Response of potato genotypes to production sites and water deficit imposed at different growth stages

By

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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 of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

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.

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DECLARATION: PLAGIARISM

I, Sizwe Goodman Mthembu, 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;

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(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.

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ABSTRACT

In South Africa, potato is an important food security crop widely cultivated by smallholder farmers due to its extensive adaptation characteristics. However, drought adaptive responses of potato genotypes vary under different environmental conditions. Potato is generally categorized as the most sensitive crop to water deficit than other root and tuber crops. However, there is insufficient evidence regarding adaptive responses of potato genotypes to water deficit imposed at different growth stages. Therefore, this study sought to identify growth stage-specific drought adaptation of selected potato genotypes for recommendation and cultivation in targeted production sites in South Africa. The specific objectives of this study were: (1) to determine morpho-physiological traits related to water use efficiency among selected potato genotypes subjected to water deficit at the different growth stages; (2) to determine the effect of water deficit imposed at different growth stages on yield performance and tuber quality of selected potato genotypes; and (3) to investigate the effect of different production sites/regions on growth, physiological and yield responses of potato genotypes.

For objective 1, a glasshouse study was conducted using a 8×4×2 factorial experiment involving the following factors: potato genotypes - 8 levels (Bikini, Challenger, Electra, Mondial, Panamera, Sababa, Sifra, and Tyson); growth stages - 4 level (vegetative stage, tuber initiation, tuber bulking and maturity) and watering regimes - 2 levels (Well-watered [Ww] and Water deficit [Wd] conditions). The treatments were replicated three times to give a total of 192 experimental units. Water deficit was imposed by withholding irrigation at the beginning to the end of each growth stage. A highly significant ($p < 0.001$) interaction among genotypes, water condition and growth stages was observed for morphological traits and physiological responses including number of leaves and total above-ground biomass, and photosynthetic rate (*A*), instantaneous water use efficiency (IWUE), transpiration rate (Tr), chlorophyll content index (CCI), and relative water content (RWC). Potato genotypes Bikini, Challenger and Mondial with growth-stage specific drought adaptation were identified and recommended for water-limited environments.

The second study (objective 2) determined the effect of water deficit imposed at different growth stages on yield performance and tuber quality of selected potato genotypes. The study was conducted as 8×4×2 factorial experiment (See objective 1) replicated three times and data was collected on tuber yield (TY), number of tubers (NT), tuber size distribution (TSD) and dry matter content (DMC). Results revealed a highly significant ($p < 0.001$) genotype x water condition x growth stages interaction for tuber yield and dry matter content. Imposing water deficit at the tuber initiation and tuber bulking stages resulted in significantly lower yields, whereas drought stress at maturity stage resulted in high number of small tubers. 'Bikini', 'Challenger', 'Mondial' and 'Tyson' were identified as tolerance genotypes to water deficit at vegetative stage, tuber initiation and maturity stage due to high yield potential and DMC. This finding suggests that these genotypes could be suitable for processing industry (chipping) and baking.

For objective 3, eight potato genotypes were grown across two environments namely: Ukulinga research farm (URF) in Pietermaritzburg which characterised with semi-arid environment and eChibini area (CB) in Bamshela with seasonal rainfall and high humidity. The experiments were laid out using a randomised complete block design (RCBD) replicated three times. Data was collected on morphological and physiological traits. Significant ($p < 0.05$) genotype x environment interaction effect was observed for studied traits at URF and CB. Potato genotypes planted at CB had a significant ($p < 0.05$) lower *gs* and Tr resulting to low *A*, than at URF. The CCI at CB compared to URF was significant ($p < 0.05$) higher at the beginning and gradually decreased towards maturity while at URF was constant. Moderately to poorly drained soils at eChibini resulted in low yields and low dry matter content. Various genotypes with better yield and high quality were obtained at URF. This suggested that genotypes were suitable for production in cool temperate regions with humid climate areas like URF. The study showed that different production regions can significantly affect the potato yield performance, suggesting URF sites as suitable environment.

Overall, the study identified potato genotypes with growth stage-specific drought tolerance and environment specific adaptation for high yield and good quality.

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CHAPTER 1: Introduction

1.1 Background

The potato (*Solanum tuberosum* L.) is an annual crop species belonging to the family *Solanaceae* (Malarian *et al*., 2014). It is a starchy vegetable crop and a good source of energy (Malarian *et al*., 2014). Potato tubers containts 79 % water, 18 % carbohydrates, 2 % proteins, 1 % vitamins (Khan *et al*., 2018). The species is consumed globally and is a staple food crop in many countries found in Africa, Asia, America and Europe (Obidiegwe *et al*., 2015). The global production of potatoes has an estimated annual yield of 374 million tonnes, obtained from 19.2 million hectares (Obidiegwe *et al*., 2015). The largest potato producing country is China with 96.13 million tons annual production followed by India with 45.4 million tons and Russia with 31.5 million tons (Department of Agriculture, Forestry and Fisheries DAFF, 2015). But, the African continent, Algeria (4.6 million tons), Egypt (4.3 million tons) and South Africa (2.4 million tons) are reported as the top three largest producers and exporter of fresh potatoes (Kesiime *et al*., 2016; VIB Facts Series, 2019). According to Food and Agriculture Organization FAO, (2008 b) the crop was first introduced to South Africa by a Dutch seafarers in the 1600s in the Cape (Western Cape) and from there it spread to the entire country. The production of potatoes in South Africa is mainly for human consumption, fresh market, seed potatoes and processing industry for different food products, such as chips, frozen French fries, table stock (DAFF, 2017).

Potato is an erect, dicotyledonous herbaceous plant, which grows up to a height of one meter with alternate and compound leaves of three to five pairs of leaflets, arranged in a prostrate and erect forms Figure 1.1 (Horton, 1987; FAO, 2008a). The colour of inflorescence produced varies from blue, cream, purple to white petals which emerged on the terminal cluster which contain five sepals, five petals, five stamens and two-celled pistil. Below inflorescence are spherical fruits, yellow-green berries (3-4 cm in diameter) formed during tuber formation. Berries are capable of producing potato true seeds (VIB Facts Series, 2019). True seeds can be used to plant potato, but they are still underused. Potato's mainly propagated vegetatively using tubers and it forms fibrous root rising from the base of sprouts/eyes. Root development is restricted to topsoil layers about 20-25 cm long. Potato plant possesses an enlarged, starchy, underground stems known as stolons that produce tubers that vary in shape and size (CIP, 2018).

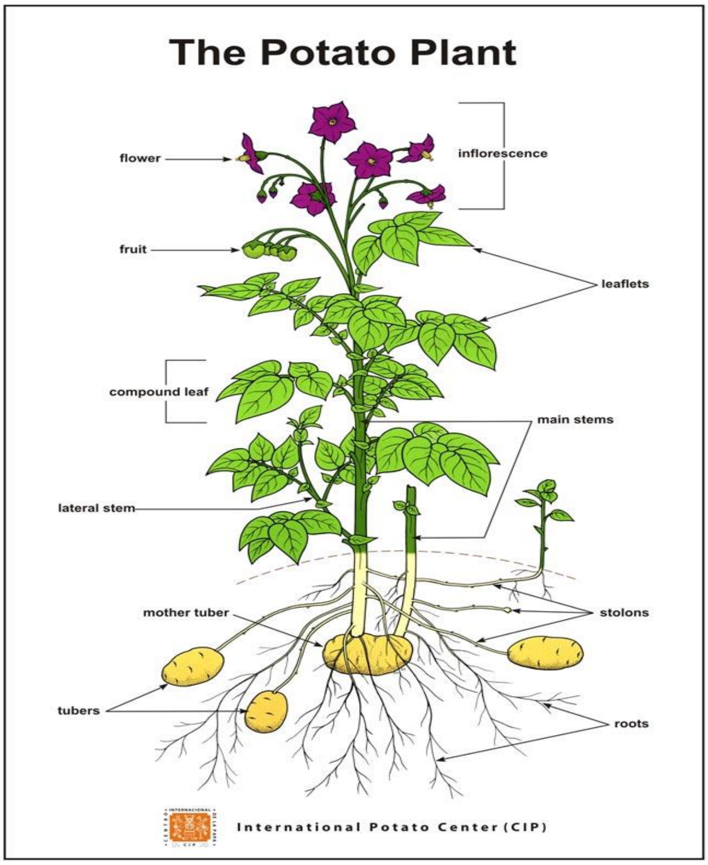

Figure 1.1: Potato morphological features (CIP, 2018).

Potato production in South Africa occurs yearly in 16 different climatic production regions (DAFF, 2017). The climatic production regions include Ceres, Eastern Cape, Eastern Free State, Gauteng, KwaZulu-Natal, Loskop Valley, Limpopo, Mpumalanga, North Eastern Cape, North West, Northern Cape, Sandveld, Southern Cape, South-Western Cape, South Western Free State, and Western Free State. According to PSA (2017/2018), based on the 16 production regions, South Africa obtained a total of 245 million of 10 kg potato bags from 52 017 hectares of planting area planted in 2017 which is lower than the previous season (2016 - 52 722 ha) with 705 hectares fewer. Also, a significant decline has been observed between the 2015 and 2016 seasons (Figure 1.2). The main producing areas among 16 regions are Limpopo (21 % of ha), the Eastern Free State (21 % of ha), the Western Free State (14 % of ha) and the Eastern Free State (11 % of ha) (DAFF, 2017; PSA, 2017/2018). Potato production occurs throughout the year under irrigation and dry land conditions (Steyn *et al*., 2016). Approximately 80 % of potato production is under irrigation, whereas under dry land conditions the production has declined from 50 % to 13 % of the total hectares planted in 1990 and 2011, respectively, due to poor precipitation (Figure 1.3) (DAFF, 2017; PSA, 2017).

