Müller *et al.*, 2014). Therefore, the use of retained seed coupled with areas of limited water availability increases the risk of low and non-uniform germination and poor seedling emergence leading to significant yield losses (Müller *et al.*, 2014).

The use of retained dry bean seed combined with limited resources and knowledge for agricultural production will continue to dominate many smallholder farmers. Water stress on developing maternal plant has been observed to affect seed mass and endosperm biochemical constituents; thus affecting seed quality (soybean and faba beans) (Trivedi, 2013), and vigour (Ghassemi-Golezani and Hosseinzadeh-Mahootchy, 2009). Ahmadi and Bahrani (2009) observed that water stress on sunflower under water limited conditions resulted in poor seed set, small and shrivelled seed; this was strongly correlated to subsequent reduction in seed quality. On the contrary, other authors have reported no significant effect on seed quality in response to production environment (Ahmad *et al.*, 2009; Kheira and Atta, 2009; Odindo, 2010).

Opportunities for improving dry bean seed quality exist in the use of good water management strategies on the maternal plant. Such strategies include the use of appropriate planting dates, plant densities and adaptable varieties. Planting dry bean at an appropriate planting date resulted in increased crop growth period, and pod number, number of grains per pod, 100-grain weight, and finally grain yield (Mirzaienasab and Mojaddam, 2014); this also translated to high progeny seed quality . A study done by Joshi and Rahevar (2014) showed that optimum plant spacing improved water use efficiency and consequently improved seed quality. Ghassemi-Golezani and Mazloomi-Oskooyi (2012) reported that the use of drought tolerant varieties increased seed quality of dry bean.

Although the use of optimum agronomic management practices can be used to improve subsequent dry bean seed quality under water-limited conditions, there is gap in information to quantify the possible gains. In-order to ensure that smallholder farmers sustainably produce dry beans, there is a need to assess and quantify the effects of different agronomic practices on subsequent seed quality. Therefore, the aim of this study was to determine the effect of planting date, plant density and water availability on subsequent seed quality of different dry bean varieties. The specific objectives were to determine (i) initial, and (ii) subsequent seed quality for three bean varieties grown under varying agronomic practices.

Materials and methods are explained in Chapter 3, section 3.2.

4.2 Results

4.2.1 Pre-planting germination

There were significant differences (P=0.027) observed for final germination for three dry bean varieties. Although these differences were nominal, the trend observed the for final germination was Mtata (91.5%) > Gadra (84.5%) > Malelane (83.5%) (Figure 4.1) (Appendix 1).

P= 0.027; LSD $_{(P>0.05)}$ = 8.64; CV%= 6.6

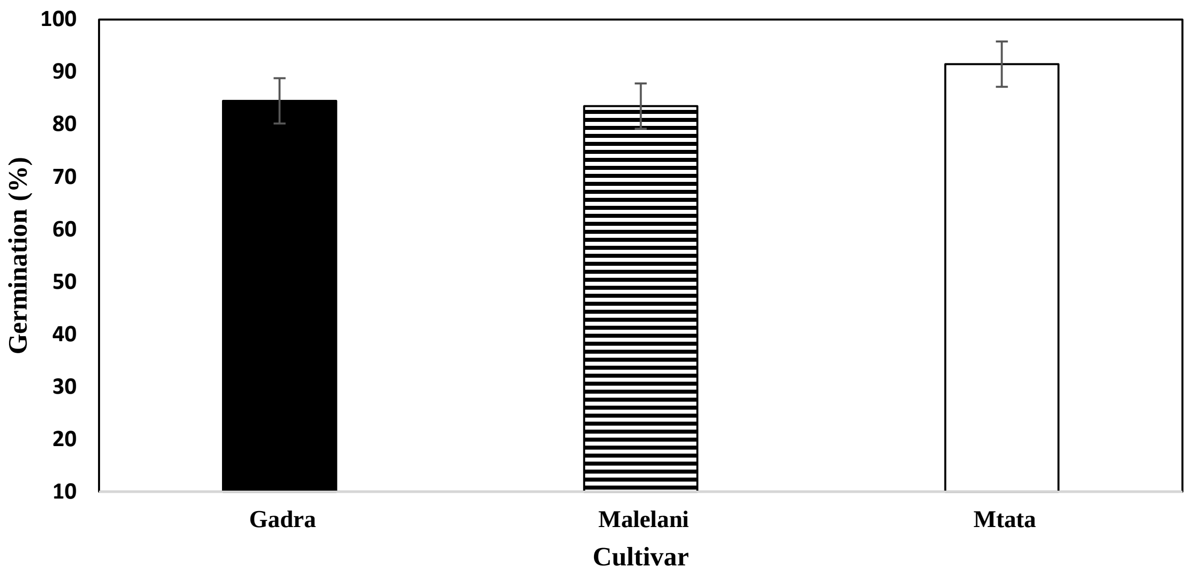

Figure 4. 1: A comparison of final germination percentage for three dry bean varieties (Mtata, Gadra and Malelane). Standard error bar represent standard deviation (±4.32).

4.2.2 Pre-planting germination velocity index (GVI)

There were significant differences (P=0.027) observed for germination velocity index (GVI) for three dry bean varieties. The trend for germination velocity index was Mtata (24) > Gadra (23.1) > Malelane (21.9) (Figure 4.2) (Appendix 2).

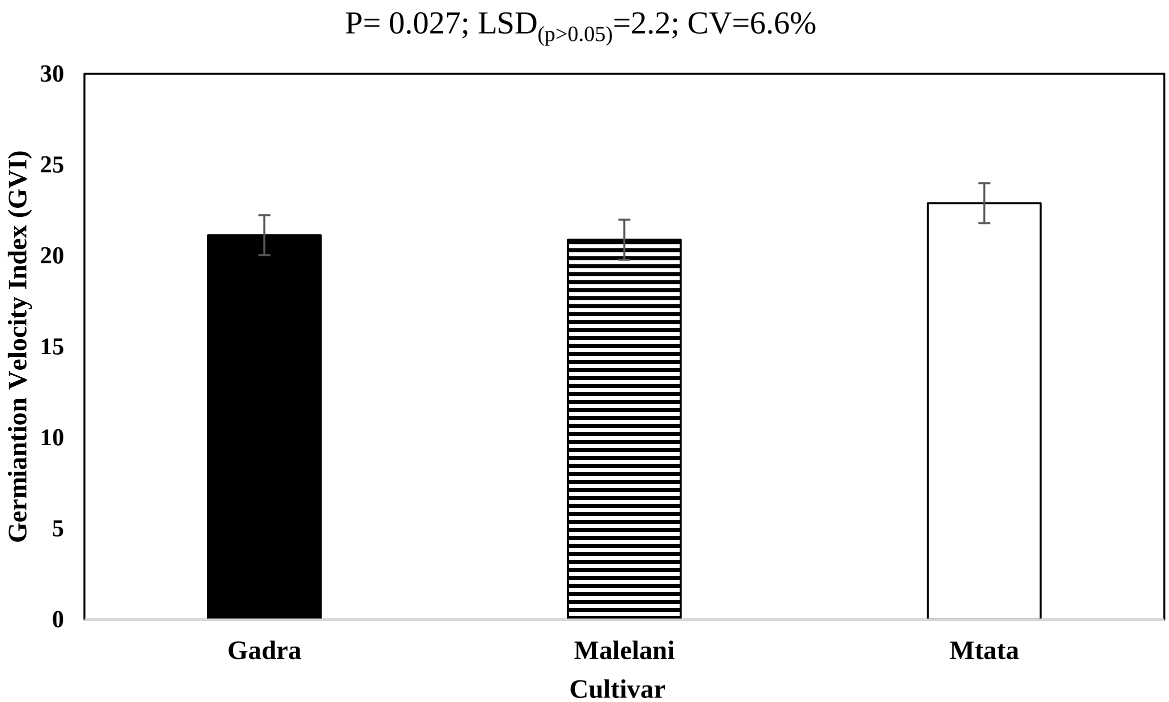

Figure 4.2: A comparison of germination velocity index (GVI) for the three dry bean varieties (Mtata, Gadra and Malelane). Standard error bar represent standard deviation (±1.10).

4.2.3 Post planting germination percentage

There was a significant difference ($P<0.05$) for germination percentage with regards to the interactions of water regime x plant density x variety x time interaction. Overall, across the water regimes and plant densities (Figure 4.3, A, B, C, D, E, and F), Gadra had the lowest germination (28.30%) and Malelane the highest germination (98.80%). Similarly, under the two water regimes irrigated (Figure 4.3, A, B and C) and rain-fed (Figure 4.3, D, E and F), Malelane had the highest germination (98.80%) and Gadra the lowest germination percentage (31.70%). Medium density (Figure 4.3, B and E) had the highest germination % (93.20%) while high density (Figure 4.3, C and F) had the lowest germination percentage (74.30%). With respect to variety Mtata and Malelane showed the highest seed germination (88.50%) while Gadra showed the lowest germination (78.70%) (Appendix 3).

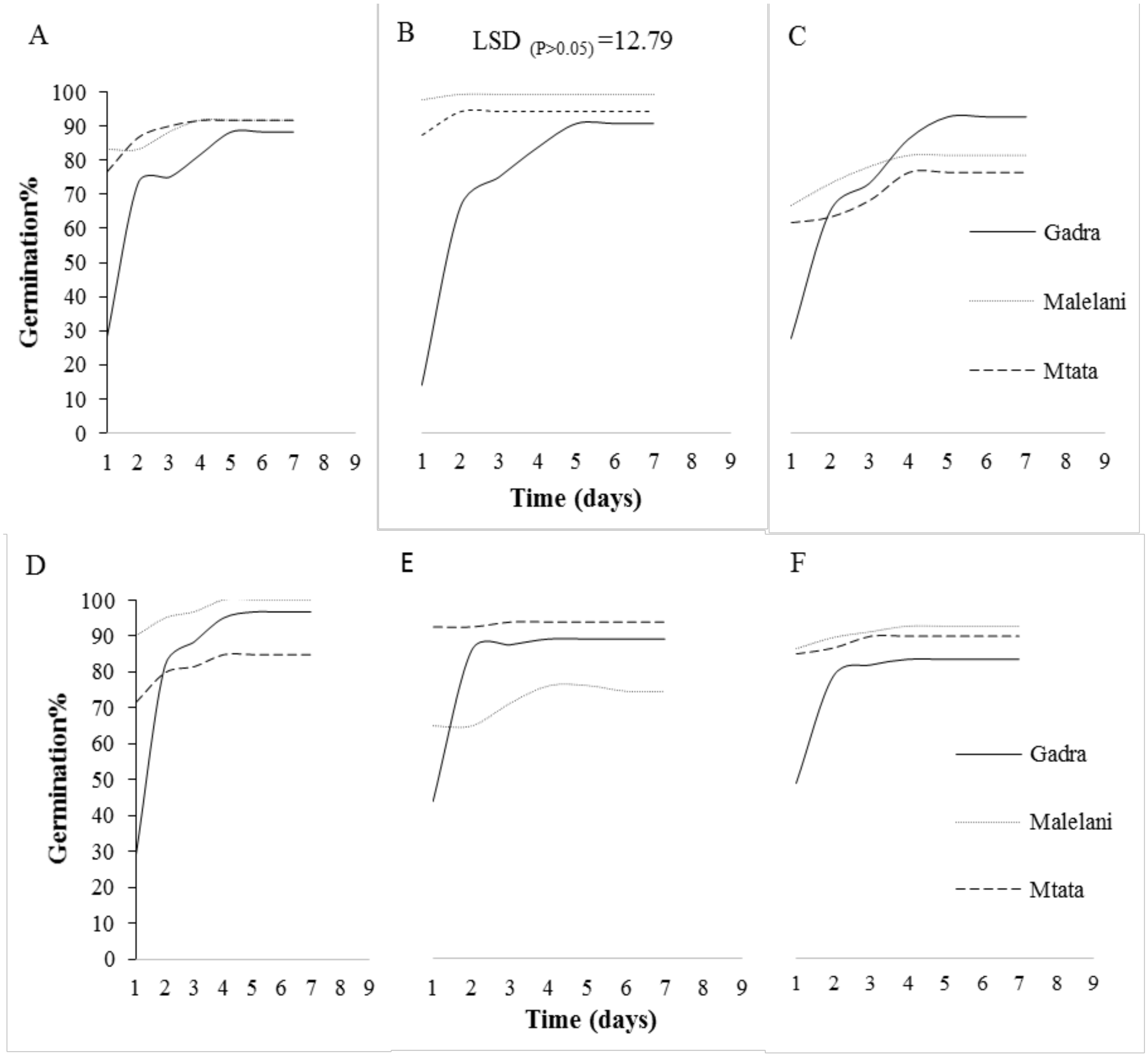

Figure 4.3: A comparison of final germination percentage for three dry bean varieties (Mtata, Gadra and Malelane) under different water regimes (rain-fed and irrigated), and plant densities (high, medium and low). A = irrigated low density, B = irrigated medium density, C = irrigated high density, D = rain-fed low density, E = rain-fed medium density, F = rain-fed high density.

4.2.4 Post planting Germination Velocity Index (GVI)

Germination Velocity Index (GVI) showed that there was a significant difference ($P<0.05$) for the interaction of water regime x plant density x variety (Appendix 4). Overall, the mean GVI for the dry bean varieties were 2.57, 2.47 and 2.57 for Malelane, Mtata and Gadra respectively (Figure 4.4). Germination Velocity Index showed that seeds harvested from maternal plants grown under irrigated conditions had higher GVI compared to under rain-fed conditions. Medium planting density had the highest GVI (3.56) relative to low planting density (2.51) and high planting density (2.19).

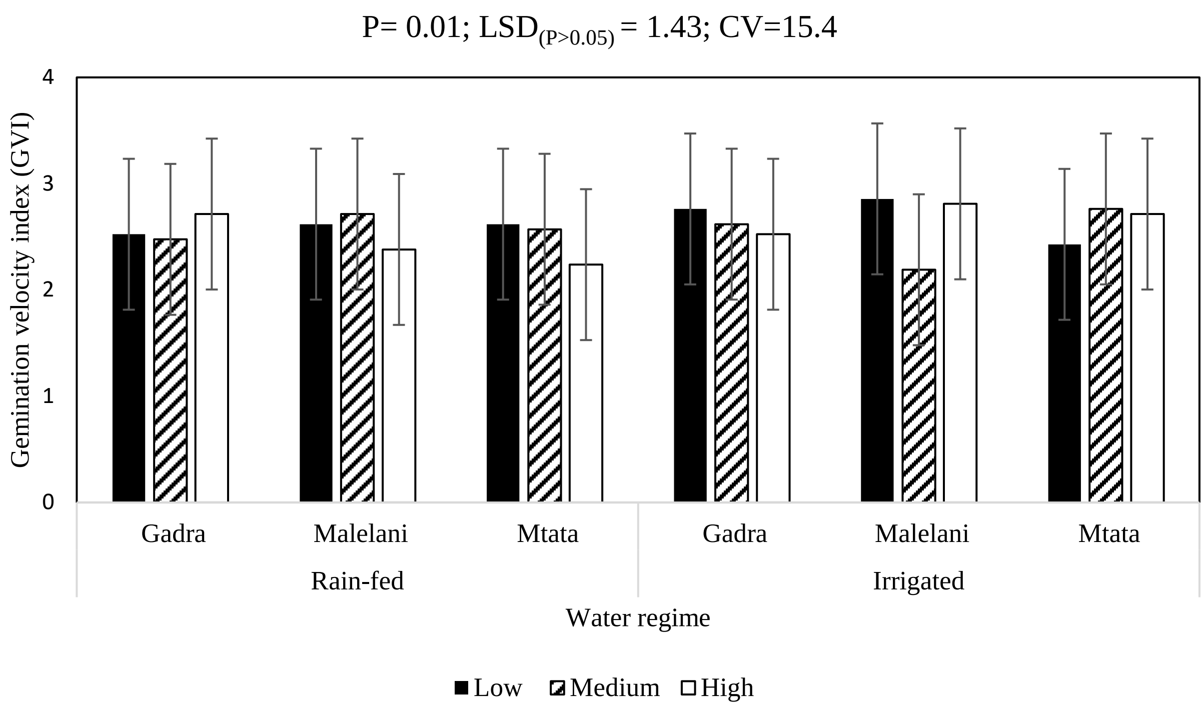

Figure 4. 4: A comparison of Germination Velocity Index (GVI) for three dry bean varieties (Mtata, Gadra and Malelane), under different water regimes (rain-fed and irrigated), and plant densities (high, medium and low). Standard error bar represent standard deviation (±0.71**).**

4.2.5 Post planting mean germination time (MGT)

There were significant differences ($P=0.01$) observed for the mean germination time (MGT) for the interaction of water regime x plant density x variety (Appendix 5). Gadra had the lowest MGT respectively to Mtata and Malelane, Malelane (0.44 days) > Mtata (0.42 days) > Gadra (0.36 days). Under irrigation, MGT was lower (0.35 days) relative to when dry beans were grown under rain-fed conditions (0.39 days). For three plant densities MGT was observed to be higher under high density (high density (0.42 days) >, medium density (0.4 days) >, and low density (0.38 days). Across all treatment combinations, Malelane under irrigation, and medium density had the highest MGT, and the lowest MGT was seen for Malelane under low density under irrigated conditions (Figure 4.5).