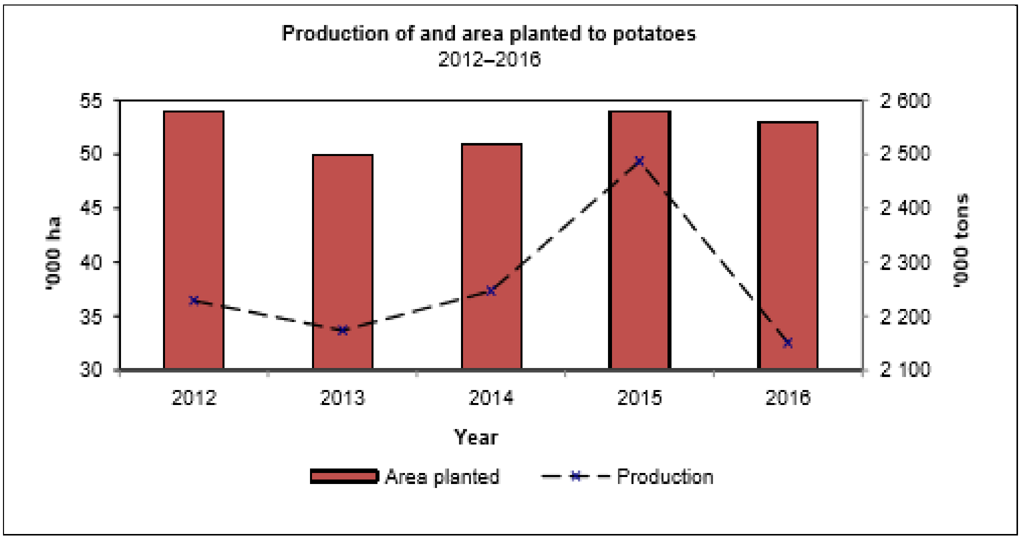

Figure 1.2: Trends of potato yield production (tonnes ha^{-1}) and area (tons) planted in South Africa from 2012 to 2016 (DAFF, 2017).

For the past five years, potato yield has been fluctuating.The fluctuations relate to the successive droughts that were experienced during the same period (Figure 1.2).

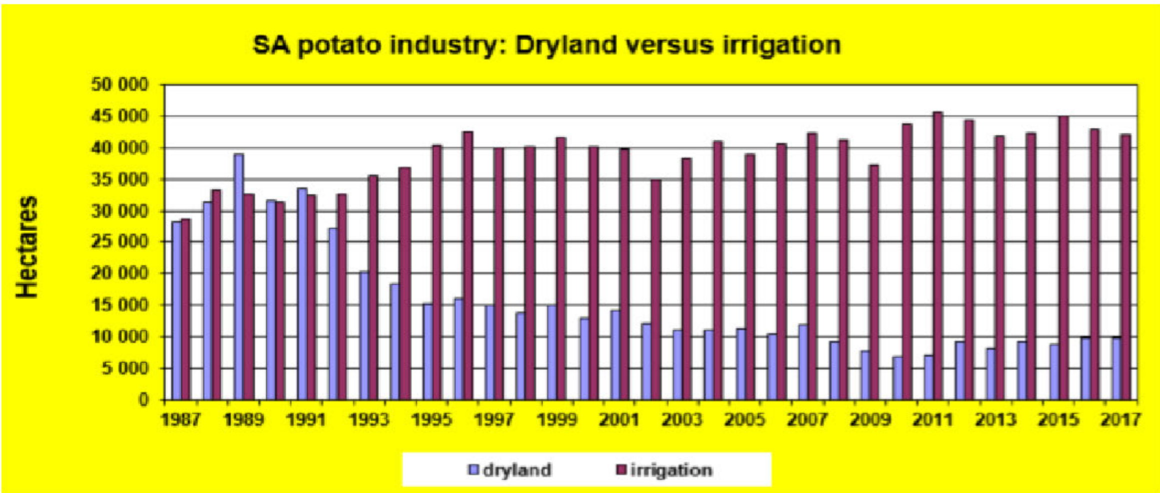

Figure 1.3: Potato production between dryland versus irrigation condition (PSA, 2017).

According to Feed the Future Kenya, (2018) potato is adapted to temperate conditions with deep, well-drained, sandy loam soils, rich in organic matter, stoneless and frost-free soils. The species is sensitive to arid and semiarid regions as well as harsh conditions like high and too low temperatures (Kandil *et al*., 2011). Potato tolerate an optimal day temperature ranging from 10-35° C for root growth and cool night's temperature range from 12-18° C for optimum growth (Nyawade *et al*., 2018), a soil pH of 5.0-6.5 is required for optimum growth, lower soil pH result in poor tuber quality whereas high soil pH triggers diseases such as common scab, blackleg and blight. Adequate fertilizer (nitrogen, phosphorus and potassium) plays a significant role in the vegetative growth and increasing yield, especially nitrogen is a very important element necessary for growth and production (Muhammad *et al*., 2015). Low soil fertility affects potato production. Average annual rainfall of 500 to 700 mm equally distributed during the growing period is needed for optimum growth (FAO, 2008a). Regions where rainfall is unreliable, supplementary irrigation is required. Potato can be cultivated as a sole crop, rotated with maize (*Zea mays*), wheat (*Triticum aestivum*) and legumes. Legumes play a vital role in improving soil fertility by fixing nitrogen into the soil (Sanginga and Mbabu, 2015). Crop rotation helps in reducing fertilizer input and the build-up of pests and diseases (Naidoo, 2011).

Potato growers in South Africa are faced with several challenges in trying to improve the yield and quality of the crop. The production of the crop is limited by environmental stress (drought, frost at high altitudes, high temperature and evaporation) and technical approaches (improper land preparation, improper crop rotation, selection of low yielding genotypes, incorrect plant spacing, high plant population, poor handling at harvest and improper post-harvest handling) (Sanginga and Mbabu, 2015). The unbearable climatic conditions such as high temperatures and low rainfall in subtropical regions significantly hinder potato growth, tuber yield and quality (Steyn *et al*., 1997; Khan *et al*., 2015). High temperatures and dry conditions lead to a high evaporation rate and that increases crop water requirement and for that reason, supplemental irrigation is recommended particularly in most sensitive stages due to water deficiency. Water deficit is a major constraints affecting crop productivity in Africa and worldwide (Levy *et al*., 2013). Elzner *et al*. (2018) reported that in the Czech Republic water deficit during the vegetation stage decline potato yields. Steyn *et al*. (1998) found that in South Africa potato genotypes exposed to water deficit produce low yields and poor tuber quality.

The unreliable rainfall distribution and limited water resources resulting in water stress is a major challenge on potato production in South Africa. This implies that the agricultural sector particularly the potato industry has to use irrigation water more efficiently in the future (Steyn *et al*., 1997). Therefore, it is very important to carefully consider crop water requirements, soil type and weather conditions to ensure proper irrigation (Eid *et al*., 2013). Also, potato production is limited by pests (aphids, leaf miner, and tuber moth) and diseases (bacterial wilt, scab, early and late blight). Bacterial wilt often significantly limits tuber production (Allemann, 2004). However, early blight and the great Irish famine have been found as the most devastating disease in many potato production regions (Wharton and Kirk, 2007). Potato blight is characterized as irregular, light tan, circular dark brown spots on lower leaves caused by fungus *Alternaria solani.* This results in an irregular and slightly sunken, dark brown border, shapeless tubers (Wharton and Kirk, 2007).

The response of potatoes to water deficit varies among genotypes and also differs from the timing, level, and duration of water deficit imposed (Banik *et al*., 2016). Mild water deficit reduces the expansion of stems and leaves, leading to reduced, leaf area index, photosynthetic efficiency and reduction in dry matter (Obidiegwe *et al*., 2015). Water deficit are closely linked with low water potential which is known to promote abscisic acid (ABA) to accumulation (Rodríguez-Perez *et al*., 2017). An increase in ABA encourages a stomatal closure, a first and well-known response against water deficit (Obidiegwe *et al*., 2015). Furthermore, studies have shown that water deficit can reduce tuber quality during tuber initiation and tuber bulking growth stages relative to other (sprouting, vegetative growth, and maturity) growth stages (Maralian *et al*., 2014; Muthoni and Kabira, 2016). Maralian *et al*. (2014), found that limited irrigation negatively affects tuber yield. Muthoni and Kabira. (2016), reported that potato genotypes "Up-to-date" as well as "Troubadour" grown under water stress had low dry matter compared to the "Alpha" genotype grown under well-watered conditions. Hassan *et al*. (2002), found that water deficit at stolonization and tuberization showed a negative impact on the yield obtained. This shows that the response of potato genotypes to water deficit differs among the genotypes and growth stages.

1.2 Problem statement

South Africa receives an average rainfall of approximately 450 mm and is mainly semi-arid (El Chami and El Moujabber, 2016). Water scarcity has always been a problem but in the past four years has been worst periods, and the country is faced with increasing spells of severe drought because of the increasing rainfall variability. The increased dry periods and hot days has impacted potato production in all regions in the country and has affected both commercial and small-scale farmers growing potatoes under dry land conditions (Steyn *et al*., 2016). For example, despite a general increase in potato yields from 17 million bags to 19 million bags between 2013 and 2015 in the Eastern Free State region, yields dropped to 12 million bags even though the planting area increased from 9 989 hectares in 2013 up to 11 533 ha in 2016 (Potato South Africa, 2018/2019). Yields are probably likely to decline further as rainfall continues to decrease and particularly under dry land conditions. It is hypothesized that potato genotypes that are exposed to water deficit at specific growth stages and are able to recover when the water stress is alleviated are better adapted to dry land conditions in South Africa. This is because such genotypes may possess morphological, physiological and biochemical traits that allow them to be more water-use efficient under water limiting conditions. There is little information on the morpho-physiological and biochemical traits that could determine the responses of potato genotypes subjected to water deficit occurring at different growth stages, and development; and how these might affect the subsequent yield performance.