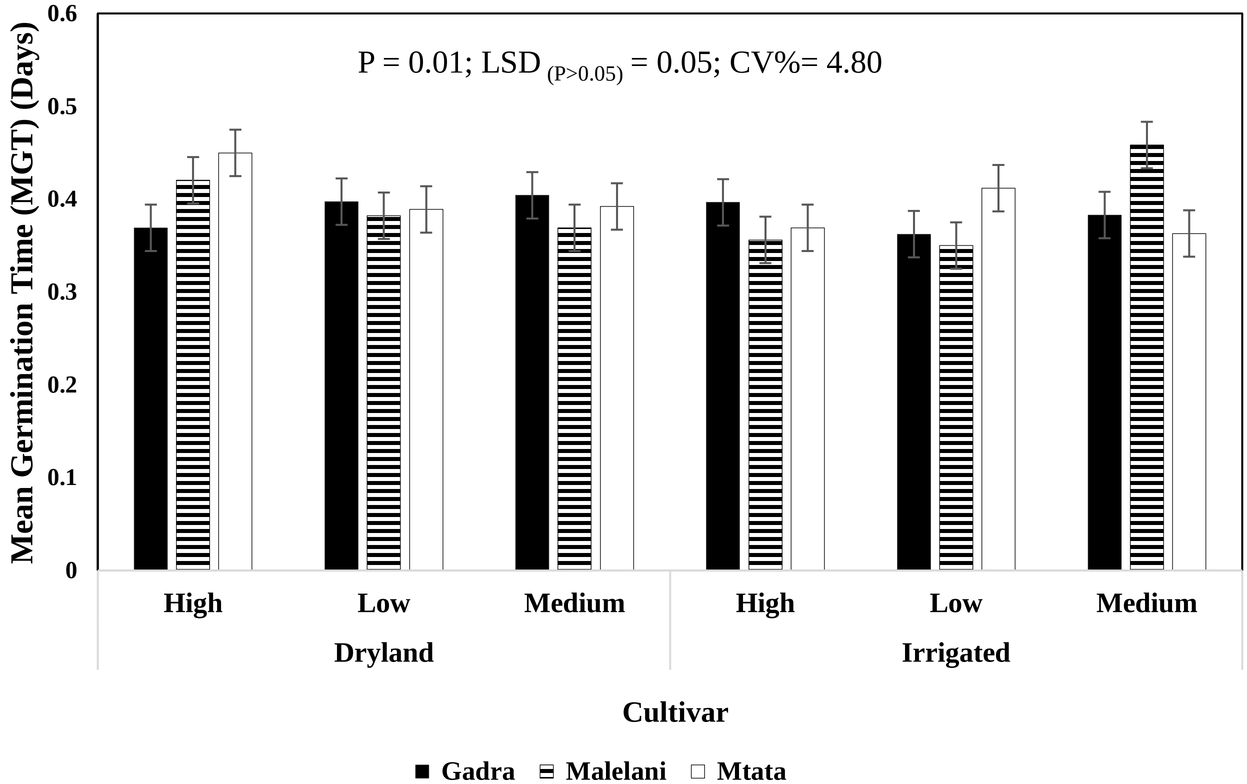

Figure 4.5: A comparison of Mean Germination Time (MGT) for three dry bean varieties (Mtata, Gadra and Malelane) under different water regimes (rain-fed and irrigated), and plant densities (high, medium and low). Standard error bar represent standard deviation (± 0.025).

4.2.6 Post planting seed moisture content (%)

An interaction of plant density and cultivar had significant effect (P=0.041) on dry bean seed moisture content. Planted under the low density treatment had the lowest seed moisture content (9.90%) relative to high (10.10%) and medium (10.20%) (Appendix 6). There was no significant difference (P > 0.05) between the three dry bean varieties Gadra (10.00%), Malelane (10.10%), and Mtata (10.00%). The treatment combination of variety (Malelane) and medium plant density had the highest seed moisture content compared to the low and high plant densities. Overall Mtata variety under high plant density showed highest grain moisture (Figure 4.6).

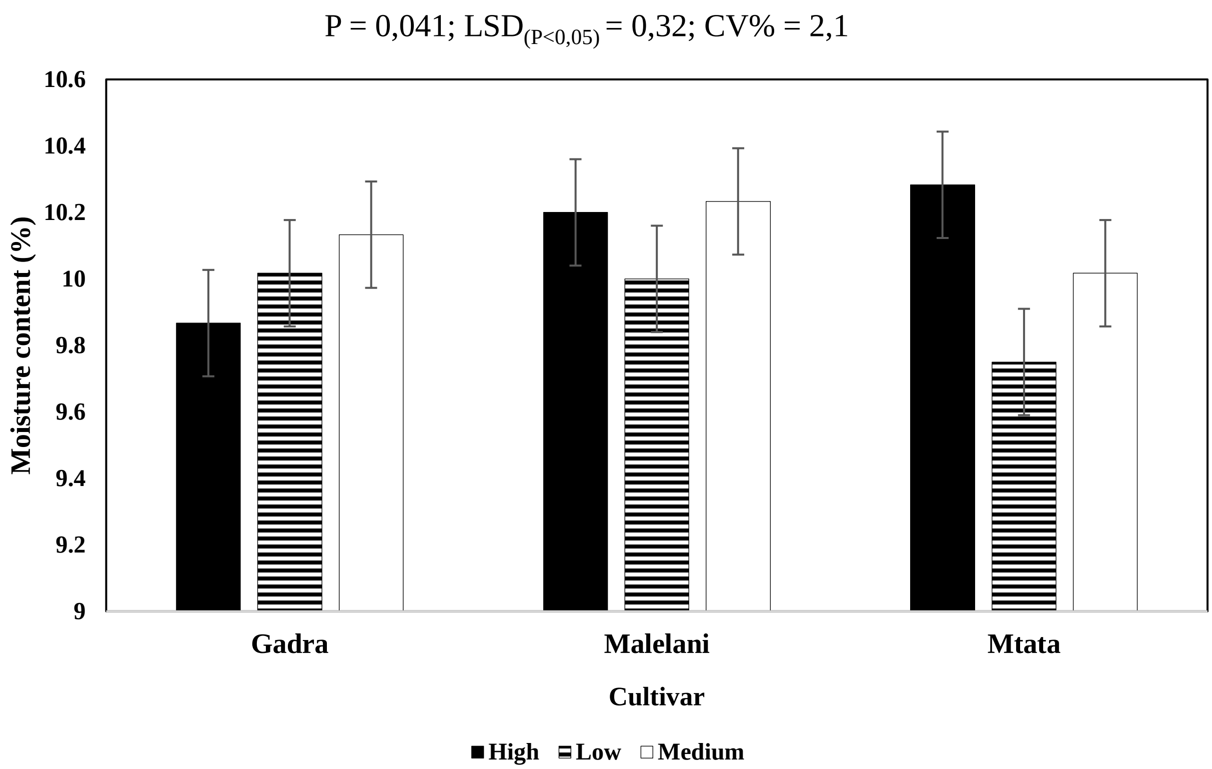

Figure 4. 6: A comparison of seed moisture content (%) for three dry bean varieties (Mtata, Gadra and Malelane) under different three plant densities (low, medium and high density). Standard error bar represent standard deviation (±0.16).

4.2.7 Post planting water activity

There were highly significant differences (P=0.001) observed for the seed water activity for the interaction of water regime x variety (Appendix 7). Seeds harvested from maternal plants grown under irrigated conditions had the lowest water activity (0.52) when compared with rain fed field (0.54) (Figure 4.7). The treatment combination of variety x water regime, seeds of Mtata harvested under rain-fed conditions had the highest water activity relative to irrigated field. While Gadra under irrigated conditions had the lowest water activity (Figure 4.7).

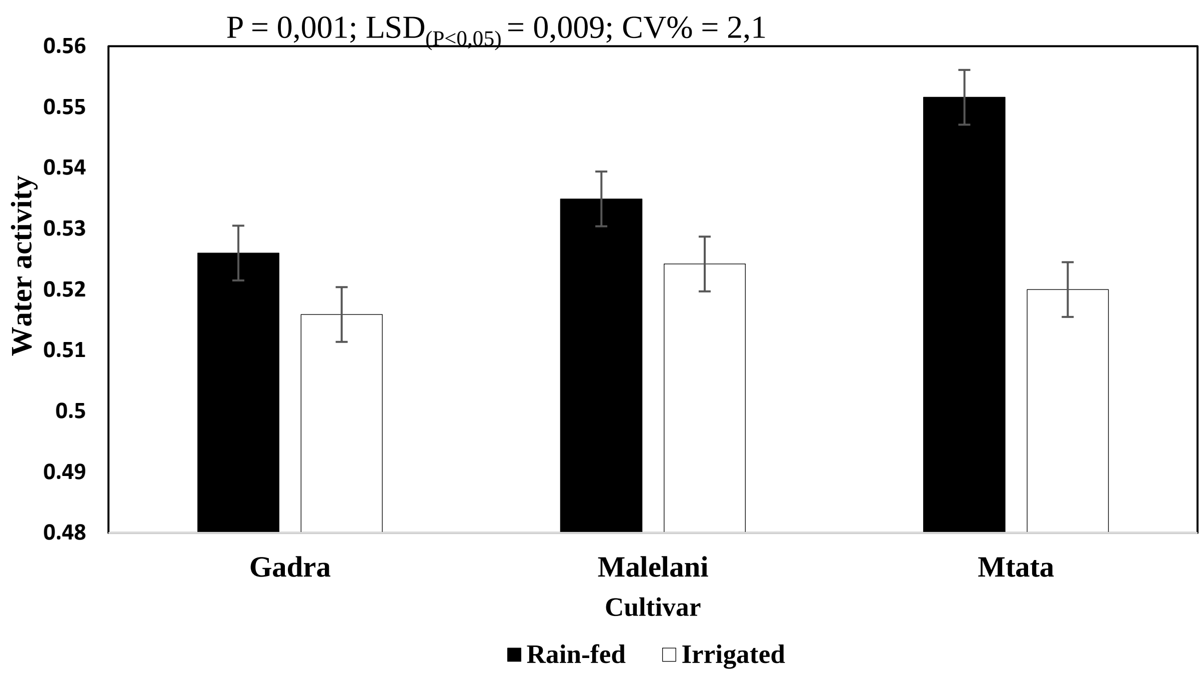

Figure 4. 7: A comparison of water activity for three dry bean varieties (Mtata, Gadra and Malelane) under different two water regimes (rain-fed and irrigated). Standard error bar represent standard deviation (±0.0045).

4.3 Discussion

Significant differences ($P<0.05$) were observed under pre-planting and post planting germination results among the dry bean seeds varieties. This confirms that studied dry bean seed varieties had an influence on the subsequent seed quality. This could because of the genetic differences amongst the dry bean seed varieties (Elballa *et al.*, 2015). Initially, Mtata variety had the highest percentage seed germination but Malelane had the highest percentage germination post-planting. This shows that subsequent dry bean seed quality was affected environmental factors due to maternal plant (Akibode and Maredia, 2012).

Seeds produced under rain-fed conditions had high germination percentage over a short period. Germination velocity index was higher under rain-fed conditions when compared with under irrigated conditions. Mean germination time was lower under rain-fed conditions meaning that the subsequent seeds were able to germinate faster than those from the irrigated trial. This could suggest that limited water availability subsequent seed quality could actually be enhanced (Ahmad *et al.*, 2009). Under water limited conditions, adaptable seed will aim to germinate and establish quickly to take advantage of available water (Ghassemi-Golezani and Mazloomi-Oskooyi, 2012). It could be that the reduction in pod number and average seed number per pod under water stress conditions helps maintain seed integrity with regards to seed quality (Odindo, 2010). It was observed also that under the lower plant densities the seed quality indices were low. This implies that planting dry bean under low plant density has no favourable gain on seed quality but only on grain yield.

4.4 Conclusion

In the present study, subsequent dry bean seed quality varied among different management practices. Mtata, Malelane and Gadra dry bean varieties varied in their responses to the varied agronomic conditions. Seed germination, GVI, and MGT were favourable under rain-fed conditions. This implies that dry bean seed can be grown under rainfed conditions for the purposes of seed without adverse effects on the quality (germination and vigour) of the seed. The study also highlights the importance of the correct combination of management practices in which the maternal plants are exposed for good quality seeds.

References

Ahmad, S., Ahmad, R., Ashraf, M. Y., Ashraf, M. and Waraich, E. A. 2009. Sunflower (*Helianthus annuus* L.) response to drought stress at germination and seedling growth stages. *Pakistan Journal of Botany,* 41, 647-654.

Ahmadi, M. and Bahrani, M. 2009. Yield and yield components of rapeseed as influenced by water stress at different growth stages and nitrogen levels. *American-Eurasian Journal of Agricultural and Environmental Sciences,* 5, 755-761.

Akibode, S. and Maredia, M. K. 2012. Global and regional trends in production, trade and consumption of food legume crops, Department of Agricultural, Food, and Resource Economics, Michigan State University.

Azadi, H., Samiee, A., Mahmoudi, H., Jouzi, Z., Rafiaani Khachak, P., De Maeyer, P. and Witlox, F. 2016. Genetically modified crops and small-scale farmers: main opportunities and challenges. *Critical Reviews in Biotechnology,* 36, 434-446.

Elballa, M., El-Amin, A., Elamin, E. and Elsheikh, E. A. 2015. Interactive effects of varieties, foliar application of micronutrients and rhizobium inoculation on snap bean (*Phaseolus vulgaris* L.) performance. *Journal of Agricultural and Environmental Sciences,* 50, 555-612.

Ghassemi-Golezani, K. and Hosseinzadeh-Mahootchy, A. 2009. Changes in seed vigour of faba bean (*Vicia faba* L.) varieties during development and maturity. *Seed Science and Technology,* 37, 713-720.

Ghassemi-Golezani, K. and Mazloomi-Oskooyi, R. 2012. Effect of water supply on seed quality development in common bean (*Phaseolus vulgaris* var.). *International Journal of Plant Production,* 2, 117-124.

Joshi, S. and Rahevar, H. 2014. Effect of dates of sowing, row spacings and varieties on growth attributing characters of rabi Indian bean (*Dolichos lablab* L.). *Trends in Biosciences,* 7, 3717-3721.

Kheira, A. A. A. and Atta, N. M. 2009. Response of *Jatropha curcas* L. to water deficits: Yield, water use efficiency and oilseed characteristics. *Biomass and Bioenergy,* 33, 1343-1350.

Kruger, H. S., Steyn, N. P., Swart, E. C., Maunder, E. M., Nel, J. H., Moeng, L. and Labadarios, D. 2012. Overweight among children decreased, but obesity prevalence remained high among women in South Africa, 1999–2005. *Public health nutrition*, 15, 594-599.

Lee, J., Gereffi, G. and Beauvais, J. 2012. Global value chains and agrifood standards: challenges and possibilities for smallholders in developing countries. *Proceedings of the National Academy of Sciences*, 109, 12326-12331.

Mirzaienasab, M. and Mojaddam, M. 2014. The effect of planting date on yield and yield components of two red bean cultivars in Azna weather conditions. *Indian Journal of Fundamental and Applied Life Sciences*, 4 (3), 417-422.

Müller, M., Siles, L., Cela, J. and Munné-Bosch, S. 2014. Perennially young: seed production and quality in controlled and natural populations of *Cistus albidus* reveal compensatory mechanisms that prevent senescence in terms of seed yield and viability. *Journal of Experimental Botany*, 65, 287-297.

Munro, H. N. 2012. Mammalian protein metabolism. Academic press publishers, New York and London, Volume IV page 23-30.

Odindo, A. O. 2010. Cowpea seed quality in response to production site and water stress. Doctoral dissertation, University of KwaZulu-Natal, page 45-56.

Trivedi, M. 2013. Biofield and fungicide seed treatment influences on soybean productivity, seed quality and weed community. *Agricultural Journal***,** 138-143.

Wani, I. A., Sogi, D. S., Shivhare, U. S. and Gill, B. S. 2015. Physico-chemical and functional properties of native and hydrolyzed kidney bean (*Phaseolus vulgaris* L.) protein isolates. *Food Research International*, 76, 11-18.

CHAPTER 5

EFFECTS OF WATER STRESS COMBINED WITH DIFFERENT AGRONOMIC MANAGEMENT PRACTICES ON DRY BEAN GROWTH PARAMETERS

5.1 Introduction

Proteins play a vital role in human nutrition (Khan *et al.*, 2014). Protein aid in muscle recovery, reduces muscle loss, builds lean muscle, building block for bones, and cartilage (Wildman *et al.*, 2016). South Africans residing in rural communities are said to be protein deficient due to low intake of complete proteins high in amino acids in their diets (Khan *et al.*, 2014). Dry beans (*Phaseolus vulgaris*) are a protein power house and considered as an important and affordable grain legume (Wheeler and Von Braun, 2013).

A large proportion of government investments have focused on promoting cereal production within smallholder farming (Department of Agriculture, 2016). In 2015/16 season, more than 1.95 million land hectares were dedicated to maize production and this yield 3.8 million t/ha while only 35 000 ha was under dry bean production yielding 1.03 million t/ha (DAFF, 2016) . This trend also reflects current production systems within smallholder farming systems which are currently dominated by cereal based cropping systems therefore, low dry bean productivity.

The observed low yields could be due to the limited knowledge regarding its production in terms of best agronomic management practices and water stress (Kadyampakeni *et al.*, 2013). Under optimum agronomic conditions the plants are able to resource the water distribution uniformly for optimal growth (Joshi and Rahevar, 2014). Water stress has been observed to cause high yield losses in agricultural systems for small holder farmers (Brevedan *et al.*, 2012). In crop production water scarcity is a limiting factor for many small scale farming systems in South Africa, and the world over (Emam *et al.*, 2010). In South Africa, smallholder farmers highly relay on summer rainfall for dry bean production (Kadyampakeni *et al.*, 2013).

Due to the impacts of climate change and variability, the onset, duration and rainfall intensity, coupled with the duration and intensity of drought episodes will further increase water stress for dry bean production (Emam *et al.,* 2010). In dry bean stress, has been observed to reduce leaf area, chlorophyll content, stomatal closure, and accelerated maturity (Emam *et al.*, 2010). It has also been observed to change protein seed content, seed antioxidant accumulation, plant osmotic adjustment, hormone composition, cuticle leaf thickness, and leaf inhibition of photosynthesis (Fenta *et al.*, 2012).

However, dry beans have adaptive mechanisms to adapt under water stress, which include drought escape, avoidance, and dehydration tolerance (Kadyampakeni *et al.*, 2013). Water-stressed dry bean have reduced morphological size, leaf area, and leaf area index (LAI) as well as abnormal opening and closing of stomata (Fenta *et al.*, 2012). Reduction of leaf number and plant height is considered a phenotypic mechanism for controlling water use efficiency and reducing oxidative injury under drought stress conditions (Fenta *et al.*, 2012). During water stress osmotic adjustment is increased to avoid dehydration and hence, improves yield under water stress (Fenta *et al.*, 2012).

However, there are dry bean varieties that are adaptable to high water stress levels (Mirzaienasab and Mojaddam, 2014). These varieties are able to grow and survive under limited water conditions and be able to produce yield (Mirzaienasab and Mojaddam, 2014). These varieties have many traits that are beneficial for survival under drought stress, thereafter, considered advantageous for dry bean production under drought (Mirzaienasab and Mojaddam, 2014). However, some of the varieties are still prone to be affected by severe water stress conditions.

Agronomic management practices include the use of adaptable varieties, appropriate planting dates and plant densities. The use of early maturing and adaptable varieties as a method for drought escape is practiced. Planting at the optimum planting date aids the plant to take full advantage of environment, with optimum rains and temperatures for growth (Emam *et al.*, 2010). A study done by Fenta *et al.* (2012) showed that the use of adaptable varieties under rain-fed conditions increases the crops adaptability towards stress, resource partitioning and dry matter production (Sani *et al.*, 2014). Planting at an appropriate planting date resulted in increased crop growth period, increased yield and yield components (pod number and number of grains per pod, 100-grain weight), (Mirzaienasab and Mojaddam, 2014) for dry bean crop. A study done by Gómez-Plaza *et al*, (2001) showed that optimum plant spacing improves water use efficiency, and consequently an increased quality seed production. However a study done by Ren *et al.* (2016) showed that under extreme water stress, crop biomass, grain yield and water use efficiency were significantly low under high planting density for maize crop.

Dry beans are important crop but there is insufficient information and skill as guidelines to aid increasing dry bean production. Thus, there is need to invest and investigate more on optimum agronomic management practices that will aid on improving dry bean production. Therefore, the aim of this study was to determine effect of plant spacing and irrigation regimes on physiological parameters of three dry bean varieties. With the objectives to evaluate growth and yield parameters for three bean varieties grown under varying agronomic practices.

Materials and methods are explained in Chapter 3, section 3.3, 3.4.

5.2 Results

5.2.1 Weather and soil water content

5.2.1.1 Weather

During the growing period, average maximum and minimum temperature were 28.95 and 17.16 °C, respectively. The temperature range was 37.48 to 10.3°C. During the growing season, total rainfall was 341.63 mm while evapotranspiration was 379.26 mm. The rainfall was observed to have an uneven pattern throughout the growing season. Rainfall received during emergence and early vegetative stage [35 days after planting (DAP)] was 148.59 mm. During mid- to late vegetative phase (35 – 49 DAP), 66.55 mm of rainfall was received. During reproductive (49 - 58 DAP) rain was received of 104.90 mm, while, 21.59 mm was received during the maturity periods (58 – 65 DAP) to harvest periods with 21.59 mm. This rainfall distribution would suggest water stress during pod maturation.

5.2.1.2 Soil water content

Soil water content for the varieties was 24.47, 24.11, and 23.43% for Gadra, Mtata and Malelane respectively. Season two showed that soil water content was Mtata (23.12%) > Malelane (22.78%) > Gadra (21.36%). Season one showed higher soil water content (24.47%) when compared with season two soil water content (22.33%). Season one soil water content for low plant density was high (26.00%) compared to medium density (23.16%) and high density (22.52%). Season two soil water content medium density (23.46%) was high when compared to high density (22.05%) and low density (21.06%). Season one soil water content under irrigated (24.70%) was relatively high but, rain fed (24.07%), whereas season two showed irrigated was higher (24.96%), than rain-fed (19.96%).

Table 5. 1: Average volumetric soil water content (% volume) for the two seasons.

Variety	**Plant density**	**Water regime**	***Soil water content (%) season one**	***Soil water content (%) season two**
Gadra	Low	Rain-fed	25.54	21.72
	Medium		25.82	18.50
	High		22.54	18.28
	Low	Irrigated	24.47	22.00
	Medium		25.17	24.15
	High		23.32	23.62
Malelane	Low	Rain-fed	24.97	18.26
	Medium		22.04	21.66
	High		18.95	19.89
	Low	Irrigated	27.62	24.01
	Medium		24.70	26.13
	High		22.35	26.86
Mtata	Low	Rain-fed	26.53	18.00
	Medium		21.44	20.41
	High		22.35	23.06
	Low	Irrigated	27.37	23.40
	Medium		24.96	30.00
	High		22.45	24.66
		Seasonal mean	24.03	22.48

*Values of soil water content were not replicated. Therefore, values presented in the table are means of treatment combinations.

5.2.2 Crop physiology

5.2.2.1 Chlorophyll content

An interaction of variety x water regime had a significant affect (P=0.013) dry bean chlorophyll content (CCI). Across the planting seasons, the highest chlorophyll content index of 18.9 was observed for season one relative to season two 8.7. This was due to optimum environmental conditions of season one relative to season two. Marginal differences for chlorophyll content index were observed across the planting densities [high (37.32) > medium (35.68) > low (35.35)] and variety Gadra [(36.99) > Malelane (36.06), Mtata (35.32)] treatments. Gadra had a high CCI

(44.20) under high planting density and rain-fed water regime. The lowest CCI (29.11) was observed under the treatment combination of Mtata x season two x irrigated (Figure 5.1) (Appendix 8).

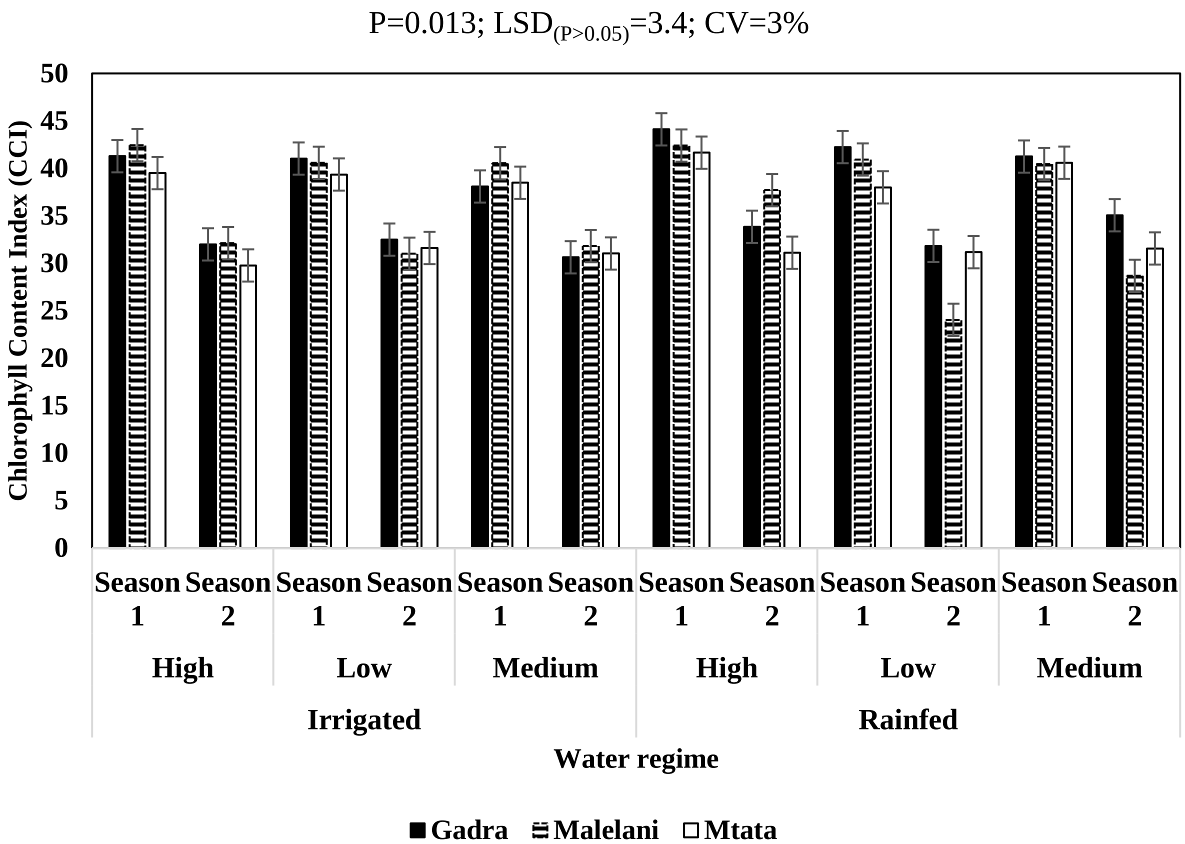

Figure 5.1: A comparison of chlorophyll content index for three dry bean varieties (Mtata, Gadra and Malelane), three planting densities (high, medium and low), and two seasons (Season one and two). Standard error bar represent standard deviation (±1.7).

5.2.2.2 Stomatal conductance

There were significant differences (P=0.018) observed for stomatal conductance for plant densities. Stomatal conductance was high for high planting density (351.06 mmol m^{-2} s^{-1}) when compared with low planting density (346.00 mmol m^{-2} s^{-1}) and medium planting density (321.62 mmol m^{-2} s^{-1}). There were significant differences (P=0.001) in stomatal conductance for the two growing seasons. Season one (18.93 mmol m^{-2} s^{-1}) had a higher stomatal conductance when compared with season two (8.70 mmol m^{-2} s^{-1}). These were also in line with soil water content results across the seasons. Variety x season x water regime had significant effects on stomatal conductance

(P=0.045). The interaction showed that between two water regimes irrigated was lower (337.00 mmol m^{-2} s^{-1}) when compared with rain-fed (341.65 mmol m^{-2} s^{-1}) (Figures 5.2 and 5.3) (Appendix 9).

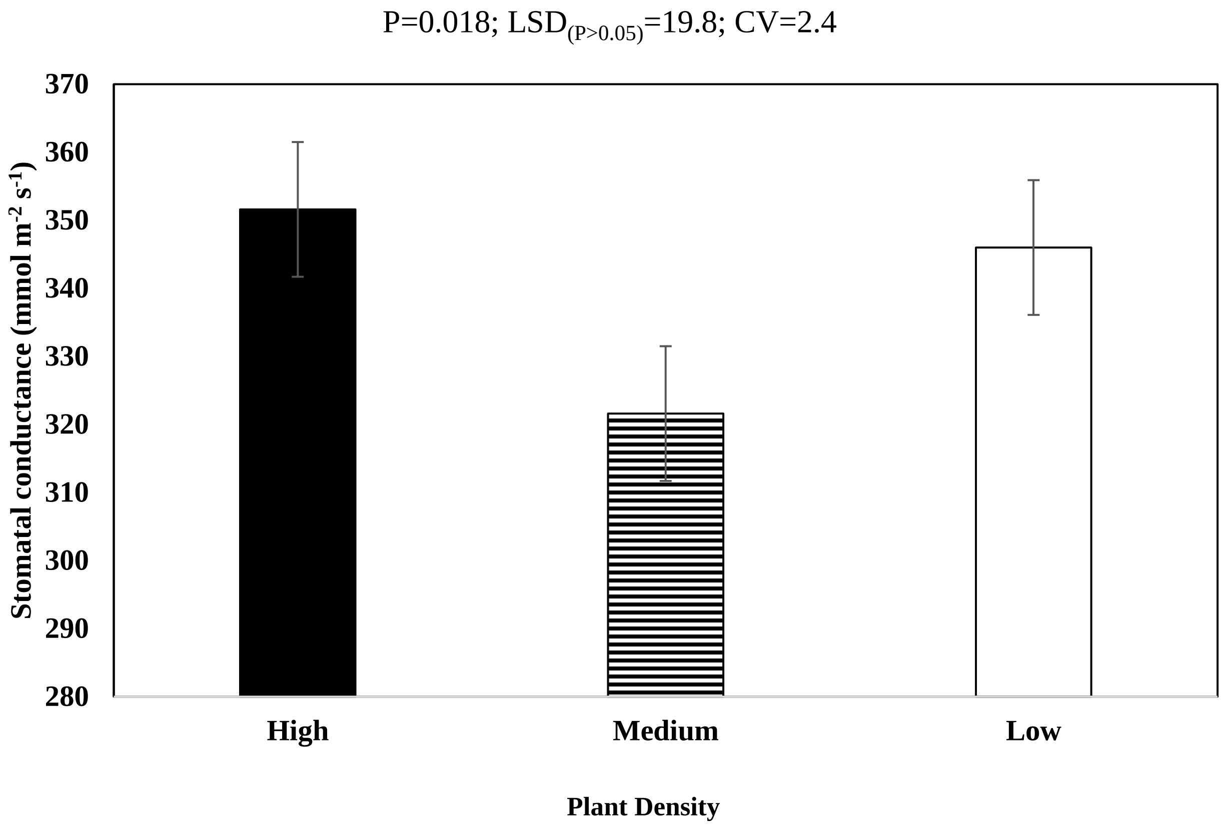

Figure 5.2: A comparison of stomatal conductance for three planting densities (high, medium, and low). Standard error bar represent standard deviation (±9.91).

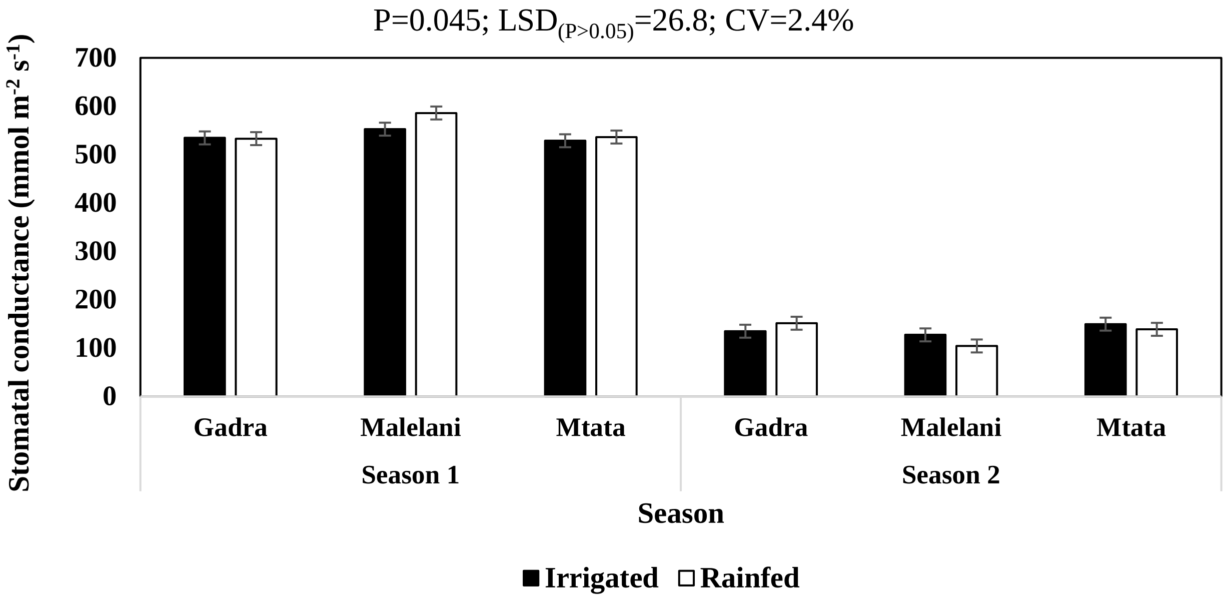

Figure 5.3: A comparison of stomatal conductance for two growing seasons (Season one and two), two water regimes (irrigated and rain-fed), and three dry bean varieties (Malelane, Gadra and Mtata). Standard error bar represent standard deviation (±13.4).

5.2.3 Crop growth

5.2.3.1 Field emergence

An interaction of water regime x variety and plant density had no significant differences (P>0.05) on dry bean emergence. However, water regime had significant differences (P=0.025) on emergence. The irrigated field had the highest emergence (70.00 %) relative to rain-fed (61.70 %) (Figure 5.4). There were significant differences (P = 0.001) observed for emergence for three dry bean varieties. Mtata had the highest emergence (75.20%) while Malelane and Gadra had a germination percentage of 64.30% and 58.00%, respectively (Figures 5.4 and 5.5) (Appendix 10).

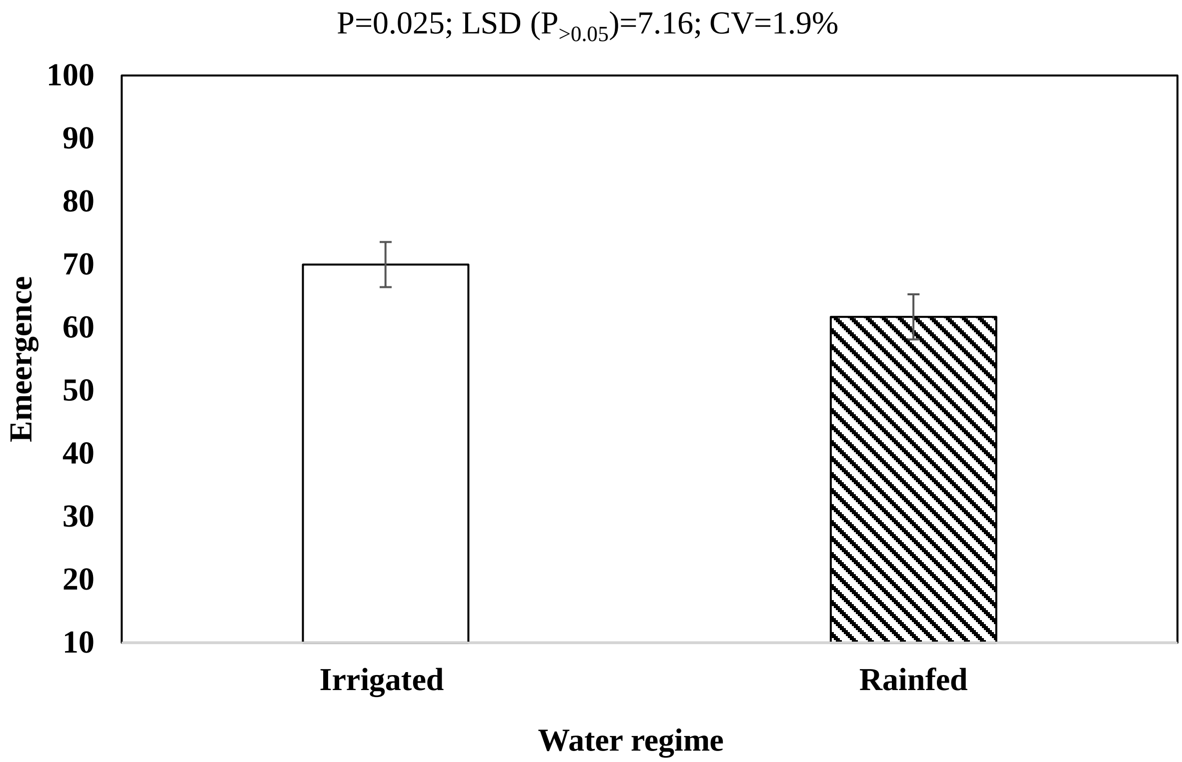

Figure 5.1: A comparison of final emergence for two water regimes (irrigated and rain-fed). Standard error bar represent standard deviation (±3.58).