1.3 Justification

Drought is an important factor influencing potato establishment, growth, yield performance and subsequently tuber quality. It has been reported that yields are likely to drop between 20 and 40 % in the future if no effective actions are taken for potato adaptation in Africa, Asia and Latin America (Romero *et al*., 2017). Drought has severe effects on the agricultural sector of South Africa (Wilhite, 2000). The driving force of drought is the El Nino Southern Oscillation (Mason and Tyson, 2000). Drought is unavoidable since it a natural hazard, but effective measures can be taken against (Vogel, 1995). South African rural economy and commercial farmers' dependent on potato production for consumption, employment and potential cash crop. Again, South Africa also exports potatoes to our neighbouring countries such as Angola, Botswana, Mozambique, Namibia, and Zimbabwe (DAFF, 2015). Thus, the supply for potatoes decreases and fails to meet demand, resulting in price increases. Therefore, it is important to gain more understanding of the relationship between genotypic and physiological factors that may determine the effect of water deficit occurring at different growth stages of potato growth and development based on yield performance. Variability in the performance of genotypes might be related to growth stages that are tolerance to water deficit (morphological, physiological and biochemical) and may account for variation in yields.

1.4 Aim

The aim of the study is to gain a deeper understanding of genotypic, phenotypic and physiological traits/factors that may determine the effect of water deficit occurring at different growth stages of potato growth and development; and how these affect subsequent biomass production and yield performance.

1.5 The objectives of this study are to:

1. Determine morpho-physiological traits related to water use efficiency among different potato genotypes subjected to water deficit imposed at the different growth stages.
2. Determine the effect of water deficit imposed at different growth stages on yield performance and internal tuber quality of different potato genotypes.
3. Investigate the effect of different production sites on growth, physiological and yield responses of potato (*Solanum tuberosum* L.) genotypes.

1.6 Research questions

1. What are the morph-physiological traits that may be associated with water use efficiency among potato genotypes subjected to water deficit at different growth stages; and do genotypes differ in their response?
2. What is the effect of water deficit on potato yield performance and internal tuber quality?
3. What is the effect of climate on potato yield performance and tuber quality grown on different regions?

1.7 Dissertation outline

Chapter 1: Introduction

This chapter provides a brief overview of the current trends in potato production from global to national scale followed by a review of the production region, adaptation, current challenges in potato production and the response of potatoes to water deficit. The problem statement, justification, research aim and objectives, and of the study are also outlined in this chapter.

Chapter 2: Literature review

The chapter offers a literature review on the influence of water deficit on potato genotypes morphology, physiology and biochemistry. It highlights recently published works and identifies the current knowledge gap that needs to be filled, then this research intended to fill that gap.

Chapter 3: The chapter provides a detailed report on morph-physiological traits related to water use efficiency among different potato genotypes subjected to water deficit imposed at the different growth stages.

Chapter 4: The chapter reports on the effect of water deficit imposed at different growth stages on yield performance and internal tuber quality of different potato genotypes.

Chapter 5: This chapter compares the effect of different location on yield performance and tuber quality of different potato genotypes grown in different regions.

Chapter 6: The chapter provides the experimental chapter's discussion, general discussion and recommendations for future research. It provides a conclusion and the contributions of this research.

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Chapter 2: Environmental factors affecting growth, yield and quality of potatoes grown under controlled and open field environment: A review

2.1 Abstract

Sub-Saharan Africa region is considered one of the poorest regions worldwide due to vulnerability to climate change which affects crop production. The production of potatoes (*Solanum tuberosum* L.) in developing countries, particularly in Sub-Saharan Africa is faced by various biotic and abiotic factors. These factors include the high occurrence of pests and diseases, poor agronomic practices, above-average temperatures, and water deficit. Potato as a field crop it turns to experience different environmental conditions, such as water deficit which result in drought stress can have a considerable negative impact on potato yield and quality. This review discusses changes occurring in potatoes morphological, physiological and biochemical responses to water deficit and its impact on yield performance. Secondly, the review also discusses the agronomic factors influencing potato growth, harvest and storage. Moreover, the pre-harvest and post-harvest factors affecting the internal quality were reviewed, to evaluate dry matter content, specific gravity, and sugar content. The main objective is to design appropriate irrigation schedules. Currently, there are no advance irrigation models for potato genotypes in South Africa, which can keep up with drought. Studies have shown that tuberization is the most sensitive stage in water deficit, but findings remain inconclusive because no study has shown or compared the response through all the five potato growth stages, on how they respond. Therefore, a deep understanding of potato genotypes response to drought regime at different growth stages could help in the identification of non-sensitive growth stages where water can be withheld and still produce optimum yields. This review focused on how we can use water efficiency and also indicated some cultural practices that need to be considered when planting potatoes.

Keywords: Potato; genotypes; water deficit; drought mechanisms; tuber quality; yield

2.2 Introduction

Potato (*Solanum tuberosum* L.) is one of the most important starchy vegetables that is globally cultivated and consumed (Obidiegwu *et al*., 2015). The species is first in the world among the root and tuber crops followed by cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), and yam (*Dioscorea alata*) in terms of production (Tolessa *et al*., 2016). In terms of human consumption, it ranks third after rice (*Oryza sativa*) and wheat (*Triticum aestivum*). But, among the world's food crop production, it ranks fourth after rice, wheat and maize (*Zea mays*) (CIP, 2018; VIB Facts Series, 2019). The annual potato production exceeds 300 million tons from 18.6 million hectares worldwide (Tolessa *et al*., 2016; Shu-han *et al*., 2018). In South Africa, the projected land under potato cultivation each year is just over 52 000 hectares (DAFF, 2017; PSA, 2017). Potato has multipurpose usage for both humans and animals, for example, the raw material is used for the production of starch and alcohol (Zaman *et al*., 2016). In developed countries like the Russian Federation and other countries found in east Europe cultivate potato to fed cattle, chickens and pigs. It serves as a good source of biological value protein compared to wheat (53 %), maize (54 %), peas (*Pisum sativum*) (48 %), beans (*Phaseolus vulgaris*) (46 %) (FAO, 2008b; Wassu, 2017). It contains high content of protein than root and tuber crops (Wassu, 2017). It also contains essential compounds such as ascorbate, β-carotene, carbohydrates, dietary fibre, vitamins, cysteine-rich polypeptides which are necessary for human health (Obidiegwe *et al*., 2015; van Niekerk *et al*., 2016; Ngobese *et al*., 2017).

Although it is mostly consumed as a vegetable in many countries, other parts of African countries such as Nigeria use potato paste as a remedy to treat skin ailments (acne, burns, frostbite, warts) in humans. The paste is prepared by slicing or grinding raw tubers and mixing with water, thereafter the paste is applied to ailments to release the pain (Umadevi *et al*., 2013). Potato peels of some genotypes are rich in phenolic compounds compared to onions (*Allium cepa*) and tomato (*Solanum lycopersicum*) (Akyol *et al*., 2016). Phenolic compounds play a significant role in human health by protecting against pathogens and diseases such as cancer, cardiovascular and inflammation (Saxena *et al*., 2012; Umadevi *et al*., 2013). Potato makes a significant contribution to the gross domestic product (GDP) as it helps to stabilize the South African economy (Steyn *et al*., 2016; PSA, 2017). According to the statistics, potatoes contribute about 3 % (R4.06 billion) to the national gross value of agriculture (PSA, 2014/2015).

Despite its importance and high consumption (1 506 779 tons per annum), potato production area in South Africa has declined under dryland conditions over the past decade (DAFF, 2017). For example, the area under potato production decreased from almost 63 000 of the total hectares planted in 1990, to 52 000 hectares in the 2016 season (PSA, 2017). Currently, almost 80 % of the production is under irrigation conditions (DAFF, 2017; PSA, 2017). One of the largest regions under potato production, Eastern Free State, which has a high number of productions under dry land (8 063 ha) compared to irrigation condition (3 470 ha) was highly affected by drought. This region (Eastern Free State) had a general increase in potato yields from 17 million of bags to 19 million bags between 2013 and 2015, however in 2016 yields dropped to 12 million bags even though the planting area increased from 9 989 hectares in 2013 up to 11 533 ha (PSA, 2018/2019). Potato SA Industry Research. (2016/17) reported that the number of commercial potato producers declined from 690 in 2010 to 540 in the 2016 season. The decline is largely attributed to climate change through poor rainfall distribution as well as above-average temperatures. The lack of skills and other necessary inputs for optimum production could also be accounted for this decline (Sanginga and Mbabu, 2015; VIB Facts Series, 2019).

Unlike irrigated potatoes, dryland potatoes depend on unreliable seasonal rainfall for water supply. However, the main source of water for both (dryland and irrigated) conditions is adequate rainfall, which has been the main problem in South Africa (Hedden and Cilliers, 2014). As the country continues to experiences minimal rain, dams are running low. The country only receives an annual average rainfall of approximately 450 mm (El Chami and El Moujabber, 2016). Consequently, South Africa has been categorized as a water-stressed country by the International Water Management Institute (IWMI, 1996; WRC, 2015b). Also, two-thirds of the country is a semi-arid region, meaning it is prone to water stress caused by insufficient precipitation (Levy *et al*., 2013; Zhang *et al*., 2018). Agricultural sector utilizes 65 % of total average surface water and it has been linked with low water use efficiency, particularly irrigated agriculture (Costa *et al*., 2007; Hedden and Cilliers, 2014). The usage of irrigation water in agriculture increased from 57 % in 2014 to 66 % in 2015 (Hedden and Cilliers, 2014; The Green Cape: Water Market Intelligence Report 2016).