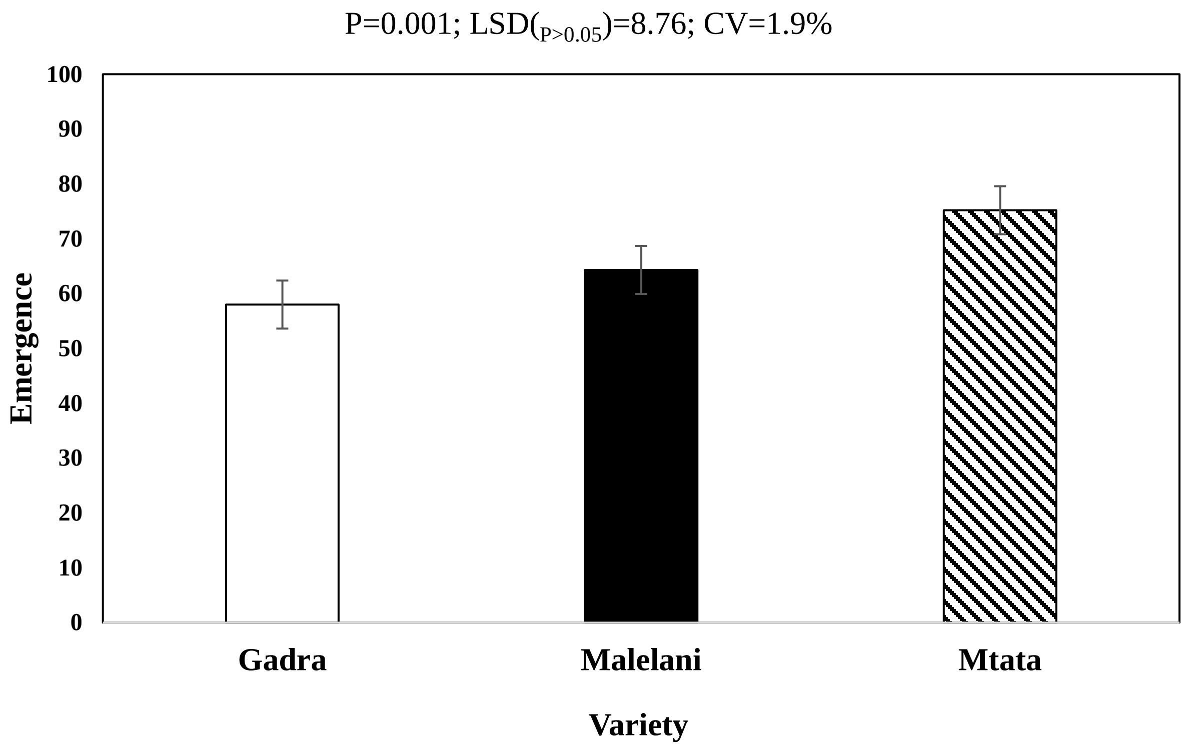

Figure 5.4: A comparison of final emergence for three dry bean varieties (Malelane, Gadra and Mtata). Standard error bar represent standard deviation (±4.38).

5.2.3.2 Leaf number

Plant density x growth season had significant effect on leaf number (P=0.008) (Appendix 11). Season one had a higher leaf number (6.80) compared to season two (3.90) (Figure 5.6). There was a slight difference under plant densities for leaf number with high planting density having a high leaf number (4.09) when compared to medium planting density (4.00) low planting density (3.80). For water regimes irrigated field had a higher leaf number (5.85) when compared to rain-fed field (4.94). With the varieties, Mtata had the highest leaf number (5.72) when compared with Gadra (5.69), and Malelane (4.82) under the two water regimes irrigated and rain-fed. Treatment combination season one, high density had the highest leaf number when compared with low density under two seasons with lowest leaf number (Figures 5.6 and 5.7).

P=0.001; LSD(P>0.05) = 0.34; CV = 3.1%

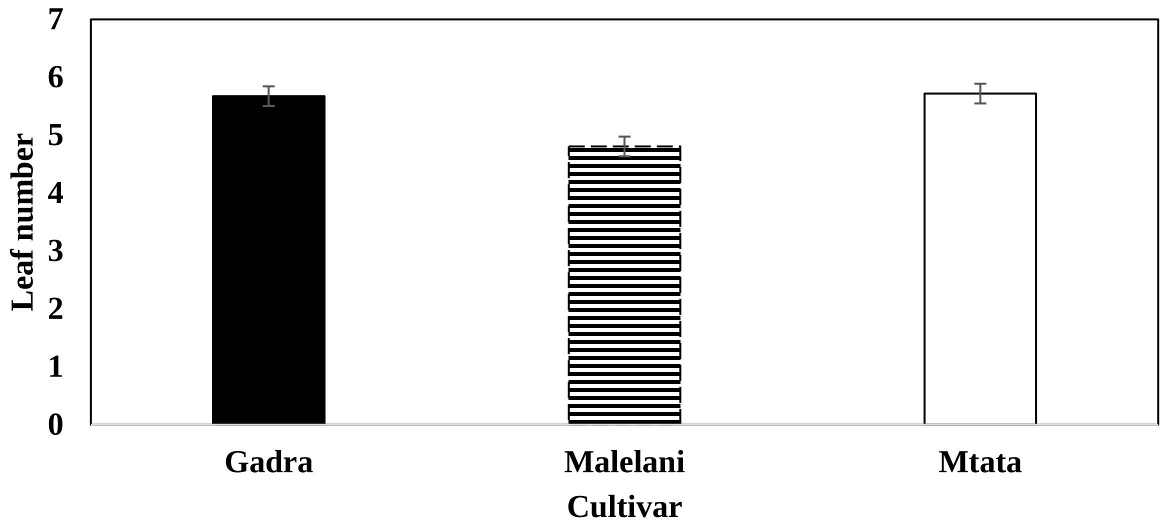

Figure 5.5: A comparison of final leaf number for three dry bean varieties (Mtata, Malelane and Gadra). Standard error bar represent standard deviation (±0.17).

P=0.008; LSD(P>0.05) = 0.64; CV = 3.1%

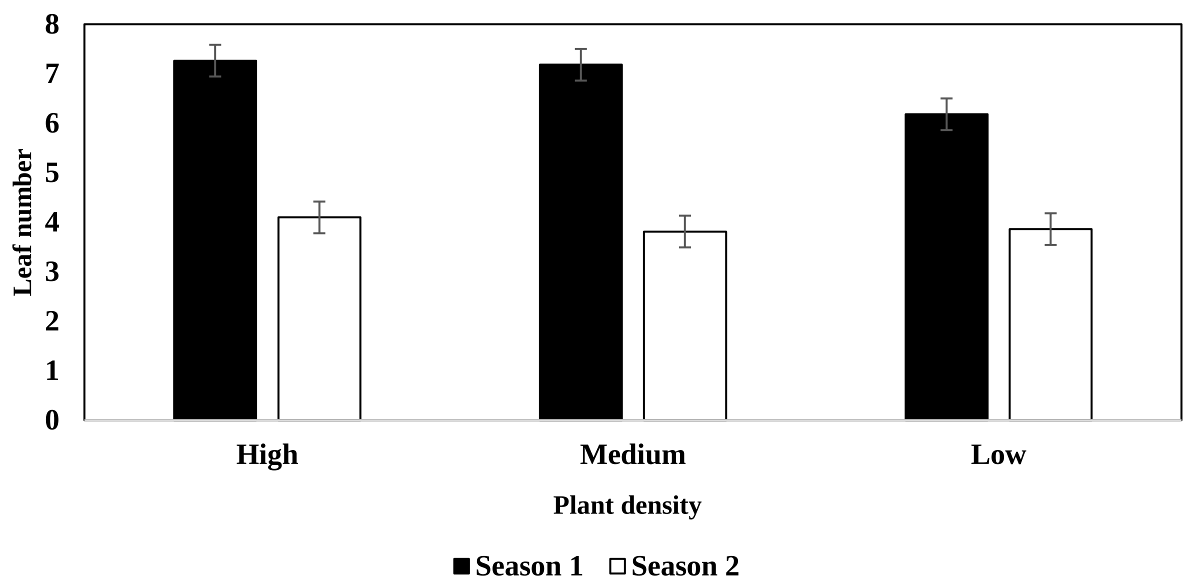

Figure 5.6: A comparison of final leaf number for plant density (high, medium and low) at two seasons (Season one and two). Standard error bar represent standard deviation (±0.32).

5.2.3.3 Plant height

Season x plant density x water regime x variety had significant effect on plant height (P=0.013) (Appendix 12). Season one had the highest plant height (18.91) when compared with season two (8.27) (Figure 5.8). This was contributed by that season one had optimum environmental conditions for dry beans production. For water regimes, irrigated had a high plant height when compared with rain-fed. Across all treatments combinations, Gadra had a high plant height (26.63) when compared with Malelane which had lowest plant height (5.83). The interaction of water regime and seasons showed that season one under both water regimes (irrigated and rain-fed) had the highest plant height relative to season two which had a low plant height (Figure 5.8).

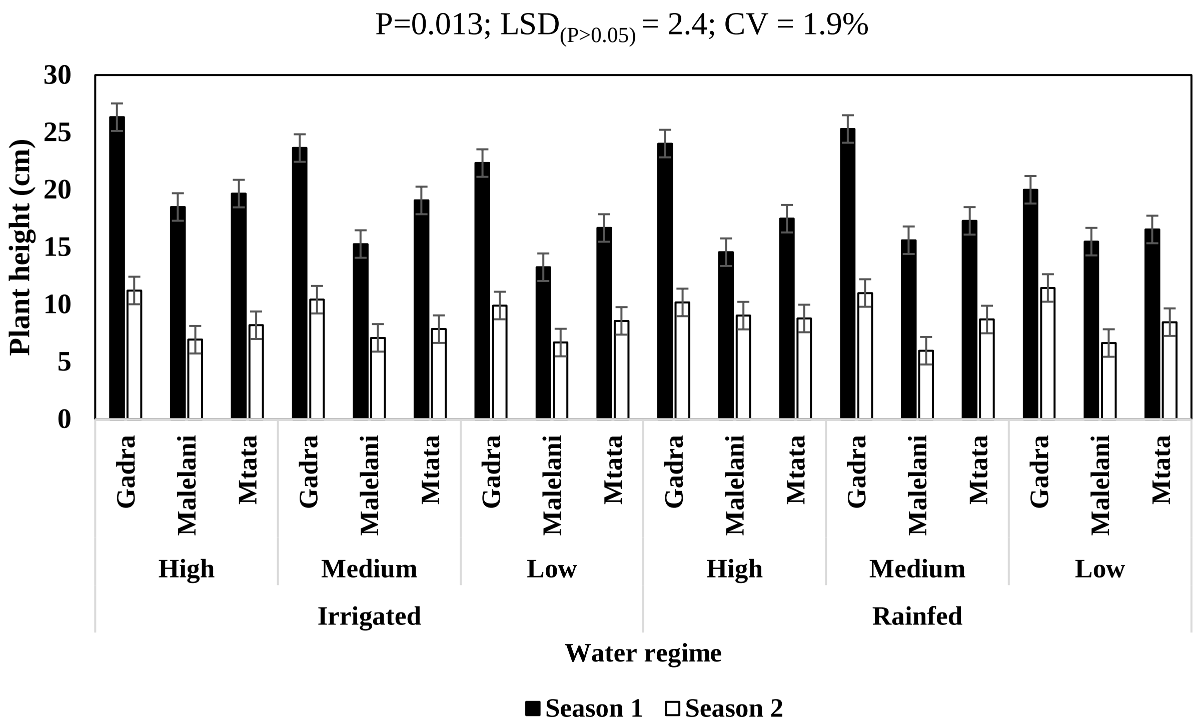

Figure 5.7: A comparison of plant height for two growing seasons (Season one and two) and two water regimes (irrigated and rain-fed), three plant densities (high, medium and low), and three dry bean varieties (Malelane, Gadra and Mtata). Standard error bar represent standard deviation (±1.2).

5.2.3.4 Leaf Area Index

There were significance differences (P=0.044) final leaf area index under three planting density (Appendix 13). A higher leaf area index was under high planting density (0.35) when compared with medium planting density (0.30) and low planting density (0.20). Water regime had significant effect (P = 0.001) on final leaf area index (Appendix 13). Irrigated had a high leaf area index (0.33) when compared with rain-fed (0.24). The same was observed on low leaf number and soil water content under rain-fed water regime. Season had significant effect (P=0.001) on final leaf area index. Between the two seasons, the results showed that season one had a high leaf area index (0.52) when compared with season two (0.048). However, there were no significant differences (P>0.05) observed for dry bean varieties. There were significance differences (P=0.006) for final leaf area index for water regime x season. The irrigated treatment had a high leaf area index (0.32) when compared to rain-fed (0.24) (Figures 5.9 and 5.10) (Appendix 13).

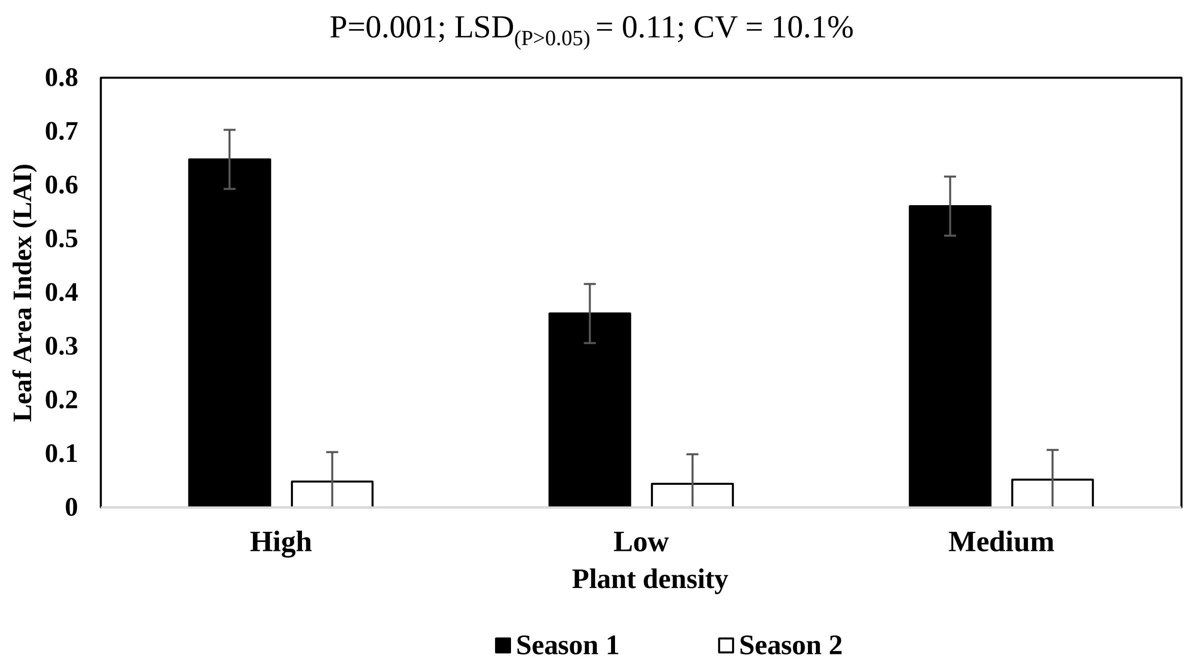

Figure 5.8: A comparison of leaf area index (LAI) for two seasons (Season one and two), and three planting densities (high, medium and low). Standard error bar represent standard deviation (±0.055).

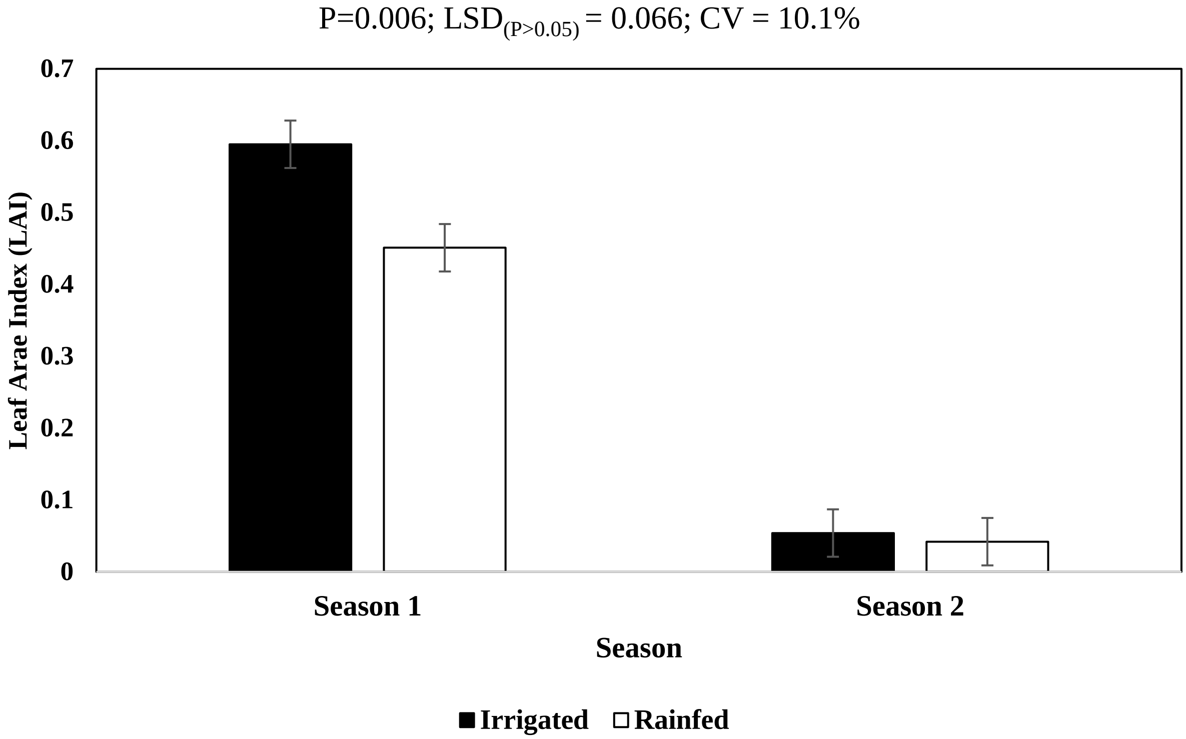

Figure 5.9: A comparison of leaf area index (LAI) for two seasons (Season one and two), and two water regimes (irrigated and rain-fed). Standard error bar represent standard deviation (±0.033).

5.2.3.5 Intercepted Photosynthetically Active Radiation (PAR)

There were significance differences (P=0.024) final intercepted photosynthetically active radiation PAR two water regimes (Appendix 14). The irrigated field had a high leaf area index (217.5 W m^{-2}) when compared with rain-fed (160.14 W m^{-2}). There were significance differences (P=0.001) for final intercepted PAR for two seasons. Season one had a high PAR (324.32 W m^{-2}) when compared with season two (53.60 W m^{-2}). Planting density had significant differences (P=0.002) for final intercepted PAR. High density planting density had a high intercepted PAR (234.40 W m^{-2}) when compared with medium planting density (192.42) and low planting density (140.22 W m^{-2}). There were significance differences (P=0.008) final intercepted PAR, water regime x season. For the water regime, irrigated field had high intercepted PAR (217.15 W m^{-2}) when compared with rain-fed (160.40 W m^{-2}). Seasons one had a high intercepted PAR (324.20 W m^{-2}) when compared with season two (53.16 W m^{-2}). Season one had high intercepted PAR (324.20 W m^{-2}) when compared with season two (53.60 W m^{-2}) (Figures 5.11 and 5.12).