The significant decline of potato production under dryland conditions as a result of drought led to the increase of production under irrigation to meet the demand of the species (PSA, 2017). This suggests that high production under irrigation conditions means more water supply required to attain optimum yield (Rolando *et al*., 2015; Muthoni and Kabira, 2016). Several research studies have been conducted to attain skills in the irrigation of crops to increase yield performance, efficiency and productivity. The research is still ongoing in promoting water use efficiency by implementing deficit irrigation (Cantore *et al*., 2014). Carli *et al*. (2014) in Central Asia found that limiting water supply after tuberization harmed yield as well as tuber quality. Hassanpanah. (2010) conducted research in Iran and learned that different potato genotypes responded differently on three levels of deficits irrigation. The research reveals that under the same level of water deficit genotypes Savalan and Satina were moderately tolerant whereas Agria, Marfona and Sante genotype susceptible to water deficit. Steyn *et al*. (1998) reported that genotypes Up-to-date and Mondial produced high yield potentials under well-watered conditions whereas under water stress conditions recorded the low yields, in South Africa. These studies reveal that the response differs among genotypes with the level and timing of water deficit imposed (Steyn *et al*., 2016). This proves that there's a variation among potato genotypes. However, the researchers did not compare how each stage of each genotype responds to water deficit and how does it affect yield, quality and tuber size distribution.

With this view, it was essential to evaluate the response of potato genotypes to water deficit imposed at different growth stages. It has been proven that potato genotypes comprise of genetic makeup that allows them to be tolerance or susceptible to harsh conditions like drought. Knowledge regarding the morph-physiological and biochemical response of potato genotypes to water deficit will be therefore important in optimizing the future of potato production. The focus is on how water deficit at different growth stages impact potato growth, tuber yield and quality, this will assist in decision making and planning irrigation schedules, hence improving yields.

2.3 The effects of water deficit on potato genotypes at different growth stages

There is a considerable amount of research that has been successfully conducted in sustaining potato production in drought occurring areas. Rodriguez *et al*. (2016) found that water deficit delays potato growth and development and subsequently reducing the yield. Saravia *et al*. (2016) also observed a similar result of yield reduction and total biomass. Al-Muhmad *et al*. (2014) revealed that all studied genotypes were negatively affected by different levels of drought. Even though, there are many research has been conducted but the yields are still declining as drought crises continue (Allemann *et al*., 2004; Haverkort *et al*., 2013; Admasu and Tamiru 2019). Drought crises, inadequate irrigation, and extreme conditions are the reasons for reduced and poor yield (Geofrey *et al*., 2014; Ramirez *et al*., 2015). Drought is caused by human action, climate change and El Nino leading to prolonged dry spell (Bahta *et al*., 2016). As a result, plants shows variety of physiological and biomchemical responses, like disturbance of plant water relations due to the loss of turgor pressure and that reduces carbon assimilation which affects photosynthesis and biomass production (Osakabe *et al*., 2014). Obidiegwu *et al*. (2015); Rodriguez *et al*. (2016); Rodríguez-Pérez *et al*. (2017) conducted research to determine how water deficit affects potato's morphological, physiological, biochemical traits and yield performance. Obidiegwu *et al*. (2015), reported that drought incidence during the vegetative stage and reproductive result in yield loss. Rodriguez *et al*. (2016) investigated the effects of water deficit on growth and phenology of the three potato genotypes in Colombia. Genotypes 'Diacol Capiro', 'Esmeralda' and 'Pastusa Suprema' were subjected to water deficit at stem elongation, flowering and senescence. The findings demonstrated that water deficit delayed flowering time in 'Diacol Capiro', while 'Esmeralda' had a decline in the development of leaves and tuber ripening and lastly 'Pastusa Suprema' displayed a decline in the development of leaves and formation of lateral shoots.

The potato growth cycle is sub-dived into five growth stages; sprout development, vegetative growth, tuber initiation, tuber bulking and maturity (Khan *et al*., 2011). All these growth stages are sensitive to water stress (Onder *et al*., 2005). However, the sensitivity to water deficit varies among each growth stage (Curwen, 1994). These stages vary in their growth duration, normally first stage (emergence) takes 20 to 30 days, second stage (the development stage) takes 30 to 40 days, third stage (tuber initiation stage) takes 40 to 60 days, fourth stage (tuber filling stage) takes 60 to 90 days, and lastly is maturity or leaf senescence (FAO, 2008a). The duration of these growth stages, when subjected to water stress, varies with cultivars. Factors that influence potato growth and development include; air, soil temperatures, light intensity and duration, length of growing season and humidity (Khan *et al*., 2011). The most crucial time for potato crop is the period of vegetative growth and tuber formation stages because at this point metabolic processes are at the peak (Tantowijoyo and van de Fliert, 2006). Water deficit have a severe effect during tuber initiation and tuber bulking due to the high rate of photosynthesis (Onder *et al*., 2005). The tuber is an important part of the crop since it stores nutrients and it is the harvestable portion of the crop. The roots and shoots transport nutrients and provide support for the crop whereas leaves play an important role in photosynthesis (Tantowijoyo and van de Fliert, 2006).

2.3.1 Stage 1: Sprout development and the emergence

The sprouting stage begins with the development of eyes on tubers which appears as black spots on the skin and this stage varies among genotypes. Tubers use available carbohydrates (energy) from the seed piece to develop sprout (Tantowijoyo and van de Fliert, 2006). At this stage during emergence, not much irrigation is required if and only if the soil water content is kept at 65-80 % field capacity, too much water can accelerate pathogen infestation such as blackleg and stem canker. High soil water content also causes metabolic stress in tubers causing respiration problems (Curwen, 1994; Tantowijoyo and van de Fliert, 2006). During the early days (15-30 DAP) of planting water, scarcity restricts roots development and delay emergence (Obidiegwu *et al*., 2015).

2.3.2 Stage 2: Vegetative growth

Vegetative growth of potato is characterized by an increase in plant height, leaf number, leaf area and formation of stolons (Tumuhimbise *et al*., 2009). According to Hossain *et al*. (2016) when the potato crop is under water stress during the vegetative stage, the plant growth (plant height, plant branching, the number of leaves, leaf area index, leaf size, and expansion) is tremendously reduced. This stage takes place at 30 to 50 DAP depending on environmental factors such as planting dates, soil temperature, and climate. The plant begins to stretch its roots absorbing small quantities of nutrients from topsoil but it still depends on the food reserved in the seed tuber (Tantowijoyo and van de Fliert, 2006). Therefore, at this stage soil water content should be around 70-80 % field capacity, less than 70 % is detrimental (Curwen, 1994). Water deficit during this stage may limit roots growth thereby compromising the uptake of nutrients (Obidiegwu *et al*., 2015). On the other hand, waterlogging during the vegetative period may also promote the leaching of nutrients and increase the susceptibility of plants to diseases (Curwen, 1994).

2.3.3 Stage 3: Tuber initiation

Tuber formation takes place at 40 to 55 DAP and it takes a short period of 10-15 days, almost two weeks forming tubers (Tantowijoyo and van de Fliert, 2006). Tuber initiation is a critical stage for water deficit (FAO, 2009). During this stage (tuber initiation) the stolon tips develop a hook, which then segregates and expand to form a small tuber (O'brien *et al*., 1998). The initiation of tubers is a physiological change in a plant since it highly regulated by photosynthesis (O'brien *et al*., 1998). Water stress and temperature conditions can cause deformed tubers (Obidiegwu *et al*., 2015). During the formation and development of tubers, water stress is more detrimental to the size distribution resulting in small tubers (Lutaladio and Castaldi, 2009). When soil water drops below 65 % of field capacity, tuber yield and quality is negatively affected (Geofrey *et al*., 2014). Therefore, soil water content of 80 to 95 % field capacity is advisable but it also varies with genotype and soil type (Curwen, 1994). Water shortage results in limited foliage, poor tuber formation and fewer number of tubers (Obidiegwu *et al*., 2015). According to Walworth and Carling. (2002), water deficit increases the number and portion of smaller sized tubers, whereas the early-season drought stress decreases the total number of tubers. Less than 15 °C of night temperatures are needed for tuber initiation (FAO, 2008b). Also, tuber development is inhibited when exposed to temperature below 10 °C and above 30 °C because they cannot withstand freezing and hot conditions (FAO, 2008a). Water deficit can promote diseases like common scab, early blight and late blight (Curwen, 1994).

2.3.4 Stage 4: Tuber bulking

Tuber bulking stage occurs at 50 to 80 DAP and is the longest growth stage as it can last up to three months, but it also depends on genotype and planting date. During this stage, large quantities of water and nutrients are needed for cell division and expansion (Tantowijoyo and van de Fliert, 2006). The soil water content of 80 to 90 % or 90 to 95 % field capacity is recommended but it also depends on the soil type (Curwen, 1994). Tuber bulking has the most influence on the yield depending on the water supply (Onder *et al*., 2005). Late planting and early harvest can cause a higher percentage of small-sized tubers (Khan *et al*., 2011). The impact of water deficit results in small tuber size, distorted tuber shape, tarnished tubers, limited development and accelerated leaf senescence (Obidiegwu *et al*., 2015). Water deficit also promote brown spots (*Alternaria solani* and *A. alternata*), early dying (*Verticillium* and *Fusarium wilts*), common scab and early blight (Curwen, 1994).

2.3.5 Stage 5: Maturity

The tuber maturity is the stage where roots and shoot growth are at maximum dry matter accumulation, it occurs at 80 to 95 DAP, however, the best time to harvest the tubers is when it is over 100 days old depending on the genotype (Khan *et al*., 2011). At this point, the metabolic processes stop and settle (Curwen, 1994). During maturity plant leaves turn yellow or brown, photosynthetic processes stop and leaves fall off, the tuber already sets and the skin and hardens (Pavlista, 2002; Tantowijoyo and van de Fliert, 2006). Furthermore, a rapid decline in the mean petiole length shoots growth is observed (Tumuhimbise *et al*., 2009). At this stage, not much water is required, and the ideal soil moisture is reduced to 60 to 65 % field capacity. Too much irrigation stimulates tuber vulnerability to water rots, pink rot and soft rot (Curwen, 1994). Furthermore, water deficit at this stage lead to limited tuber density and tuber size (Obidiegwu *et al*., 2015).