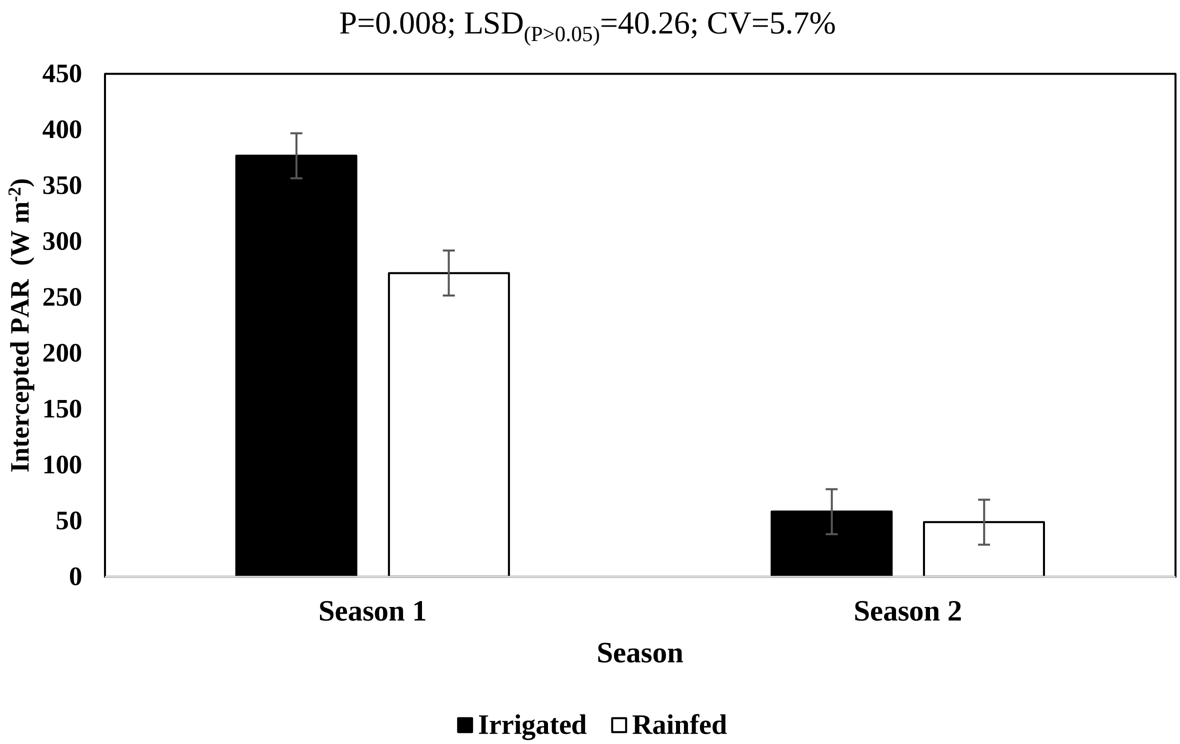

Figure 5.10: A comparison of intercepted photosynthetically active radiation (PAR) (W m^{-2}) for two growth seasons (season one and two) and two water regimes (irrigated and rain-fed). Standard error bar represent standard deviation (±20.13).

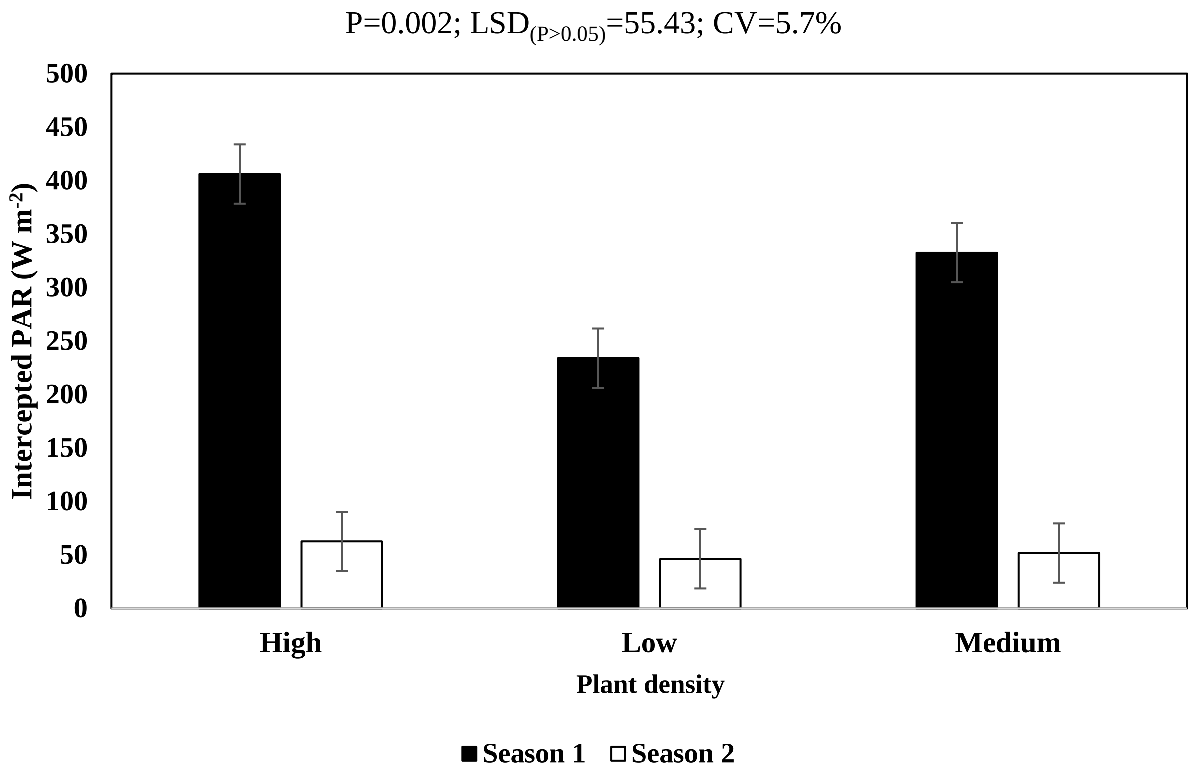

Figure 5.11: A comparison of intercepted photosynthetically active radiation (PAR) (W m^{-2}) for three planting densities (high, medium and low), and growth seasons (Season one and two). Standard error bar represent standard deviation (±27.72).

5.2.3.6 Flowering percentage

There were significance differences (P=0.001) for final flower percentage for three dry bean varieties (Appendix 15). Gadra had a high flower percentage (50.43%) when compared with Mtata (48.33%) and Malelane (42.23%). Seasons also showed significant differences (P=0.001) with respect to flower percentage. Season one had a high flower percentage (78.19%) when compared with seasons two (15.06%). There were no significant differences (P>0.05) for plant densities. An interaction of season and water regime had significance differences (P=0.003) on flower percentage. Season one had a high flower percentage (78.09%) when compared with season two (15.06%). Between the two water regimes rain-fed had a high flowering percentage (49.21%) when compared with irrigated (44.48%) (Figures 5.13 and 5.14).

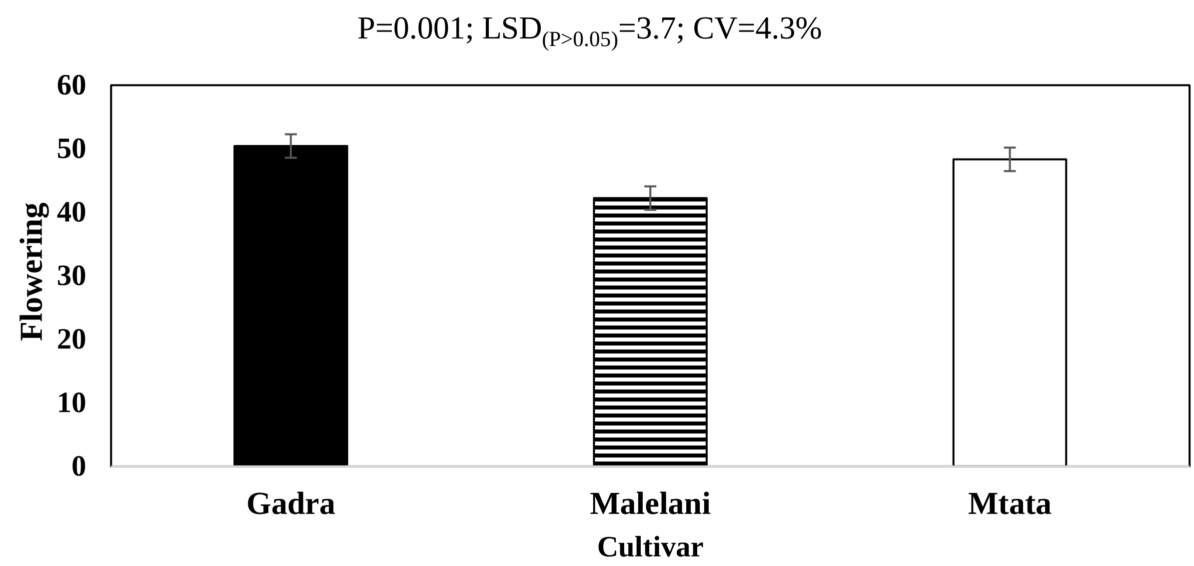

Figure 5.2: The evaluation of flower percentage for three dry bean varieties (Mtata, Gadra and Malelane). Standard error bar represent standard deviation (±1.85).

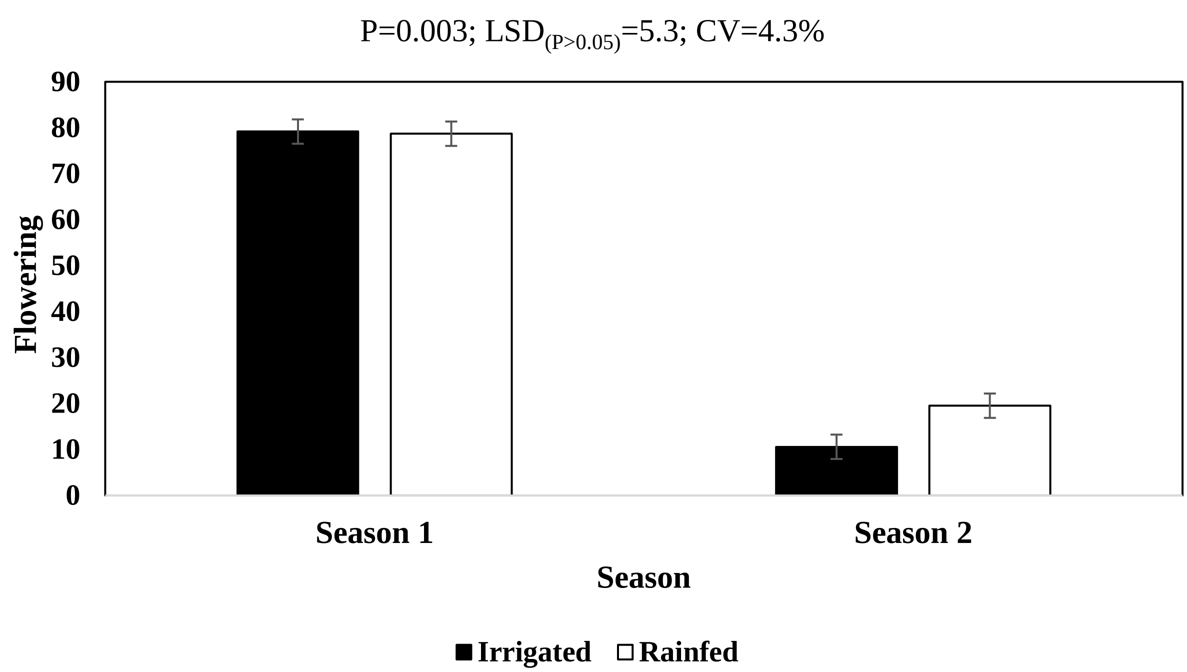

Figure 5.3: The evaluation of flower percentage for two seasons (Season one and two) and under two water regimes (irrigated and rain-fed). Standard error bar represent standard deviation (±2.65).

5.2.4 Yield and yield parameters

5.2.4.1 Biomass

Planting density had significant effect (P=0.002) on biomass (Appendix 16). Biomass was higher for high planting density (284.5 g) when compared with medium planting density (176.5 g) and low planting density (102.00 g). There were significant differences (P=0.001) observed final biomass, over season one and two. Season one had a high biomass (371.00 g) when compared with season two (10.00 g). There were no significant differences (P>0.05) observed amongst the three dry bean varieties in terms of final biomass. There were significant differences (P=0.001) observed final biomass, treatment combination growth seasons x plant density. Season one had the highest biomass (371.00 g) compared to season two (4.00 g). High biomass was observed under high planting density (284.50 g) when compared with medium planting density (176.50 g) and low planting density (102.00 g) (Figure 5.15).

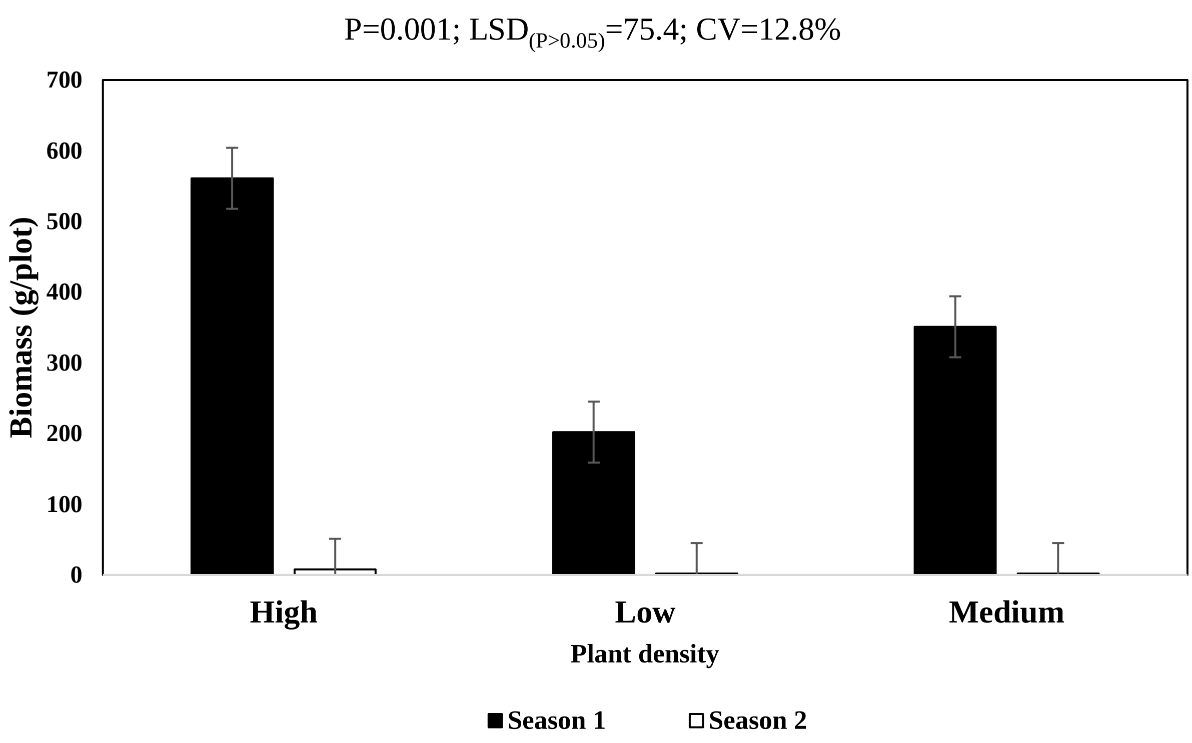

Figure 5.4: A comparison of final biomass for two seasons (Season one and two) and three plant densities (high, medium and low). Standard error bar represent standard deviation (±37.70).

5.2.4.2 Grain yield

Planting density had a significant effect (P=0.008) on final grain yield (Appendix 17). High planting density had a high grain yield (71.12 g/plot) when compared with medium planting density (51.01 g/plot) and low planting density (34.47 g/plot). There were significant differences (P=0.001) observed for final grain yield on two growth seasons. Season one had a high grain yield (103.51 g/plot) when compared with season two (1.20 g/plot). Grain yield showed that there was significance differences (P=0.001) among the three dry bean varieties. Gadra had a high grain yield (75.39 g/plot) when compared with Malelane (42.82 g/plot) and Mtata (42.18 g/plot). There were significance differences (P=0.001) final grain yield on planting density x variety. High planting density had a high grain yield (71.52 g/plot) when compared with medium planting density (51.11 g/plot) and low planting density (34.70 g/plot). Season x variety had significant effect (P = 0.001) on grain. Season one had a high grain yield (103.20 g/plot) when compared with season two (1.20 g/plot) (Figure 5.16 and 5.17).

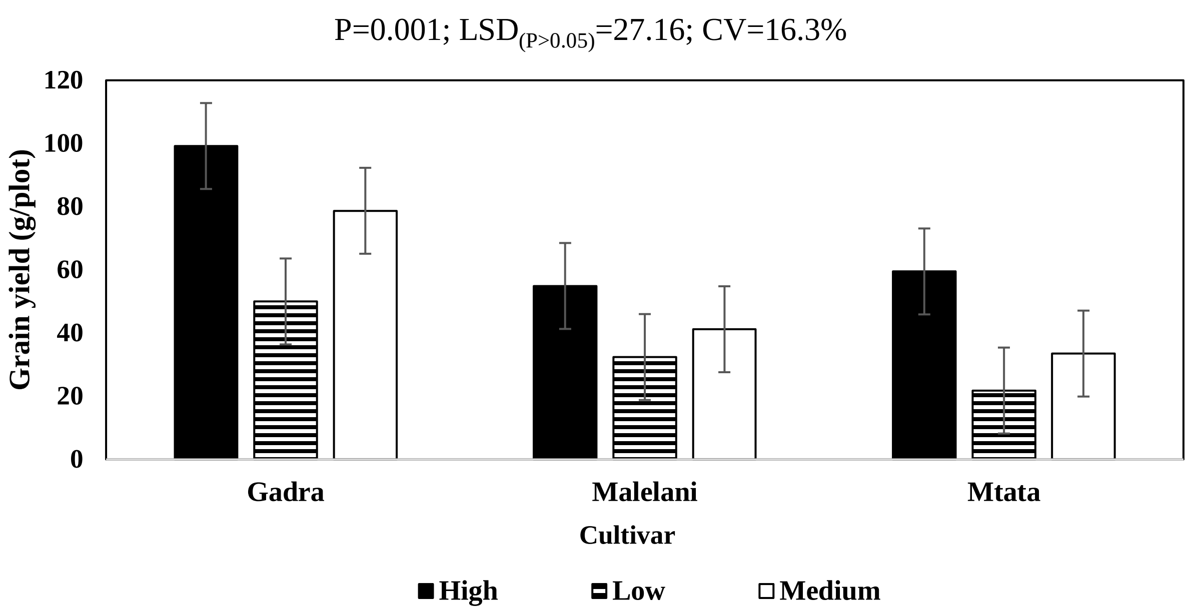

Figure 5.5: A comparison of final grain yield for three dry bean varieties (Mtata, Gadra and Malelane) and plant density (high, medium and low). Standard error bar represent standard deviation (±13.58).