2.4 Drought and water deficit

Drought is the most devastating factor in crop production. The dry spell can be declared after 20 days, whereas drought can last for months or years (Kemiise *et al*., 2016). It occurs when there is a change in atmospheric conditions resulting to the lack of sufficient soil water content to support crop growth in the soil surface at a certain time. South Africa is a semi-arid and arid region that characterised by the periods of dry spell (WRC, 2015a). For instance, Bahta *et al*. (2016) reported that in 2015 drought crisis cost South African farmers' losses up to R10 million. This shows that more research is in need to describe and understand sensitive crop's responses to water deficit as well as their mechanisms.

Potato is the most sensitive crop to drought stress compared to other major field crops such as wheat, maize and rice (Monneveux *et al*., 2013). The sensitivity of the species is due to its sparse and short root system (Amel *et al*., 2015; Zin El-Abedin *et al*., 2017). For that reason, the crop cannot absorb water from deeper soil zones (Banik *et al*., 2016; Mohamed *et al*., 2017). In a study conducted by Hijmans (2003) predicted that between 2040 and 2069 potato production will decline by 18-32 % due to climate change worldwide. In another study by Holden *et al*. (2003) anticipated that potato yield will decline significantly by 2055 as a consequence of drought and global warming. Consequently, to improve potato yield performance, it is essential to identify the non-sensitive growth stages where water can be withheld and still produce optimum yields and best agronomic practices suitable for studied genotypes. The ability to conserve water for future usage differs among genotypes. Potato genotypes are possessed with physiological mechanisms that allow them to tolerate and survive to water deficit during their growth (Zhang *et al*., 2018). These physiological mechanisms include drought avoidance, drought escape, drought recovery, and drought tolerance (Muthoni and Kabira, 2016).

2.4.1 Mechanisms of drought avoidance and tolerance

Drought avoidance involves morphological (roots, shoots, and leaves) and physiological traits (stomata conductance) (Zhang *et al*., 2018). For example, in response to drought stress for drought avoidance mechanisms, plants develop long roots to reach deep soil moisture while closing stomata conductance and reducing leaf area. Therefore, the loss of plant water through the process of transpiration is reduced (Miura and Tada, 2014; Zhang *et al*., 2018). Furthermore, in saving the energy within the plant morphological changes such as plant height, leaf number, and leaf area are reduced (Muthoni and Kabira, 2016). On the other hand, drought tolerance performs more or less the same as avoidance, but tolerance is achieved through physiological and biochemical mechanisms (Zhang *et al*., 2018). For instance, drought tolerance mechanisms refer to the plant stability to withstand the period of water deficit and grow to mitigate (Miura and Tada, 2014). Drought tolerant plants focus on using water more efficiency by increases root size, extending root length and developing water storage organs (Blum, 2005). Furthermore, the plant maintains tissue turgor using osmotic adjustment during water stress, enabling plants to maintain growth. The adjustment includes the production of abscisic acid in the roots (Zhang *et al*., 2018). This reduces the uptake of nutrients due to the reduction of soil water also (Miura and Tada, 2014).

2.4.2 Mechanisms of drought escape and recovery

Drought escape is correlated with the occurrence of the phenological stage of the plant. Plants that have a short period of growing, therefore, complete their life cycle before severe drought strikes using the maximum moisture available in soil (Muthoni and Kabira, 2016). They escape drought by hastening the development of flowers and early maturity. However, crops can only escape drought when soil water available matches with phenological development.

Whereas, drought recovery refers to genotypes that show a slow growth during drought stress and rapid growth after re-irrigation (Muthoni and Kabira, 2016).

2.4.3 Morphological responses to water deficit

Morphology refers to the growth structures such as roots, stem, leaves, flowers, and fruits. It is an indication of plant growth and development (Kaya *et al*., 2006). Roots establishment is considered an important part of the plant for the transportation of water and nutrients from the soil to the entire plant (Geremew *et al*., 2007). Some plants when upper soil becomes dry they develop short suberized to minimize water loss in plants (Lipiec *et al*., 2013). Drought stress has been found to delaying the emergence of potatoes (Obidiegwe *et al*., 2015). Heuer and Nadler. (1998) reported that water deficit reduces plant height in potatoes. The shortage of water in plants disrupt the process of osmosis (water and nutrients uptake). Consequently, wilting and shedding of leaves is observed because of the negative pressure created by low turgor pressure (Banik *et al*., 2016). Negative turgor pressure in plants decreases leaf expansion rate, leaf area index (LAI) and inhibits the development of new leaves (Fahad *et al*., 2017).

In response to water deficit some plants, like aloe, increase the roots system to withstand water deficit (Lipiec *et al*., 2013). Roots and shoots show an abnormal enlargement due to the dislocation of dry matter/assimilate and cause a roots pressure (Obidiegwe *et al*., 2015). Furthermore, the number of leaves and leaf size per plant and leaf longevity are reduced due to limited water in soil (Anjum *et al*., 2001). Khan *et al*. (2001) revealed that plant height, stem girth, leaf area of maize decreases as water stress rises. Water deficit in potato encourage early senescence, deformed (dumb-bell shaped, bent or pointed end) tubers and diseases like a common scab (Muthoni and Kabira, 2016).

2.4.4 Physiological responses to water deficit

Physiological responses refer to the internal response of a plant to water deficit. Water deficit impair the plant water relations, uptake of nutrients, carbohydrates and photosynthetic activity (Obidiegwu *et al*., 2015). The first response of crops to water deficit is the closing of stomata to avoid water loss through transpiration and drying out of leaves (Hossain *et al*., 2016). Relative water content (RWC) is an important indicator of water status in plant leaf (Byrd *et al*., 2014; Khamssi *et al*., 2014). According to Muthoni and Kabira, (2016) water deficit cause a significant decrease in RWC leading to a loss of turgor. Therefore, the cell turgor becomes less than the wall threshold, resulting in a decline in leaf size and expansion

(Hossain *et al*., 2016). The elongation and expansion of leaves are very crucial to dry matter production and photosynthesis (Kaya *et al*., 2006). For that reason, leaf gaseous exchange (stomatal conductance, photosynthesis and transpiration rate) is negatively affected (Li *et al*., 2017).

The decline in cell division is triggered by the closure of stomata and that prevents the intake of carbon dioxide (CO_2) on leaves (Mathobo *et al*., 2017). As a result, the concentration of solutes increases in the cytoplasm thereby leading to the toxic cytoplasm (Muthoni and Kabira, 2016). This results in a low rate of photosynthesis causing the imbalance of energy in photosystem II, dehydration and shrinkage of cell volume (Obidiegwu *et al*., 2015; Mashilo *et al*., 2017). The uptake of CO_2 and carbon-fixing reactions drop significantly on the leaves when the stomata close under drought conditions and that prevent the light-independent reactions in producing energy (Fahad *et al*., 2017; Mashilo *et al*., 2017). The plant loses turgor pressure if the cell membrane pulls away from the cell wall due to loss of water within the cell, as a result, the plant wilts. If there is no photosynthesis (due to loss of turgor pressure) it means the plant cannot grow and carry out metabolic processes properly (Lipiec *et al*., 2013). This alters gene expression and decreases proteins in the leaves due to suppressed synthesis (Fahad *et al*., 2017). Water deficit could lead to plant dysfunctional or even plant death.

2.4.5 Biochemical responses to water deficit

The biochemical responses of potato to water deficit are complex (Obediegwu *et al*., 2015). Water deficit activate many solutes in plant leaves including proline. Proline is a natural amino acid produced by the plant under environmental stress condition, without enough proline plants are vulnerable to stress. It provides strength and energy to overcome any kind of stress in plants (Hayat *et al*., 2012). Proline accumulation prevents plant dehydration by adjusting plant cell osmotic and decreases cell osmotic potential (Kelaleche *et al*., 2018). Jaleel *et al*. (2007) stated that genotype with high proline content advocated as a stress tolerance genotype. This entails that proline content is one of the parameters of selection for stress tolerance in genotypes. Levy. (1983) revealed that water deficit resulted in the rise of proline content in potato leaves of some of the genotypes studied. However, during the early developmental stages of stress, the non-alteration of protein content was detected. This indicates that proline content is correlated to the loss of turgor pressure in potato leaves and the adjustments in osmotic potentials occurring (Levy, 1983). Turgor reduction causes external (tuber cracks, bruise) and internal (cell wall) damages (Praeger *et al*., 2009).

Abscisic Acid (ABA) is another plant (hormone) defender against water deficit that produced from the roots. ABA is transported by xylem through plant shoot to the leaves in the guard cell and regulates stomata (Obediegwu *et al*., 2015). An exponential increase of ABA in the roots results in drastically decrease of stomatal conductance (Ahmadi *et al*., 2010). Under stress condition ABA take charge of plant growth by reducing transpiration rate, however, this denies the leaves of CO_2 and decrease photosynthetic carbon assimilation (Anjum *et al*., 2011). This limits the leaf expansion, leaf area and leaf number of the species. It also triggers the production of reactive oxygen species (ROS) which is a by-product of oxygen metabolism (Hossian *et al*., 2016). The flow of electron capacity results in the overproduction of ROS production in the chloroplast (Molinari *et al*., 2007). Water deficit, therefore, triggers the accumulation of ROS in plants such as singlet oxygen, superoxide radical, hydroxyl radical and hydrogen peroxide in the chloroplast (Lei *et al*., 2006). Reactive oxygen species in plants serves as a second messenger and pathologic mediator. Excessive production of ROS causes membrane injury and changes the metabolic activities of a plant (Muthoni and Kabira, 2016).

Under normal circumstances, Adenine Tri-Phosphate (ATP) and Nitrogen Adenine Di-Phosphate (NADPH) are generated through photosynthetic electron transport chain when light-harvesting centers absorb sunlight and CO_2 in the chloroplast. These molecules are essential for carbohydrate production in the Calvin cycle (Dahal *et al*., 2019). However, in water deficit condition regeneration of ATP and NADP is reduced as a result of limited CO_2 on the leaf (Obidiegwu *et al*., 2015). This causes protein damage in photosystem II (Molinari *et al*., 2007; Hasanuzzaman *et al*., 2013). Therefore, enzymes such as Ribulose-1, 5-bisphosphate carboxylase (RuBisCO) cannot operate under the injured membrane (Lipiec *et al*., 2013). The rate of transporting sucrose from source to sink is altered due to insufficient CO_2 leading to deformed tubers with uneven distribution of dry matter and low starches (Fahad *et al*., 2017; Dahal *et al*., 2019).

2.5 Factors affecting tuber quality

Quality is influenced by pre-harvest and post-harvest events occurring during growth and development. Such factors include agronomic practices; planting dates, fertilizer application, harvesting dates, handling and storage (Solaiman *et al*., 2015; Bekele and Haile, 2019). Tuber quality is the most significant parameter for the consumers and the processing industry (Bekele and Haile, 2019). The internal quality of potato is often based on dry matter, specific gravity, starch and reducing sugars contained. The processing industry requires a certain percentage in terms of dry matter, specific gravity, starch and reducing sugars (Solaiman *et al*., 2015). It has been noted that dry matter and specific gravity are positively correlated (Abong *et al*., 2009; Steyn *et al*., 2009). For example, tubers with high dry matter and specific gravity are best suited for French fries' production (Bekele and Haile, 2019). According to Abong *et al*. (2015), long growing season (120 days) genotypes have higher dry matter content compared to short growing season (90 days) genotype (Laboski and Kellings, 2007; Solaiman *et al*., 2015). This suggests that potatoes harvested at or after 120 days of planting are well developed physiologically and structurally whereas potatoes harvested at or before 90 days of planting their cell structure still underdeveloped. For example, Kenya genotype Tigoni harvested at 90 and 120 days had a different dry matter content of 19.66 and 22.28 % respectively (Abong *et al*., 2015). The recommended dry matter percentage range from 20 to 25. 6. Below (20 %) average range of dry matter content is unacceptable because it turns to absorb more oil (for fried chips) during frying, while above (26 %) average range of dry matter content turn to be pale at the sliced edges (Gegov *et al*., 2007). The content of specific gravity and dry matter of potato tubers vary within genotypes (Kumar *et al*., 2005). The specific gravity is determined by the weight in air and weight in water (Equation 1.1). An ideal specific gravity of 1.08 g ml^{-1} or greater is accepted for processing, while low (<1.08 g ml^{-1}) specific gravity, they are used for canning and boiling (Rady and Guyer, 2015; Bekele and Haile, 2019). These authors further reported that potato tuber with low (less than 0.2 g 100 g^{-1}) reducing sugar contents are best suited for the processing industry. The high concentration of reducing sugars gives an undesirable brown colour to fried chips (Figure 1) (Potato South Africa, 2016). Size distribution, shape, skin and flesh colour are among the main physical characteristics considered in the evaluation of potato quality (Abong and Kabira, 2011; Bekele and Haile, 2019). Various studies have shown the variation among genotypes of dry matter content ranging from 15.83 to 27.3 g m^{-1} specific gravity ranging from 1.022 to 1.130 and size distribution from small tubers (< 35 mm) to large (> 55 mm), depending on the genotype (Table1). Therefore, ensuring a high quality of potato production, pre-harvest and post-harvest factors that affect the quality need to be carefully considered.

$$SG = \frac{\mathrm{Ms}}{\mathrm{Msw}}$$

Equation 1.1: Where: Ms = mass of the sample and Msw = mass of the sample in water

Figure 2.1: Chips made from potato tubers with a high concentration of reducing sugars (PSA, 2016).

Table 1.1: Raw tubers with different qualities for the processing industry.

Genotypes	Origin	Dry matter (%)	Specific gravity (g m^{-1})	Size category			Sugar content in (g 100 g^{-1}, fmb)	reference
				Small (< 35 mm)	Medium (35 – 55 mm)	Large (> 55 mm)		
Ajax	Jordan	18.9	1.097	-	-	-	-	Ereifej *et al.*, (1997)
Belete	Ethiopia	17.50^{C}	1.07^{C}	10.47^{E}	72.18^{B}	17.35^{A}	-	Bekele and Haile, (2019)
Chala	Ethiopia	20.00^{B}	1.08^{B}	29.95^{C}	66.39^{DE}	3.66^{DE}	-	Bekele and Haile, (2019)
Desiree	Kenya	22.2	-	-	50	-	-	Abong *et al.*, (2009)
Degemegn	Ethiopia	18.33^{C}	1.07^{C}	20.80^{D}	67.85^{CD}	11.35^{C}	-	Bekele and Haile, (2019)
Gudanie	Ethiopia	21.67^{A}	1.084^{A}	13.59^{E}	77.443^{A}	8.97^{C}		Bekele and Haile, (2019)
Golden Purple	Kenya	20.8	1.080	-	-	-	Fructose – 0.031 Glucose – 0.016 Sucrose – 0.056	Abong and Kabira, (2011)
Kenya Mpya	Kenya	25.8	1.130	-	-	-	Fructose – 0.023 Glucose – 0.018 Sucrose – 0.065	Abong and Kabira, (2011)
Kenya Sifa	Kenya	20.88	-	-	-	-	-	Abong *et al.*, (2009)
Kenya Karibu	Kenya	21.14	-	-	-	-	-	Abong *et al.*, (2009)
Mondial	Jordan	17.6	1.022	-	-	-	-	Ereifej *et al.*, (1997)
Maracharre	Ethiopia	15.83^{D}	1.06^{D}	34.35^{A}	60.68^{G}	4.97^{D}	-	Bekele and Haile, (2019)
Sherekea	Kenya	27.3	1.090	-	-	-	Fructose – 0.026 Glucose – 0.023 Sucrose – 0.055	Abong and Kabira, (2011)

2.6 Other factors affecting potato production

2.6.1 Potato genotypes

To ensure higher productivity and lower crop vulnerability to pest and diseases, it very important to select the best genotype adapted to the location and consider the planting season. The usage of certified seeds is recommended for both commercial and subsistence farmers because they have a low risk of diseases and pest infection (Wilson *et al*., 2001; Lutaladio and Castaldi, 2009). Seed quality of any potato genotype is regarded as a yield-reducing factor if it not of the best quality (Haverkort and Struit, 2015). The genotypes that are mostly used in South Africa are imported from other countries such as Netherland and Ireland (Ngobese *et al*., 2017). These genotypes are grown in 16 different agronomic regions, which guarantees a constant supply of fresh potatoes throughout the year (van Niekerk *et al*., 2016). South Africa is currently registered more 80 % of genotypes with Mondial being popularly followed by Sifra, Lanorma, and Valor genotypes dominating in terms of performance in growth and yield (Figure 2) (Potatoes South Africa, 2016).

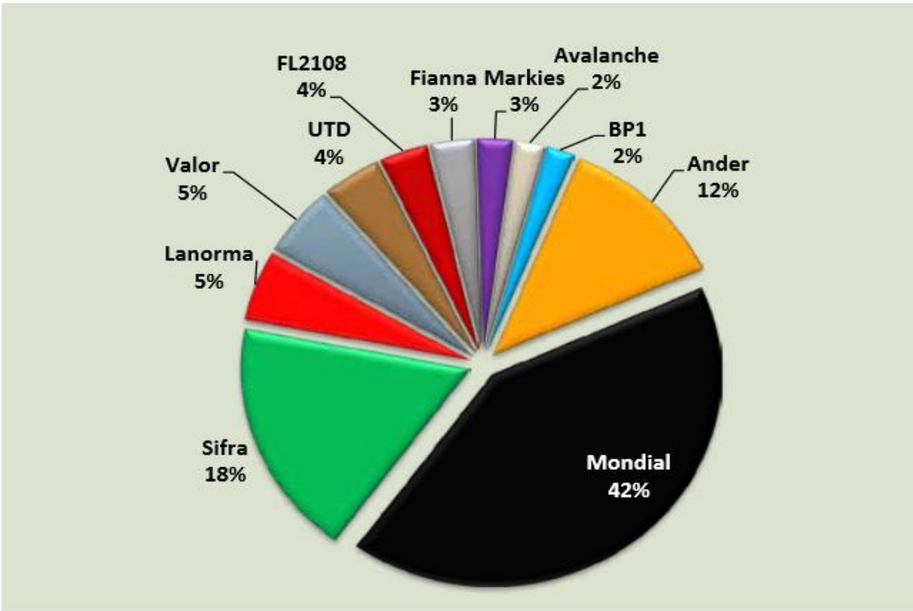

Figure 2.2: The most dominating potato genotypes planted in 2016, in South Africa (van der Merwe and van Zyl, 2016).

The response of potatoes to water deficit varies among genotypes, timing and level of water deficit imposed (Banik *et al*., 2016; Caliska, 2016; Fahad *et al*., 2017). Fahad *et al*. (2017) reported that severe drought stress inhibits crop development, nutrients uptake and alters dry mass content. On the other hand, Banik *et al*. (2016) reported that a short period of drought stress results in a reduction of tuber production, quality tubers and eventually cause a significant decrease in crop yield. Geofrey *et al*. (2014) stated that water deficit during tuber bulking stage reduce yield and tuber quality. These results suggested that the absorption of nutrients and the partitioning of photosynthesis products in plants rely on the type of genotype used. Therefore, research evaluating the best performing genotypes in a different location is vital.

2.6.1.1 Bikini

According to Irish Potato Marketing, (2017) Bikini is an early maturing multi-colored genotype with a widespread and unique red splash. It produces a consistent yield of very uniform tubers that are good-looking and distinctive when pre-packed. Bikini tubers are oval with red skin colour, yellow flesh, and splash as well as shallow yellow eyes. Generally, it has high dry matter content, also excellent for cooking quality. This genotype is good for the chipping industry, French fried since it does not discolour after cooking. Bikini is very sensitive to drought stress. It is resistant to common scab, powdery scab, foliage blight, rust, tuber blight, blackleg, and wart diseases (IPM, 2017).