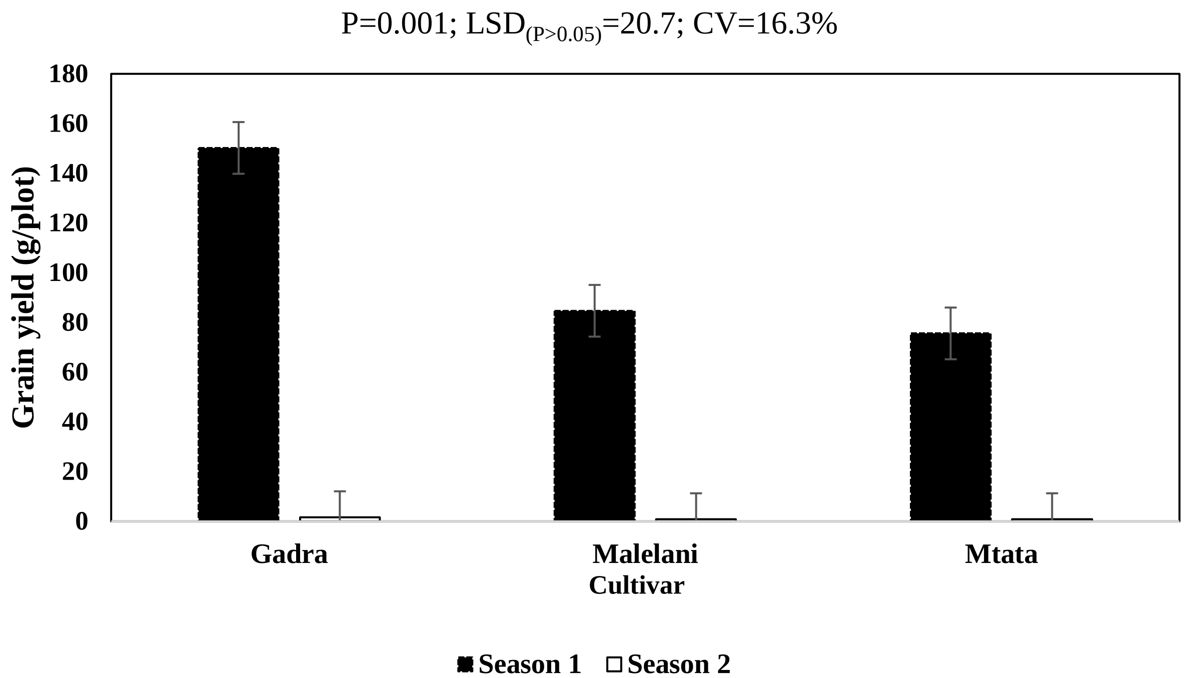

Figure 5.6: A comparison of final grain yield for three dry bean varieties (Mtata, Gadra and Malelane) and under two seasons (Season one and two). Standard error bar represent standard deviation (±10.35).

5.2.4.3 Harvest Index

Variety had significant effect (P=0.001) on harvest index (Appendix 18). Gadra had higher harvest index (20.7%) when compared with Malelane (13.12%) and Mtata (9.99%). There were significant differences (P=0.001) final harvest index on water regimes. Irrigated had higher harvest index (29.05%) when compared with rain-fed (0.23%). Water regime x season had significant effect (P = 0.001) on final harvest index. Season one had higher harvest index (27.00%) when compared with season two (2.00%). Planting density x season had significant effect (P=0.005) on harvest index. Low density had high harvest index (16.71%) when compared with medium (14.55%) and high density (12.62%) (Figures 5.18, 5.19 and 5.20).

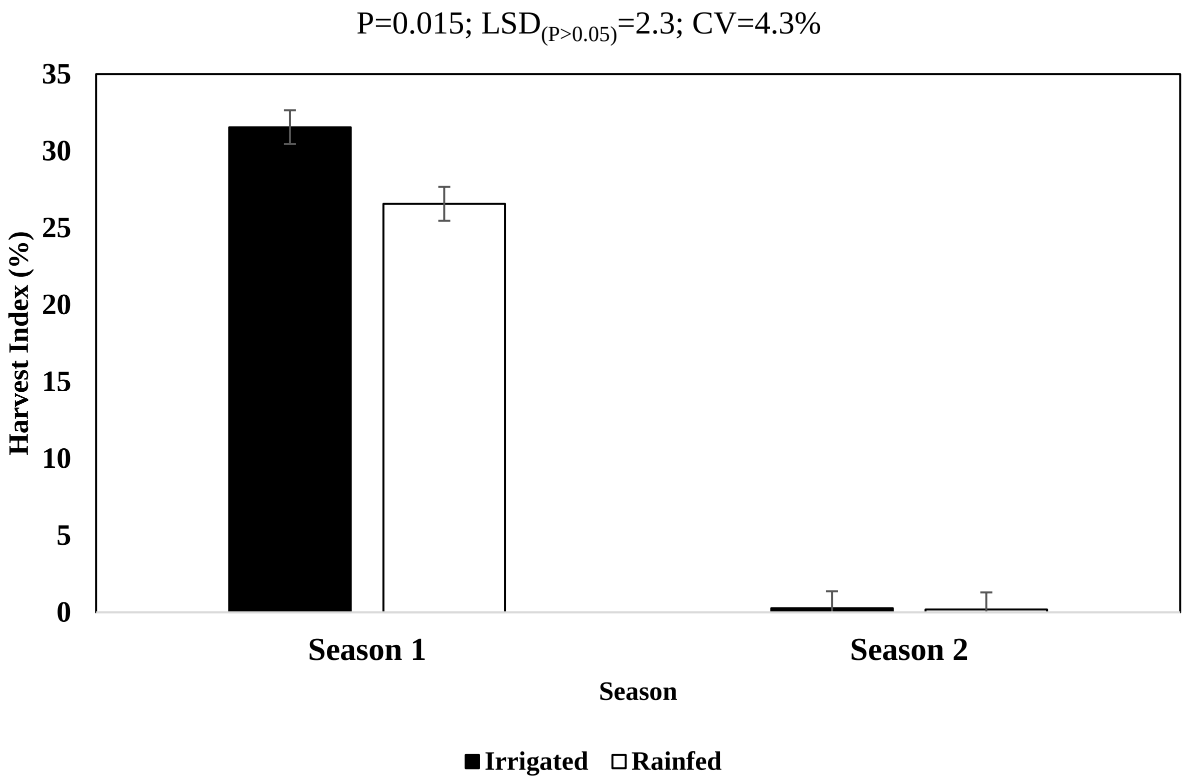

Figure 5.7: A comparison of harvest index (HI) for two water regimes (irrigated and rain-fed) and two seasons (Season one and two). Standard error bar represent standard deviation (±1.15).

P=0.005; $LSD_{(P>0.05)}$=3.9; CV=4.3%

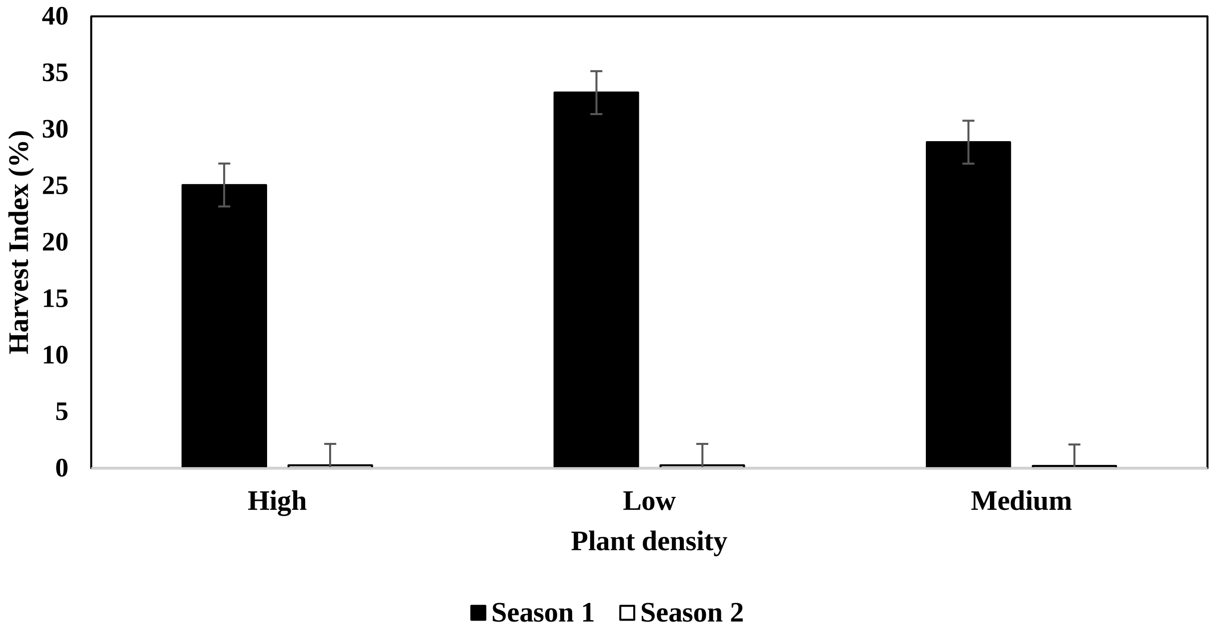

Figure 5.8: A comparison of harvest index (HI) for two seasons (Season one and two seasons) and three planting densities (high, medium and low). Standard error bar represent standard deviation (1.95).

P=0.001; $LSD_{(P>0.05)}$=3.4; CV=4.3%

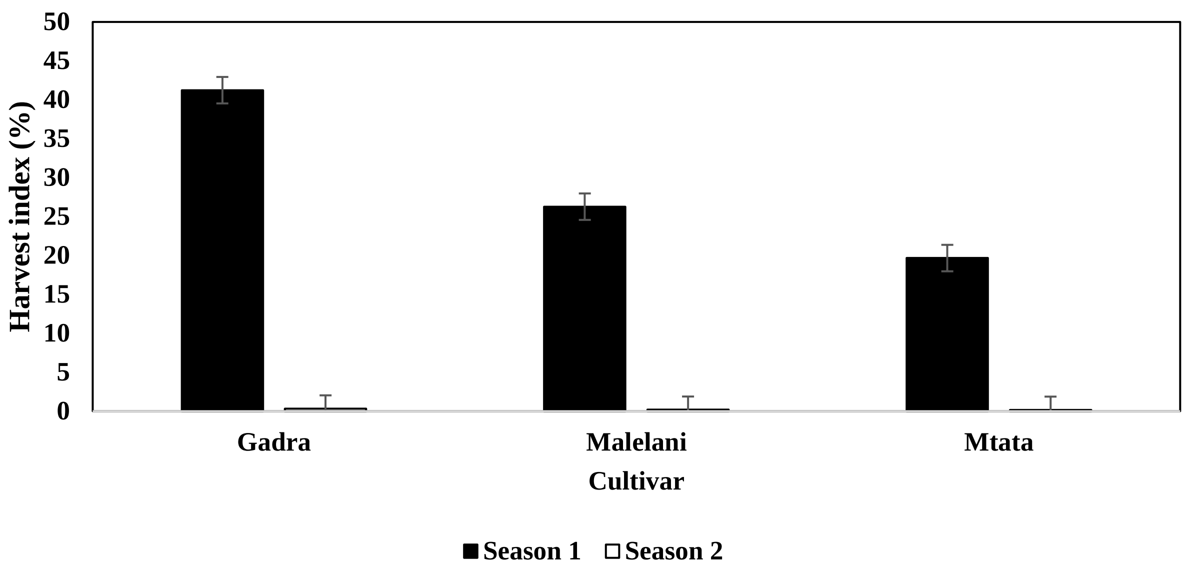

Figure 5.9: A comparison of harvest index (HI) for two seasons (Season one and two) and three varieties (Malelane, Gadra and Mtata). Standard error bar represent standard deviation (±1.7).

5.2.5 Crop water use and water use efficiency

Crop water use for three dry bean varieties Malelane had a high crop water use (320.42 mm) when compared with Gadra (287.19 mm) and Mtata (283.54 mm). Water use efficiency was high for Gadra (0.0037 kg m^{-3}) when compared with Malelane (0.00091 kg m^{-3}) and Mtata (0.00088 kg m^{-3}). For water regimes, crop water use was high for irrigated (329.92 mm) and relatively low for rain-fed (263.50 mm). Water use efficiency was low for rain-fed (0.0013 kg m^{-3}) when compared with irrigated (0.0024 kg m^{-3}). Crop water use for plant density was high for medium planting density (310.86 mm) when compared with high (291.83 mm) and low planting density (287.47 mm). Water use efficiency for plant density was high for medium planting density (0.0031 kg m^{-3}) when compared with high planting density (0.0016 kg m^{-3}) and low planting density (0.00083 kg m^{-3}) (Table 5.2).

Table 5.2: Crop water use, yield and water use efficiency comparisons for dry bean varieties (Mtata, Gadra and Malelane), water regimes (irrigated and rain-fed), and plant density (high, medium and low).

Variety	**Plant density**	**Water regime**	**Crop water use (mm)**	**Water use efficiency (kg m^{-3})**
Gadra	Low	Rain-fed	249.18	0.0011
	Medium		276.38	0.0021
	High		265.70	0.0020
	Low	Irrigated	290.76	0.0013
	Medium		351.98	0.0131
	High		289.12	0.0026
Malelane	Low	Rain-fed	274.25	0.0010
	Medium		307.04	0.0011
	High		289.11	0.0014
	Low	Irrigated	347.71	0.0004
	Medium		351.00	0.0006
	High		347.46	0.0009
Mtata	Low	Rain-fed	247.68	0.0007
	Medium		215.25	0.0009
	High		247.07	0.0010
	Low	Irrigated	315.22	0.0004
	Medium		363.50	0.0007
	High		312.53	0.0017

*Values of crop water use, yield and water use efficiency were not replicated. Therefore, values presented in the table are means of treatment combinations.

5.3 Discussion

Soil water content for growth seasons was observed to be higher under season one when compared with season two. Seasonal variations in the soil water content were due to the fact that under season one there were optimal weather conditions namely rainfall, hence the soil received adequate amounts of water (Gómez-Plaza *et al.*, 2001). Treatment combination of medium planting density under both growing seasons had a high soil water content. Hence, this combination can be suggested for dry bean production under season one and two.

Irrigation under season one and two had a high soil water content when compared with rainfed. This can be explained by that water was received through irrigation, hence, rain-fed had water stress, therefore, lower soil water content (Brevedan *et al.*, 2012). Furthermore, crop water use and water use efficiency was high for irrigated and relatively low for rain-fed. According to Mathobo *et al.* (2017), WUE was high under occasionally irrigated field. Crop water use and water use efficiency varied amongst the dry bean varieties. Different dry bean variety choice as they had different adaptability towards water stress, root structure and metabolic rate (Chaves *et al.*, 2002) .Malelane had a high crop water use when compared with Gadra and Mtata and water use efficiency was high for Gadra when compared to Malelane and Mtata. Thus, supporting that different dry bean varieties had varied adaptability. The results showed that the optimum agronomic management practices were medium planting density that had high water use efficiency compared with low and high planting density.

Water regime had significant effect (P=0.025) on final emergence. The differences were similar to those observed for soil water content whereby irrigated treatment had high emergence when compared with rainfed. This suggests that high water content under season one influenced crop stand when compared with rainfed which most likely was under water stress resulted in low emergence. Suggesting that water availability influences final crop stand establishment (Brevedan *et al.*, 2012). This supports that water is required for good crop emergence (Department of Agriculture, 2010). A study done by Brevedan *et al.* (2012) showed that under reduced water potential, reduced shoot length on lovegrass. Futhermore, a similar trend was observed for different variety responses towards emergence under the plant growth conditions.

Interaction of variety x water regime had a significant affect (P=0.013) dry bean chlorophyll content (CCI). Across the planting seasons, the highest chlorophyll content index of was observed for season one relative to season two. This was due to optimum environmental conditions of season one relative to season two. In which supports that optimum growth season had positive influence on maize crop production (Ma *et al.*, 2007). Higher CCI suggest that the plant had a high photosynthetic rate leading to high plant growth and yield components (Chaves *et al.*, 2002). However, rainfed field had lower CCI due to water stress, meaning the plants had water stress defence mechanism by lowering the metabolic rate/photosynthesis rate, hence, the low CCI (Chaves *et al.*, 2002). A study done by Mathobo *et al.* (2017) showed that under water stress leaf function is reduced and, therefore, low chlorophyll content. Variety x season x water regime had significant effect (P=0.045) on final stomatal conductance. An interaction between the two water regimes showed that irrigation treatment had a lower stomatal conductance when compared with rain-fed (Figure 5.3).

Interaction of plant density x plant growth seasons had significant differences (P=0.008) observed for leaf number. Season one had a higher leaf number when compared with season two. Thus, supporting that the high soil water content under season one and for irrigated had influence on plant growth. Water regimes results showed that irrigated field had a higher leaf number compared to rainfed field. Hence, water availability had positive influence on plant growth. Irrigated treatment had higher water use efficiency, therefore, explaining high leaf number observed from the leaf number results. According to Poni *et al.* (2015) reduced leaf number was induced by water stress. Treatment combination season one x high density had the highest leaf number when compared with low density x season two had lower leaf number (Figure 5.7). Significant differences (P = 0.013) for the interaction of season x plant density x water regime x cultivar were observed for plant height. Plant height results had similar trend as those of leaf number in terms of treatment effects on plant height.

An interaction of water regime x season had significance differences (P=0.006) for final leaf area index. The observed trend was similar as for plant height. As water stress lead to reduced leaf area index (Mathobo *et al.*, 2017). Water regime x season had significant effect (P=0.008) on for final intercepted PAR. The observed results were similar as that of leaf area index. Water stress caused a lower intercepted PAR due to the lowered leaf area index.

An interaction of season and water regime had significance differences (P=0.003) on plant flowering percentage. Seasons had similar effects on flowering as the above mentioned parameters. However, flowering percentage was higher under rainfed when compared with irrigated trials and earlier flowering is characteristic of drought escape mechanisms (Fenta *et al.*, 2012). Hence, higher flowering percentage observed under rainfed was due to the limited water conditions.

5.4 Conclusion

The investigation showed that dry bean growth and productivity is responsive agronomic management practices (dry bean varieties, plant density, season, and water availability). The variability among the three dry bean cultivars confirmed the initial hypothesis that variety selection is critical. The results show that soil water content highly influenced plant growth. Planting date highly influenced water availability. Planting date (season), and water regime showed to be one universal factor with an impact on growth and yield parameters. The results of the study confirmed that agronomic practices such as variety and planting date selection, planting density and water availability have an effect on crop growth and productivity. The results of this study could contribute to the development of best management practices to assist farmers improve productivity, especially under rainfed conditions.

References

Ahmadi, M. and Bahrani, M. 2009. Yield and yield components of rapeseed as influenced by water stress at different growth stages and nitrogen levels. *American-Eurasian Journal of Agricultural and Environmental Sciences,* 5, 755-761.

Brevedan, R., Klich, M., Sanchez, E. and Fioretti, M. 2012. Effects of water stress on germination and seedling growth of lovegrass species. *Plant Physiology and Growth.* 35-36.

Chaves, M. M., Pereira, J. S., Maroco, J., Rodrigues, M. L., Ricardo, C. P. P., Osório, M. L., Carvalho, I., Faria, T. and Pinheiro, C. 2002. How plants cope with water stress in the field? Photosynthesis and growth. *Annals of Botany,* 89**,** 907-916.