2.6.1.2 Challenger (Aziza x Victoria)

Challenger has broad adaptation and tubers have a medium late growth period. It produces high, medium-size tubers. The shape of Challenger tuber is oval/long oval uniform tubers with yellow skin as well as shallow eyes (Hettema and ZPC HZPC, 2018a). This genotype is susceptible to spraing and foliage blight, moderate resistance to Alternaria, common scab, tuber blight, and slightly susceptible to powdery scab. Challenger can withstand drought stress and therefore it is a good drought tolerance genotype (HZPC, 2018a).

2.6.1.3 Electra

Electra is adaptive to a wide range of geographic regions and can tolerate harsh temperatures such as high temperatures and water deficit. It is an early maincrop. Electra produces large high yields, smooth bright clean yellow oval tubers with faint pink eye. This genotype is slightly susceptible to late blight (*Phytophthora infestans*) on leaves as well as on tubers. However, it is resistant to common scab, powdery scab, foliage blight, tuber blight, blackleg, wart disease and soil-borne diseases (IPM, 2015).

2.6.1.4 Mondial

Mondial is one of the most popular and planted genotypes in all production regions of South Africa. It originated from the Netherlands and can be grown in all soil types as it is well-adaptive, and they have a good tolerance of drought stress (HZPC, 2018c). Extreme conditions such as heat and water strain result in a large number of deformed tubers experienced during tuber initiation. The plant produces pure white flowers, grows quick and strong in an upright orientation to medium 90 - 110 days from emergence until the death of natural foliage (ANSA, 2008). Mondial is likely to produce high yield when it grows during late spring, summer and early winter season. Mondial tubers size range from medium to large and long oval cylindrical tuber shape with shallow eyes (Aartappel Netwerk Suid-Afrika ANSA, 2008; HZPC, 2018c). They produce a high yield of big tubers with bright attractive, yellow skin colour and light-yellow flesh colour (HZPC, 2018c). Usually, Mondial has good dry matter content and specific gravity, however not suitable for the processing industry because of low density (ANSA, 2008). This genotype is susceptible to common scab and slightly susceptible to foliage blight, tuber blight and powdery scab (HZPC, 2018c). It also highly susceptible to late blight and *fusarium*-wilt (ANSA, 2008).

2.6.1.5 Sababa

Sababa is a newly introduced genotype, therefore there is currently no scientific information available.

2.6.1.6 Sifra (Mondial x Robinta)

Sifra originated from the Netherlands, which can be grown in all types of soil and produce high yield (HZPC, 2016; 2018d). The plants grow higher with erect, tall stems and provide vigorous ground-covering foliage. Sifra produces a round, oval-shaped tuber with bright white smooth skin, medium-deep eyes and white flesh. They are classified as late maturing genotype which can be used for any purpose (HZPC, 2016)**.** Sifra is susceptible to powdery scab, slightly susceptible to common scab, Alternaria and foliage blight also resistance to tuber bight and golden nematodes. This genotype has a low nitrogen requirement but it very sensitive to water deficit (HZPC, 2018d).

2.6.1.7 Panamera

Panamera has a very low nitrogen requirement and can be grown in all types of soil except those with a risk of diseases like a powdery scab. This genotype produces a great yield of big tubers under favourable conditions (HZPC, 2018b). Panamera tubers are oval, with yellow skin colour as well as shallow eyes. It is slightly susceptible to foliage blight, tuber blight, and powdery scab. Furthermore, it is resistant to common scab (HZPC, 2018b).

2.6.1.8 Tyson (Sylvana x Cyrano)

Tyson is an early bulking table potato for the wholesale fresh markets in Europe and southwest Asia (Set Holland, 2018). The growth pattern of Tyson is medium maturing, with an early tuberisation. It also produces a high number of bigger tubers per plant with round oval shape, cream skin and cream flesh colour with shallow eyes. They have moderate dry matter and specific gravity (Set Holland, 2018). Tyson is resistance to cyst nematodes, wart diseases but susceptible to foliage blight (*Phytophthora infestans*). This genotype is good for the baker market (Set Holland, 2018).

2.6.2 Agronomic factors

Agronomic factors such as soil type, pH, soil composition and crop rotation or past use of the soil as well as exposure to pests and diseases affect the potato yield and quality of tubers (Khan *et al*., 2011). Potato plants adapt in a wide range of climatic conditions, however temperate climate is advised for optimal growth (Haverkort and Struit, 2015). It can be also produced in a wide variety of soils, but the most suitable is loose loamy, loamy and sandy loam soils that have good drainage, aeration and rich in organic matter (FAO, 2008a). The largest production in the country comes from regions that are highly dominated with loam, and sandy loam soils and those regions are found in Limpopo, Eastern and Western Free State (Steyn *et al*., 2016). Likely, South African soil types also vary with regions of production from loam, loam-clay loam, sand, sandy and sandy loam (Steyn *et al*., 2016).

Monitoring soil pH in both controlled and open field environments is essential for optimum growth to avoid the acidity and alkalinity of the soil. A high concentration of pH affects the uptake of nutrients by the plant from the soil. For potato production, slightly acidic soils in the range of pH 5.0 to 6.0 are important for growth (FAO, 2018). At high soil pH (>7) the crop becomes more susceptible to pests and diseases such as common scab while low pH (<5) leads to leaching of nutrients and subsequently reduces the yield (Waterer, 2002; McCauley *et al*., 2017). Soil aeration is vital for gaseous exchange in potatoes during growth because soil compaction often limits tuber expansion (Lutaladio and Castaldi, 2009). Planting potatoes in the same field over a long period leads to the accumulation of nematodes and diseases. Studies have shown that rotating potatoes with dry beans, maize or wheat reduces the risk of diseases and ensures health benefits and yields (Naidoo *et al*., 2011; Saravia *et al*., 2016). Maintaining required soil moisture all the time is important because it improves tuber size and yield (Tolessa *et al*., 2016). Extreme temperatures or deficient moisture during tuber formation especially in the late spring and early summer reduces yield. Therefore, optimum soil temperature for the tuber development range between 15 ºC and 18 °C (FAO, 2018). Agronomic factors need to be fully considered when one planning to grow crops because they determine the yield and quality to be obtained.

2.6.3 Cultural and management practices

2.8.1 Potato Spacing

Plant spacing is one of the most important cultural practices affecting potato growth and yield. The growth, yield, size, and quality are always influenced by how far apart or close potato seeds/tubers were spaced in the field during planting (Mangani *et al*., 2015). Getachew *et al*. (2012) conducted a study comparing the effect of different spacing (10, 20, 30 and 40 cm) in yield and number of tubers. The results reveal that potato plants with wider intra-row spacing (40 and 30 cm) had the highest number of tubers but lowest yield whereas plants with closer intra-row spacing (20 and 10 cm) scored the lowest number of tubers yet high yield. The study conducted by Razaq *et al*. (2015) also found that the highest number of tubers was recorded on wider intra-row spacing (35 and 25 cm) whereas the lowest tuber number was found at closer intra-row spacing (15 cm). Arega *et al*. (2018) reported similar results where a high number of tubers were obtained at 30 cm intra-row spacing but fewer in 20 cm and 40 cm which is wider. This tells us that the wider the intra-row spacing the higher the number of tubers per plant. Furthermore, Razaq *et al*. (2015) found that the highest number of small tubers was obtained on closer spacing (10 cm) while the highest larger tubers were recorded on wider spacing (40 cm). Considering plant spacing is essential for the plant uptake of nutrients and radiation.

The competition of plant resources is minimized on wider intra-row spacing. Lack of information on plant spacing could go as far as interfering with internal quality (biomass accumulation, dry matter, and specific gravity) (Getachew *et al*., 2012; Mangani *et al*., 2015). For example, Getachew *et al*. (2013) found that the highest dry matter content of 21. 53 % was observed on plants with a wider intra-row spacing of 30 cm, on the other hand, the lowest dry matter of 19. 57 % was obtained at 10 cm intra-row spacing. Similarly, on the specific gravity, the highest (1.082) was recorded on wider-spacing and lowest (1.072) was obtained in closer plant intra-row spacing. Overcrowding plants increases competition among the plants reduces the amount of nutrients uptake, water and light received by the plants resulting in reduced photosynthesis, transpiration. Plant density is one of the most important cultural practices affecting potato yield that need to be considered because ignoring plant density or crowding plants triggers the accumulation of pest and diseases (Fiers *et al*., 2012). Therefore, it is advisable to use low plant density only when producing for the market that considers tuber size while high plant density for the market with no size restriction of tubers. However, in most cases, the size distribution for potatoes remain the main factor in price determination.

2.8.2 Weed control and earthing-up

Weeding should be done properly to reduce nutrients competition. Usually, deep cultivation is not recommended for potato because it damages roots and tubers. Proper earthing-up creates favorable conditions for tuber initiation and development and eventually increases yield (Getachew *et al*., 2013). Tafi *et al*. (2010) reported that first earthing-up should be done when plants reach a height of 10 cm and this could be repeated twice every after two-three weeks. Earthing-up ensures plant stability, increases underground stolons that will produce tubers (Tafi *et al*., 2010; Getachew *et al*., 2013). Getachew *et al*. (2012) conducted a study on the influence of early and late earthing-up on potato yield and found that early earthing-up (after 15 days of planting) results in high yield and a high number of tubers than late earthing-up (after 30 and 40 days of the plantation). Therefore, early weeding and ridging improves yield and number of tubers produced per plant.