Department of Agriculture. 2016. Crop estimate committe. Department of Agriculture, Forestry and Fisheries (Republic of South Africa).

Emam, Y., Shekoofa, A., Salehi, F. and Jalali, A. 2010. Water stress effects on two common bean cultivars with contrasting growth habits. *American-Eurasian Journal of Agricultural and Environmental Sciences,* 9**,** 495-499.

Fenta, B. A., Driscoll, S., Kunert, K. J. and Foyer, C. H. 2012. Characterization of drought-tolerance traits in nodulated soya beans: The importance of maintaining photosynthesis and shoot biomass under drought-induced limitations on nitrogen metabolism. *Journal of Agronomy and Crop Science,* 198**,** 92-103.

Gitelson, A. A., Vina, A., Ciganda, V., Rundquist, D. C. and Arkebauer, T. J. 2005. Remote estimation of canopy chlorophyll content in crops. *Geophysical Research Letters,* 32, 66-80.

Gómez-Plaza, A., Martınez-Mena, M., Albaladejo, J. and Castillo, V. 2001. Factors regulating spatial distribution of soil water content in small semiarid catchments. *Journal of hydrology,* 253**,** 211-226.

Joshi, S. and Rahevar, H. 2014. Effect of dates of sowing, row spacings and varieties on growth attributing characters of rabi Indian bean (*Dolichos lablab* L.). *Trends in Biosciences,* 7**,** 3717-3721.

Kadyampakeni, D. M., Mloza-Banda, H. R., Singa, D. D., Mangisoni, J. H., Ferguson, A. and Snapp, S. 2013. Agronomic and socio-economic analysis of water management techniques for dry season cultivation of common bean in Malawi. *Irrigation Science,* 31**,** 537-544.

Khan, Z. R., Midega, C. A., Pittchar, J. O., Murage, A. W., Birkett, M. A., Bruce, T. J. and Pickett, J. A. 2014. Achieving food security for one million sub-Saharan African poor through push–pull innovation by 2020. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 369**,** 201-218.

Ma, G., Xue, J., Lu, H., Zhang, R., Tai, S. and Ren, J. 2007. Effects of planting date and density on population physiological indices of summer corn (*Zea mays* L.) in central Shaanxi irrigation area]. *Ying yong sheng tai xue bao. The journal of applied ecology/Zhongguo sheng tai xue xue hui, Zhongguo ke xue yuan Shenyang ying yong sheng tai yan jiu suo zhu ban*, 18**,** 1247-1253.

Mathobo, R., Marais, D. and Steyn, J. M. 2017. The effect of drought stress on yield, leaf gaseous exchange and chlorophyll fluorescence of dry beans (Phaseolus vulgaris L.). *Agricultural Water Management,* 180**,** 118-125.

Mirzaienasab, M. and Mojaddam, M. 2014. The effect of planting date on yield and yield components of two red bean cultivars in azna weather conditions. *Indian Journal of Fundamental and Applied Life Sciences ISSN,* 4 (3)**,** 417-422.

Pietragalla, J. and Pask, A. 2012. Stomatal conductance. Physiological breeding II: a field guide to wheat phenotyping. CIMMYT, Mexico**,** 15-17.

Poni, S., Lakso, A., Turner, J. and Melious, R. 2015. The effects of pre-and post-veraison water stress on growth and physiology of potted Pinot Noir grapevines at varying crop levels. *VITIS-Journal of Grapevine Research,* 32**,** 207-218.

Ren, X., Sun, D. and Wang, Q. 2016. Modeling the effects of plant density on maize productivity and water balance in the Loess Plateau of China. *Agricultural Water Management,* 171**,** 40-48.

Sani, A., Abubakar, B., Abubakar, D., Atala, T. and Abubakar, L. 2014. Socio-economic factors influencing adoption of dual-purpose cowpea production technologies in Bichi Local Government Area of Kano State, Nigeria. *Asian Journal of Agricultural Extension, Economics And Sociology,* 3**,** 257-274.

Stanhill, G. 1986. Water use efficiency. *Advances in Agronomy,* 39**,** 53-85.

Tsimba, R., Edmeades, G. O., Millner, J. P. and Kemp, P. D. 2013. The effect of planting date on maize grain yields and yield components. *Field Crops Research,* 150**,** 135-144.

Wheeler, T. and Von Braun, J. 2013. Climate change impacts on global food security. *Science,* 341**,** 508-513.

Wildman, R. E., Wildman, R. and Wallace, T. C. 2016. *Handbook of nutraceuticals and functional foods*, CRC press.

CHAPTER SIX

6.1 General Discussion

Opportunities for improving dry bean production exist through the use of water quantity and agronomic management practices. These include the use of appropriate planting dates, plant densities and adaptable varieties.

The key findings of the study were that seed quality for pre– and post–planting dry beans varied among varieties with Mtata, Malelane and Gadra, having varied responses when subjected to the varied agronomic conditions. Seed quality parameters test varied significantly among varieties, plant densities, and water availability with high significant differences observed between two planting seasons. The results showed that planting in summer was ideal for dry production. It was observed that seed germination, GVI, and MGT was low under rain-fed conditions. This showed that the varieties under review had similar disadvantages over water stress as those used by smallholder farmers who mostly practice rain-fed farming and retain seed for planting in the next season.

Overall, the study confirmed that agronomic management practices are an important crop production factor as they influence crop growth, physiology and yield. Therefore, careful and appropriate selection of agronomic practices is best suited to farmers' environment critical to a successful crop production. Since smallholder farmers typically retain seed from the previous harvest for planting in the subsequent season, appropriate selection of planting date is key to attaining high quality seed. Inappropriate planting date selection could lead to poor seed quality thus negatively affecting the subsequent season's crop.

6.2 Conclusions

The study confirmed that agronomic practices that the maternal plant was exposed to affected plant growth, physiology and yield; and therefore, subsequent seed quality. The study also showed that all varieties were adapted to rain-fed conditions, thus, making them ideal for production in rain-fed agro-ecologies. The effects of planting date and water regime had almost similar effect on crop growth, physiology and yield. Thus, planting date and water regime should be managed in conjunction with each other. Under rain-fed conditions, appropriate planting date influence water availability during the season. The results suggested that dry bean production was more suited to grow adaptable under season one when compared with second season as dry bean failed to produce yield due to low and sub-optimum temperatures. Seed quality is a function of production environment. Thus, the use of best management is critical to producing seed of high quality. The fact that dry bean seed quality was relatively high under rain-fed production is encouraging for smallholder farmers who practice rain-fed agriculture.

6.3 Recommendations

The following recommendations can be made based on this study's findings:

- the use of good agronomic management practices, through best management practices, is recommended as it leads to high yields. Farmers should seeks advisory services to obtain information on the best management practices suited to their specific agro-ecologies;
- subsequent seed quality is heavily linked to how maternal plants were managed i.e. quality is grown in the field. Again, the use of good agronomic practices such as proper planting date selection and plant density is strongly encouraged for farmers who wish to retain seed for subsequent seasons;
- farmers practising rain-fed production can produce seed of good quality given that they adhere to best management practices; and
- future research should elucidate more on the effect of agronomic practices on subsequent seed quality, paying special attention to seed physiology and the acquisition of seed quality i.e. sugar profiles and protein analyses.

APPENDICES

APPENDIX 1: Analysis of variance table for germination percentage.

1) Variate: Germination_%

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	167.33	55.78	1.70	
Rep.*Units* stratum					
Variety	2	304.00	152.00	4.63	0.027
Day	1	80.67	80.67	2.46	0.138
Variety.Day	2	5.33	2.67	0.08	0.922
Residual	15	492.67	32.84		
Total	23	1050.00			

APPENDIX 2: Analysis of variance table for Germination Velocity Index (GVI).

2) Variate: GVI

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	10.458	3.486	1.70	
Rep.*Units* stratum					
Variety	2	19.000	9.500	4.63	0.027
Day	1	5.042	5.042	2.46	0.138
Variety.Day	2	0.333	0.167	0.08	0.922
Residual	15	30.792	2.053		
Total	23	65.625			

APPENDIX 3: Analysis of variance table for germination percentage.

3) Variate: Germination_%

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.

Replication stratum	2	280.29	140.15	0.56	
Replication.Water stratum					
Water	1	3348.21	3348.21	13.36	0.067
Residual	2	501.19	250.60	0.97	
Replication.Water.Density stratum					
Density	2	250.13	125.07	0.49	0.632
Water.Density	2	3324.21	1662.10	6.47	0.021
Residual	8	2056.61	257.08	0.71	
Replication.Water.Density.Variety stratum					
Variety	2	7149.34	3574.67	9.86	<.001
Water.Variety	2	972.62	486.31	1.34	0.281
Density.Variety	4	3554.63	888.66	2.45	0.074
Water.Density.Variety	4	9530.56	2382.64	6.57	0.001
Residual	24	8704.76	362.70	21.52	
Replication.Water.Density.Variety.*Units* stratum					
Days	6	28209.92	4701.65	278.96	<.001
Water.Days	6	698.54	116.42	6.91	<.001
Density.Days	12	395.24	32.94	1.95	0.030
Variety.Days	12	22923.81	1910.32	113.34	<.001
Water.Density.Days	12	830.42	69.20	4.11	<.001
Water.Variety.Days	12	843.12	70.26	4.17	<.001
Density.Variety.Days	24	505.56	21.06	1.25	0.202
Water.Density.Variety.Days	24	881.48	36.73	2.18	0.002
Residual	216	3640.48	16.85		
Total	377	98601.12			

APPENDIX 4: Analysis of variance table for Germination Velocity Index (GVI).

4) Variate: GVI

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	1.5822	0.7911	1.00	
Replication.*Units* stratum					
Days	6	4424.0289	737.3382	928.29	<.001
Water	1	31.2078	31.2078	39.29	<.001
Density	2	0.5006	0.2503	0.32	0.730
Variety	2	211.5109	105.7554	133.14	<.001
Days.Water	6	40.1385	6.6897	8.42	<.001

Days.Density	12	5.7849	0.4821	0.61	0.836
Water.Density	2	29.6359	14.8180	18.66	<.001
Days.Variety	12	936.5430	78.0452	98.26	<.001
Water.Variety	2	12.6216	6.3108	7.95	<.001
Density.Variety	4	26.9566	6.7391	8.48	<.001
Days.Water.Density	12	42.7633	3.5636	4.49	<.001
Days.Water.Variety	12	21.8765	1.8230	2.30	0.009
Days.Density.Variety	24	38.9300	1.6221	2.04	0.004
Water.Density.Variety	4	60.1598	15.0400	18.93	<.001
Days.Water.Density.Variety	24	56.4112	2.3505	2.96	<.001
Residual	250	198.5738	0.7943		
Total	377	6139.2254			

APPENDIX 5: Analysis of variance table for Mean Germination Time (MGT).

5) Variate: MGT

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.0013248	0.0006624	1.98	
Rep.water_regime stratum					
water_regime	1	0.0025165	0.0025165	7.51	0.111
Residual	2	0.0006698	0.0003349	0.43	
Rep.water_regime.density stratum					
density	2	0.0017914	0.0008957	1.15	0.365
water_regime.density	2	0.0061105	0.0030552	3.91	0.065
Residual	8	0.0062501	0.0007813	0.98	
Rep.water_regime.density.*Units* stratum					
variety	2	0.0009912	0.0004956	0.62	0.544
water_regime.variety	2	0.0017053	0.0008526	1.07	0.357
density.variety	4	0.0089002	0.0022250	2.80	0.048
water_regime.density.variety	4	0.0248011	0.0062003	7.81	<.001
Residual	24	0.0190502	0.0007938		
Total	53	0.0741110			

APPENDIX 6: Analysis of variance table for seed moisture content.

6) Variate: Seed_moisture content

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.14111	0.07056	2.10	
Rep.water_regime stratum					
water_regime	1	0.35852	0.35852	10.70	0.082
Residual	2	0.06704	0.03352	0.28	
Rep.water_regime.density stratum					
density	2	0.48111	0.24056	2.02	0.195
water_regime.density	2	0.12037	0.06019	0.51	0.621
Residual	8	0.95185	0.11898	2.38	
Rep.water_regime.density.variety stratum					
variety	2	0.21444	0.10722	2.14	0.139
water_regime.variety	2	0.31593	0.15796	3.16	0.061
density.variety	4	0.77778	0.19444	3.89	0.014
water_regime.density.variety					
	4	0.30519	0.07630	1.53	0.226
Residual	24	1.20000	0.05000		
Total	53	4.93333			

APPENDIX 7: Analysis of variance table for water activity.

7) Variate: Water_activity

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	11222.	5611.	1.00	
Rep.water_regime stratum					
water_regime	1	5621.	5621.	1.00	0.422
Residual	2	11224.	5612.	1.00	
Rep.water_regime.density stratum					
density	2	11220.	5610.	1.00	0.410
water_regime.density	2	11225.	5613.	1.00	0.410
Residual	8	44888.	5611.	1.00	
Rep.water_regime.density.variety stratum					
variety	2	11230.	5615.	1.00	0.382
water_regime.variety	2	11230.	5615.	1.00	0.382
density.variety	4	22441.	5610.	1.00	0.427

water_regime.density.variety					
	4	22443.	5611.	1.00	0.427
Residual	24	134664.	5611.		
Total	53	297408.			

APPENDIX 8: Analysis of variance table for chlorophyll content index.

8) Variate: Chlorophyll_content index

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	686.90	343.45	1.83	
Replication.Water_regime stratum					
Water_regime	1	110.10	110.10	0.59	0.523
Residual	2	374.48	187.24	2.33	
Replication.Water_regime.Plant_density stratum					
Plant_density	2	643.51	321.75	4.00	0.063
Water_regime.Plant_density					
	2	485.81	242.91	3.02	0.106
Residual	8	644.18	80.52	2.43	
Replication.Water_regime.Plant_density.*Units* stratum					
Season	1	18253.09	18253.09	549.81	<.001
Days_after_planting	7	6865.46	980.78	29.54	<.001
Variety	2	402.22	201.11	6.06	0.002
Water_regime.Season	1	40.11	40.11	1.21	0.272
Plant_density.Season	2	87.81	43.90	1.32	0.267
Water_regime.Days_after_planting					
	7	544.41	77.77	2.34	0.023
Plant_density.Days_after_planting					
	14	460.52	32.89	0.99	0.461
Season.Days_after_planting					
	7	6883.43	983.35	29.62	<.001
Water_regime.Variety	2	292.38	146.19	4.40	0.013
Plant_density.Variety	4	538.73	134.68	4.06	0.003
Season.Variety	2	141.43	70.72	2.13	0.120
Days_after_planting.Variety					
	14	213.55	15.25	0.46	0.953
Water_regime.Plant_density.Season					
	2	148.84	74.42	2.24	0.107
Water_regime.Plant_density.Days_after_planting					

	14	296.97	21.21	0.64	0.833
Water_regime.Season.Days_after_planting					
	7	496.60	70.94	2.14	0.038
Plant_density.Season.Days_after_planting					
	14	266.73	19.05	0.57	0.886
Water_regime.Plant_density.Variety					
	4	230.27	57.57	1.73	0.141
Water_regime.Season.Variety					
	2	13.56	6.78	0.20	0.815
Plant_density.Season.Variety					
	4	533.89	133.47	4.02	0.003
Water_regime.Days_after_planting.Variety					
	14	466.46	33.32	1.00	0.448
Plant_density.Days_after_planting.Variety					
	28	681.08	24.32	0.73	0.841
Season.Days_after_planting.Variety					
	14	351.44	25.10	0.76	0.717
Water_regime.Plant_density.Season.Days_after_planting					
	14	454.78	32.48	0.98	0.474
Water_regime.Plant_density.Season.Variety					
	4	425.30	106.33	3.20	0.013
Water_regime.Plant_density.Days_after_planting.Variety					
	28	688.72	24.60	0.74	0.832
Water_regime.Season.Days_after_planting.Variety					
	14	306.19	21.87	0.66	0.815
Plant_density.Season.Days_after_planting.Variety					
	28	478.02	17.07	0.51	0.983
Water_regime.Plant_density.Season.Days_after_planting.Variety					
	28	358.46	12.80	0.39	0.998
Residual	564	18724.16	33.20		
Total	863	62589.62			

APPENDIX 9: Analysis of variance table for stomatal conductance.

9) Variate: Stomatal_conductance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	39858.	19929.	77.47	
Replication.Water_regime stratum					
Water_regime	1	3039.	3039.	11.81	0.075
Residual	2	515.	257.	0.02	

Replication.Water_regime.Plant_density stratum					
Plant_density	2	146181.	73091.	6.93	0.018
Water_regime.Plant_density					
	2	6847.	3424.	0.32	0.732
Residual	8	84368.	10546.	1.32	
Replication.Water_regime.Plant_density.*Units* stratum					
Season	1	36471602.	36471602.	4565.62	<.001
Days_after_planting	7	78747259.	11249608.	1408.26	<.001
Variety	2	3353.	1677.	0.21	0.811
Water_regime.Season	1	19314.	19314.	2.42	0.121
Plant_density.Season	2	36709.	18354.	2.30	0.101
Water_regime.Days_after_planting					
	7	330617.	47231.	5.91	<.001
Plant_density.Days_after_planting					
	14	338142.	24153.	3.02	<.001
Season.Days_after_planting					
	7	46119625.	6588518.	824.77	<.001
Water_regime.Variety	2	3215.	1608.	0.20	0.818
Plant_density.Variety	4	20226.	5056.	0.63	0.639
Season.Variety	2	196431.	98216.	12.29	<.001
Days_after_planting.Variety					
	14	256529.	18324.	2.29	0.005
Water_regime.Plant_density.Season					
	2	17151.	8575.	1.07	0.343
Water_regime.Plant_density.Days_after_planting					
	14	110020.	7859.	0.98	0.468
Water_regime.Season.Days_after_planting					
	7	725899.	103700.	12.98	<.001
Plant_density.Season.Days_after_planting					
	14	342475.	24462.	3.06	<.001
Water_regime.Plant_density.Variety					
	4	14099.	3525.	0.44	0.779
Water_regime.Season.Variety					
	2	49697.	24848.	3.11	0.045
Plant_density.Season.Variety					
	4	8791.	2198.	0.28	0.894
Water_regime.Days_after_planting.Variety					
	14	62588.	4471.	0.56	0.896
Plant_density.Days_after_planting.Variety					
	28	224720.	8026.	1.00	0.460
Season.Days_after_planting.Variety					
	14	304144.	21725.	2.72	<.001
Water_regime.Plant_density.Season.Days_after_planting					
	14	162052.	11575.	1.45	0.126
Water_regime.Plant_density.Season.Variety					
	4	15795.	3949.	0.49	0.740

Water_regime.Plant_density.Days_after_planting.Variety					
	28	114171.	4078.	0.51	0.984
Water_regime.Season.Days_after_planting.Variety					
	14	57902.	4136.	0.52	0.923
Plant_density.Season.Days_after_planting.Variety					
	28	307495.	10982.	1.37	0.097
Water_regime.Plant_density.Season.Days_after_planting.Variety					
	28	98771.	3528.	0.44	0.995
Residual	564	4505408.	7988.		
Total	863	169945006.			

APPENDIX 10: Analysis of variance table for emergence %.

10) Variate: Emergence

Analysis of variance

Variate: Emergence

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	56.3	28.1	0.06	
Replication.Plant_density stratum					
Plant_density	2	6799.6	3399.8	6.77	0.052
Residual	4	2009.6	502.4	3.03	
Replication.Plant_density.*Units* stratum					
Water_regime	1	929.2	929.2	5.61	0.025
Cultivar	2	2716.0	1358.0	8.19	0.001
Plant_density.Water_regime					
	2	930.5	465.2	2.81	0.076
Plant_density.Cultivar	4	531.9	133.0	0.80	0.533
Water_regime.Cultivar	2	124.7	62.4	0.38	0.690
Plant_density.Water_regime.Cultivar					
	4	623.0	155.7	0.94	0.454
Residual	30	4971.4	165.7		
Total	53	19692.1			

APPENDIX 11: Analysis of variance table for leaf number.

11) Variate: Leaf_number

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	8.010	4.005	3.05	
Replication.Water_regime stratum					
Water_regime	1	91.209	91.209	69.46	0.014
Residual	2	2.626	1.313	0.35	
Replication.Water_regime.Plant_density stratum					
Plant_density	2	33.378	16.689	4.39	0.052
Water_regime.Plant_density	2	1.550	0.775	0.20	0.820
Residual	8	30.398	3.800	1.69	
Replication.Water_regime.Plant_density.*Units* stratum					
Variety	2	76.295	38.148	16.94	<.001
Days_after_planting	3	1415.104	471.701	209.49	<.001
Season	1	940.755	940.755	417.80	<.001
Water_regime.Variety	2	2.550	1.275	0.57	0.568
Plant_density.Variety	4	3.056	0.764	0.34	0.851
Water_regime.Days_after_planting	3	20.238	6.746	3.00	0.031
Plant_density.Days_after_planting	6	37.700	6.283	2.79	0.012
Variety.Days_after_planting	6	25.756	4.293	1.91	0.080
Water_regime.Season	1	6.380	6.380	2.83	0.093
Plant_density.Season	2	22.295	11.148	4.95	0.008
Variety.Season	2	9.573	4.786	2.13	0.121
Days_after_planting.Season	3	1353.562	451.187	200.38	<.001
Water_regime.Plant_density.Variety	4	5.093	1.273	0.57	0.688
Water_regime.Plant_density.Days_after_planting	6	17.177	2.863	1.27	0.271
Water_regime.Variety.Days_after_planting	6	11.760	1.960	0.87	0.517
Plant_density.Variety.Days_after_planting	12	8.435	0.703	0.31	0.987
Water_regime.Plant_density.Season	2	12.253	6.127	2.72	0.068
Water_regime.Variety.Season	2	4.837	2.418	1.07	0.343
Plant_density.Variety.Season	4	6.236	1.559	0.69	0.598

Water_regime.Days_after_planting.Season					
	3	96.696	32.232	14.31	<.001
Plant_density.Days_after_planting.Season					
	6	16.895	2.816	1.25	0.281
Variety.Days_after_planting.Season					
	6	9.034	1.506	0.67	0.675
Water_regime.Plant_density.Variety.Days_after_planting					
	12	13.028	1.086	0.48	0.924
Water_regime.Plant_density.Variety.Season					
	4	7.264	1.816	0.81	0.522
Water_regime.Plant_density.Days_after_planting.Season					
	6	13.622	2.270	1.01	0.420
Water_regime.Variety.Days_after_planting.Season					
	6	20.622	3.437	1.53	0.169
Plant_density.Variety.Days_after_planting.Season					
	12	13.421	1.118	0.50	0.916
Water_regime.Plant_density.Variety.Days_after_planting.Season					
	12	14.097	1.175	0.52	0.900
Residual	276	621.465	2.252		
Total	431	4972.370			

APPENDIX 12: Analysis of variance table for plant height.

12) Variate: Plant_height

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	20.770	10.385	1.37	
Replication.Water_regime stratum					
Water_regime	1	8.656	8.656	1.14	0.398
Residual	2	15.193	7.596	0.18	
Replication.Water_regime.Plant_density stratum					
Plant_density	2	181.435	90.718	2.13	0.182
Water_regime.Plant_density					
	2	38.980	19.490	0.46	0.649
Residual	8	341.067	42.633	4.60	
Replication.Water_regime.Plant_density.*Units* stratum					
Variety	2	2620.641	1310.321	141.48	<.001
Days_after_planting	3	7347.368	2449.123	264.44	<.001
Season	1	11277.668	11277.668	1217.70	<.001

Water_regime.Variety	2	2.798	1.399	0.15	0.860
Plant_density.Variety	4	32.207	8.052	0.87	0.483
Water_regime.Days_after_planting	3	343.177	114.392	12.35	<.001
Plant_density.Days_after_planting	6	217.767	36.294	3.92	<.001
Variety.Days_after_planting	6	204.936	34.156	3.69	0.002
Water_regime.Season	1	46.250	46.250	4.99	0.026
Plant_density.Season	2	115.089	57.545	6.21	0.002
Variety.Season	2	408.216	204.108	22.04	<.001
Days_after_planting.Season	3	5711.194	1903.731	205.55	<.001
Water_regime.Plant_density.Variety	4	37.007	9.252	1.00	0.409
Water_regime.Plant_density.Days_after_planting	6	40.699	6.783	0.73	0.624
Water_regime.Variety.Days_after_planting	6	52.578	8.763	0.95	0.462
Plant_density.Variety.Days_after_planting	12	59.901	4.992	0.54	0.888
Water_regime.Plant_density.Season	2	58.018	29.009	3.13	0.045
Water_regime.Variety.Season	2	4.844	2.422	0.26	0.770
Plant_density.Variety.Season	4	31.519	7.880	0.85	0.494
Water_regime.Days_after_planting.Season	3	211.654	70.551	7.62	<.001
Plant_density.Days_after_planting.Season	6	168.994	28.166	3.04	0.007
Variety.Days_after_planting.Season	6	68.216	11.369	1.23	0.292
Water_regime.Plant_density.Variety.Days_after_planting	12	94.797	7.900	0.85	0.596
Water_regime.Plant_density.Variety.Season	4	118.959	29.740	3.21	0.013
Water_regime.Plant_density.Days_after_planting.Season	6	47.516	7.919	0.86	0.529
Water_regime.Variety.Days_after_planting.Season	6	59.779	9.963	1.08	0.377
Plant_density.Variety.Days_after_planting.Season	12	35.146	2.929	0.32	0.986
Water_regime.Plant_density.Variety.Days_after_planting.Season	12	66.207	5.517	0.60	0.845
Residual	276	2556.153	9.261		

Total	431	32645.400				

APPENDIX 13: Analysis of variance table for Intercepted Photosynthetically Active Radiation (PAR).

13) Variate: Intercepted_PAR

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	66162.	33081.	1.89	
Replication.Water_regime stratum					
Water_regime	1	704294.	704294.	40.25	0.024
Residual	2	34994.	17497.	0.42	
Replication.Water_regime.Plant_density stratum					
Plant_density	2	1282374.	641187.	15.56	0.002
Water_regime.Plant_density	2	17238.	8619.	0.21	0.816
Residual	8	329644.	41206.	0.60	
Replication.Water_regime.Plant_density.*Units* stratum					
Season	1	15819439.	15819439.	229.17	<.001
Variety	2	1278.	639.	0.01	0.991
Water_regime.Season	1	492876.	492876.	7.14	0.008
Plant_density.Season	2	886554.	443277.	6.42	0.002
Water_regime.Variety	2	197735.	98867.	1.43	0.239
Plant_density.Variety	4	257298.	64325.	0.93	0.445
Season.Variety	2	6614.	3307.	0.05	0.953
Water_regime.Plant_density.Season	2	37690.	18845.	0.27	0.761
Water_regime.Plant_density.Variety	4	135562.	33890.	0.49	0.742
Water_regime.Season.Variety	2	204710.	102355.	1.48	0.228
Plant_density.Season.Variety	4	185507.	46377.	0.67	0.612
Water_regime.Plant_density.Season.Variety	4	50173.	12543.	0.18	0.948
Residual	816	56328919.	69031.		
Total	863	77039062.			

APPENDIX 14: Analysis of variance table for Leaf Area Index (LAI).

14) Variate: LAI

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	0.4799	0.2400	1.13	
Replication.Plant_density stratum					
Plant_density	2	3.2355	1.6177	7.59	0.044
Residual	4	0.8528	0.2132	1.74	
Replication.Plant_density.*Units* stratum					
Water_regime	1	1.3098	1.3098	10.72	0.001
Variety	2	0.0533	0.0267	0.22	0.804
Season	1	48.7730	48.7730	399.08	<.001
Days_after_planting	7	30.7619	4.3946	35.96	<.001
Plant_density.Water_regime	2	0.1906	0.0953	0.78	0.459
Plant_density.Variety	4	0.6802	0.1701	1.39	0.235
Water_regime.Variety	2	0.2242	0.1121	0.92	0.400
Plant_density.Season	2	3.0203	1.5101	12.36	<.001
Water_regime.Season	1	0.9348	0.9348	7.65	0.006
Variety.Season	2	0.0605	0.0303	0.25	0.781
Plant_density.Days_after_planting	14	7.4867	0.5348	4.38	<.001
Water_regime.Days_after_planting	7	1.9447	0.2778	2.27	0.027
Variety.Days_after_planting	14	1.8316	0.1308	1.07	0.382
Season.Days_after_planting	7	33.4133	4.7733	39.06	<.001
Plant_density.Water_regime.Variety	4	0.2603	0.0651	0.53	0.712
Plant_density.Water_regime.Season	2	0.2457	0.1229	1.01	0.367
Plant_density.Variety.Season	4	0.4087	0.1022	0.84	0.503
Water_regime.Variety.Season	2	0.3247	0.1624	1.33	0.266
Plant_density.Water_regime.Days_after_planting	14	1.7598	0.1257	1.03	0.423
Plant_density.Variety.Days_after_planting	28	2.1276	0.0760	0.62	0.937
Water_regime.Variety.Days_after_planting	14	0.4744	0.0339	0.28	0.996
Plant_density.Season.Days_after_planting					

	14	6.9443	0.4960	4.06	<.001
Water_regime.Season.Days_after_planting	7	2.3226	0.3318	2.71	0.009
Variety.Season.Days_after_planting	14	1.7668	0.1262	1.03	0.418
Plant_density.Water_regime.Variety.Season	4	0.4222	0.1056	0.86	0.485
Plant_density.Water_regime.Variety.Days_after_planting	28	3.2041	0.1144	0.94	0.561
Plant_density.Water_regime.Season.Days_after_planting	14	1.4076	0.1005	0.82	0.645
Plant_density.Variety.Season.Days_after_planting	28	2.1358	0.0763	0.62	0.936
Water_regime.Variety.Season.Days_after_planting	14	0.5915	0.0423	0.35	0.988
Plant_density.Water_regime.Variety.Season.Days_after_planting	28	3.3399	0.1193	0.98	0.502
Residual	570	69.6616	0.1222		
Total	863	232.6506			

APPENDIX 15: Analysis of variance table for flower percentage.

15) Variate: Flower_%

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	1161.4	580.7	1.95	
Replication.Water_regime stratum					
Water_regime	1	1938.0	1938.0	6.49	0.126
Residual	2	596.8	298.4	0.78	
Replication.Water_regime.Plant_density stratum					
Plant_density	2	2414.5	1207.3	3.15	0.098
Water_regime.Plant_density	2	44.1	22.0	0.06	0.945
Residual	8	3069.4	383.7	1.44	

Replication.Water_regime.Plant_density.*Units* stratum

Variety	2	5228.3	2614.1	9.81	<.001
Season	1	440641.7	440641.7	1653.42	<.001
Days_after_planting	3	255117.0	85039.0	319.09	<.001
Water_regime.Variety	2	390.5	195.3	0.73	0.482
Plant_density.Variety	4	268.7	67.2	0.25	0.908
Water_regime.Season	1	2384.8	2384.8	8.95	0.003
Plant_density.Season	2	1392.5	696.3	2.61	0.075
Variety.Season	2	1054.2	527.1	1.98	0.140
Water_regime.Days_after_planting	3	4494.6	1498.2	5.62	<.001
Plant_density.Days_after_planting	6	1653.3	275.6	1.03	0.403
Variety.Days_after_planting	6	7251.4	1208.6	4.53	<.001
Season.Days_after_planting	3	118069.3	39356.4	147.68	<.001
Water_regime.Plant_density.Variety	4	681.8	170.4	0.64	0.635
Water_regime.Plant_density.Season	2	295.3	147.6	0.55	0.575
Water_regime.Variety.Season	2	422.9	211.5	0.79	0.453
Plant_density.Variety.Season	4	146.3	36.6	0.14	0.968
Water_regime.Plant_density.Days_after_planting	6	6208.7	1034.8	3.88	<.001
Water_regime.Variety.Days_after_planting	6	1208.3	201.4	0.76	0.605
Plant_density.Variety.Days_after_planting	12	2661.5	221.8	0.83	0.617
Water_regime.Season.Days_after_planting	3	4047.9	1349.3	5.06	0.002
Plant_density.Season.Days_after_planting	6	2675.3	445.9	1.67	0.128
Variety.Season.Days_after_planting	6	11425.5	1904.3	7.15	<.001

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Water_regime.Plant_density.Variety.Season					
	4	380.6	95.2	0.36	0.839
Water_regime.Plant_density.Variety.Days_after_planting					
	12	4528.4	377.4	1.42	0.158
Water_regime.Plant_density.Season.Days_after_planting					
	6	5957.5	992.9	3.73	0.001
Water_regime.Variety.Season.Days_after_planting					
	6	1175.9	196.0	0.74	0.622
Plant_density.Variety.Season.Days_after_planting					
	12	2783.9	232.0	0.87	0.578
Water_regime.Plant_density.Variety.Season.Days_after_planting					
	12	4829.5	402.5	1.51	0.120
Residual	276	73555.0	266.5		
Total	431	970155.0			

APPENDIX 16: Analysis of variance table for biomass.

16) Variate: Biomass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	41555.	20777.	1.51	
Replication.Water_regime stratum					
Water_regime	1	3786.	3786.	0.27	0.652
Residual	2	27550.	13775.	0.72	
Replication.Water_regime.Plant_density stratum					
Plant_density	2	607043.	303521.	15.76	0.002
Water_regime.Plant_density					
	2	23270.	11635.	0.60	0.570
Residual	8	154118.	19265.	1.69	
Replication.Water_regime.Plant_density.*Units* stratum					
Season	1	3645578.	3645578.	320.11	<.001
Variety	2	25280.	12640.	1.11	0.336
Water_regime.Season	1	5244.	5244.	0.46	0.500
Plant_density.Season	2	565804.	282902.	24.84	<.001
Water_regime.Variety	2	46523.	23261.	2.04	0.139
Plant_density.Variety	4	15990.	3998.	0.35	0.842
Season.Variety	2	24917.	12458.	1.09	0.341
Water_regime.Plant_density.Season					

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
	2	19706.	9853.	0.87	0.426
Water_regime.Plant_density.Variety					
	4	16688.	4172.	0.37	0.832
Water_regime.Season.Variety					
	2	42745.	21373.	1.88	0.162
Plant_density.Season.Variety					
	4	14118.	3529.	0.31	0.870
Water_regime.Plant_density.Season.Variety					
	4	14688.	3672.	0.32	0.862
Residual	60	683303.	11388.		
Total	107	5977906.			

APPENDIX 17: Analysis of variance table for grain yield.

17) Variate: Grain_yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	5267.1	2633.5	8.44	
Replication.Water_regime stratum					
Water_regime	1	399.3	399.3	1.28	0.375
Residual	2	623.8	311.9	0.24	
Replication.Water_regime.Plant_density stratum					
Plant_density	2	23998.3	11999.1	9.31	0.008
Water_regime.Plant_density					
	2	5351.6	2675.8	2.08	0.188
Residual	8	10310.4	1288.8	1.32	
Replication.Water_regime.Plant_density.*Units* stratum					
Season	1	282907.8	282907.8	289.17	<.001
Variety	2	30464.6	15232.3	15.57	<.001
Water_regime.Season	1	241.2	241.2	0.25	0.621
Plant_density.Season	2	21984.4	10992.2	11.24	<.001
Water_regime.Variety	2	6086.5	3043.2	3.11	0.052
Plant_density.Variety	4	2651.3	662.8	0.68	0.610
Season.Variety	2	29160.3	14580.1	14.90	<.001
Water_regime.Plant_density.Season					
	2	4639.3	2319.7	2.37	0.102
Water_regime.Plant_density.Variety					
	4	3575.2	893.8	0.91	0.462
Water_regime.Season.Variety					
	2	5561.4	2780.7	2.84	0.066
Plant_density.Season.Variety					

	4	2370.8	592.7	0.61	0.660
Water_regime.Plant_density.Season.Variety					
	4	3179.6	794.9	0.81	0.522
Residual	60	58699.8	978.3		
Total	107	497472.7			

APPENDIX 18: Analysis of variance table for Harvest Index (HI).

18) Variate: Harvest_Index

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	28.35	14.17	1.79	
Replication.Water_regime stratum					
Water_regime	1	172.43	172.43	21.75	0.043
Residual	2	15.86	7.93	0.20	
Replication.Water_regime.Plant_density stratum					
Plant_density	2	301.55	150.77	3.83	0.068
Water_regime.Plant_density					
	2	16.90	8.45	0.21	0.812
Residual	8	315.33	39.42	1.52	
Replication.Water_regime.Plant_density.*Units* stratum					
Variety	2	2233.23	1116.62	43.08	<.001
Season	1	22436.33	22436.33	865.62	<.001
Water_regime.Variety	2	45.84	22.92	0.88	0.418
Plant_density.Variety	4	199.08	49.77	1.92	0.119
Water_regime.Season	1	162.70	162.70	6.28	0.015
Plant_density.Season	2	301.24	150.62	5.81	0.005
Variety.Season	2	2162.46	1081.23	41.72	<.001
Water_regime.Plant_density.Variety					
	4	35.14	8.78	0.34	0.851
Water_regime.Plant_density.Season					
	2	16.52	8.26	0.32	0.728
Water_regime.Variety.Season					
	2	43.89	21.95	0.85	0.434
Plant_density.Variety.Season					
	4	193.35	48.34	1.86	0.128
Water_regime.Plant_density.Variety.Season					
	4	29.09	7.27	0.28	0.889
Residual	60	1555.16	25.92		

Total	107	30264.45