2.8.3 Pest and diseases

Pests and diseases are another main limiting factors of potato production (FAO, 2008b). Unbearable environmental conditions cause a high risk of diseases and pest infestation (Steyn *et al*., 2016). Pests such as the beetle, tuber moth, leaf miner fly and diseases such as early blight, late blight, bacterial wilt, blackleg, viruses decrease the yield and lead to crop death (Tantowijoyo and van de Fliert, 2006; FAO, 2008b). Early blight (caused by *Alternaria solani*) and late blight (caused by *Phytophthora infestans*) are the most serious diseases worldwide that have a devastating effect on potato production (FAO, 2008a). Beetles (*Leptinotarsa decemlineata*) and leaf miner fly (*Liriomyza huidobrensis*) are serious pests with strong resistance to insecticides as they destroy leaves, shoots and eventual the entire crop. Late blight is characterized by brown spots on the leaves with brown patches and some yellowish. Once the blight spores washed down by rain or irrigation it reaches the soil and starts ruining tubers and from there it destroys the entire plant (Curwen, 1994). Early blight is noted by an irregular series of dark and light tan concentric rings, as a result of this, discoloured irregular tubers are produced and can cause major yield reductions (Curwen, 1994; FAO, 2008a). It is always advisable to control pests and diseases as early as possible to avoid crop losses.

2.8.4 Harvesting and storage conditions

Harvesting potatoes at the maturity stage (after the foliage has died back) requires full attention to avoid bruising, skinning and mechanical damage. Physically damaged tubers are prone to diseases, rotting and are rejected by consumers. Moreover, inappropriate harvesting reduces tuber quantity and quality, therefore it is important to handle tubers with care (Pandey *et al*., 2017). Delaying harvesting particularly in summer can cause tubers to become glassy (Figure 3) which not good for the market. After harvesting is also important to wash them and group into size and grading according to the market.

When potatoes reach physiological maturity, tubers stay dormant up until they are stored at a particular storage temperature based on the final usage. Tuber dormancy is governed by both exogenous and endogenous factors (Alamar *et al*., 2017). The period of dormancy ranges from one month to over three months, but it differs from genotypes (Freitas *et al*., 2012; Alamar *et al*., 2017). After this period, the quality of tubers changes based on storage conditions (Heltoft *et al*., 2017). The storage conditions and duration of potatoes after harvest are very crucial because they contribute to the chemical composition (Chemeda *et al*., 2014; Heltoft *et al*., 2017). Even if potatoes are to be marketed as seed, fresh potato or for the processing industry, storage temperature and duration remain vital parameters. Storing potatoes at a very high or low temperature over some time could lead to a vast variability in quality. For example, high temperature as 26.7 ^{o}C or above triggers the spread of disease and encourage sprouting while low temperatures 10 ^{o}C or below leads to soft rot, black spot and accelerates conversion of starch into fructose and glucose (Voss *et al*., n.d; Freitas *et al*., 2012; Khanal *et al*., 2014). Again, low storage temperatures lower the sprouting process and respiration rate (Freitas *et al*., 2012; Alamar *et al*., 2017). Potato reducing sugars also decrease when stored at low temperatures and that negatively affects the chipping industry

(Kumar *et al*., 2004; Heltoft *et al*., 2017). Nevertheless, the level of reducing sugars varies among genotypes and with maturity (Kumar *et al*., 2004; Khanal *et al*., 2014). This articulates that, each genotype is genetically unique and requires specific storage conditions that would keep the internal quality unchanged. Understanding the storage temperature requirements for each genotype would help in storing potatoes in a conducive temperature that will not accelerate the convention of sugars which will result in rejected by the chipping industry if it to be market for the processing industry.

Figure 2.3: Glassy flesh caused by the disappearance of starch after a delayed harvest in summer (Phelan, 2018).

2.8.5 Effect of fertilizer on potato growth

It is always advisable to take into consideration the soil status before applying fertilizer to avoid insufficient or excess application. The roots system plays a vital role in the absorption of nutrients, however, it can only uptake mobile fertilizer that is well dissolved in a solution (Barber, 1995; Stubbs, 2016). The elements that are essential for plant growth and development are categorized into basic nutrients (carbon (C), hydrogen (H) and oxygen (O)), primary macronutrients (nitrogen (N), phosphorus (P) and potassium (K)), secondary macronutrients (magnesium (Mg), calcium (Ca) and sulphur (S)) and lastly micronutrients (iron (Fe), zinc (Zn), manganese (Mn) and boron (B)) (Stubbs, 2016). Plants require basic nutrients like carbon dioxide (CO_2), light, water (H_2O) and they are needed in large amounts to build larger organic molecules of the cells**.** Even though micronutrients are needed in small quantities they do play an essential role like activating various enzymes, depending on the crop growth stage (Tavakoli *et al*., 2014). For example, Mn plays role in leaves by activating carboxylation, carbohydrates metabolism, phosphorus reactions and oxidation reactions (Tavakoli *et al*., 2014). However, potato requires macronutrients (N, P, and K) in large quantities for plant growth and development to produce optimum yield (Suh *et al*., 2015; Kahsay, 2019).

Nitrogen is an essential nutrient required for plant growth especially during vegetative growth and it facilitates photosynthesis, whereas phosphorus stimulates root growth, improves plant shoot and increases flower formation. Likewise, potassium is one of the most important nutrients regulating various physiological processes (protein synthesis, role in photosynthesis, translocation of sugars) (Muhammad *et al*., 2015). Kandil *et al*. (2011) stated that nitrogen fertilizer is an important element for the high number of tubers and quality. Furthermore, insufficient supply of nitrogen fertilizer decreases dry matter content and specific gravity. It also plays an important role during the vegetative stage and tuberization of potatoes (Adhikari *et al*., 2009). Kandil *et al*. (2011) stated that N fertilizer increases the plant height, leaf number, tuber weight per plant and average tuber. A constant supply of nitrogen and water guarantees high yield performance and tuber quality (Saravia *et al*., 2016). Rosen *et al*. (2014) pointed out that phosphorus fertilizer plays a vital role in cell division, photosynthesis, and respiration which eventually influence plant metabolism. Phosphorus goes as far as speeding up the cell division rate and by doing that it accelerates plant maturity. Generally, P fertilizer is more involved in physiological and biochemical mechanisms. Razoq *et al*. (2015) reported that potato requires a sufficient amount of potassium more than any other vegetable because of its significant role in regulating guard cells in stomata, ensuring plant stability and increasing tuber size and quality. It is important to understand soil status and proper fertilizer rate required is very important to enhance crop vigor and yield.

2.8.6 Irrigation

Water accounts for more than 80 % of plant growth tissues (Ati *et al*., 2012). It is considered a scarce resource in several parts of the world particularly in arid and semi-arid areas (Kandil *et al*., 2011). In agriculture, several irrigation systems have been successfully used for potato production which includes, drip irrigation, furrow, and overhead sprinkler irrigation system. The drip irrigation system has been widely used particularly in the greenhouse and tunnels production. Even though it has some higher cost for installation it's known as a good water-saving system while increases yield and tuber quality and reducing the chances of disease infestation (Onder *et al*., 2005). Irrigation in potatoes is an important factor required for optimum growth, transpiration and metabolic processes (Sarani *et al*., 2014). It plays a significant role in the yield and quality of the crop. However, the amount of irrigation required depends on soil type or growth media, climatic condition, genotype, and growth stage (Khanna-Chopra and Singh, 2011). For example, hot conditions with dry soils require a high amount of water because of the high evaporation rate (Steyn *et al*., 1997). Adequate and consistence supply of water ensures high yield performance and quality tubers (Saravia *et al*., 2016).

Excessive irrigation or inadequate irrigation has an adverse impact on crop development and tuber quality. Excessive irrigation results in leaching of nutrients, disease vulnerability, erosion whereas under irrigation delays normal crop growth, decreases yield, while the crops become more vulnerable to diseases. Furthermore, the shortage of water reduces the photosynthesis rate and absorption of plant nutrients (Obidiegwu *et al*., 2015). A minimum of 500 to 700 mm of water is recommended for long growing season genotypes (120-150) to optimum yield (FAO, 2008b). Some genotypes cannot undergo physiological changes through natural rainfall only, they also require supplemental irrigation to enhance yields (Xie *et al*., 2012). FAO. (2008a) reported that 50 % of soil water is not sufficient enough to meet the crop demand for the growing period because it leads to lower yields. Badr *et al*. (2012) found that under four irrigation treatments 40 %, 60 %, 80 % and 100 % the highest yield was obtained under full water irrigation (100 % and 80 %), while 40 % and 60 % irrigation had a significantly low yield. Rodriguez *et al*. (2016) found that tuber yield per plant was reduced by 15.45 % for genotype Pastusa Suprema (SUP) d, 16.68 % for genotype Capiro (CAP) d and 19.46 % for Esmeralda (ESM) d due to water deficit (Figure 4). Variation within genotypes was observed.

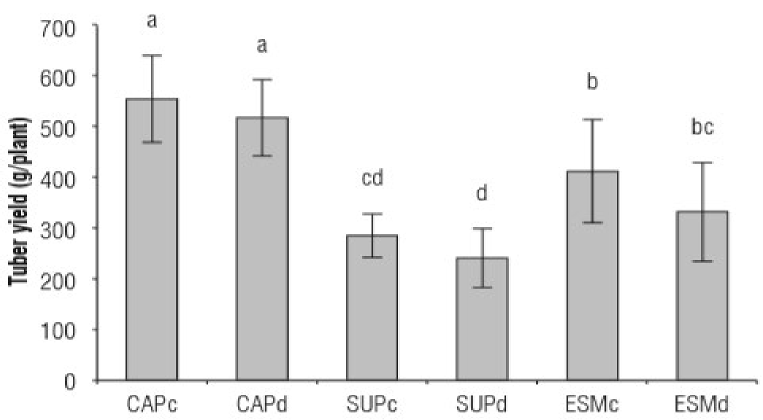

Figure 2.4: Potato yield genotypes Capiro (CAP), Pastusa Suprema (SUP) and Esmeralda (ESM) under c: irrigation and d: water deficit (Rodriguez *et al*., 2016).

Potato can be grown in both conditions open field and controlled environment, but the crop is mainly grown on the open field global. There is no much work that has been done on potato production under a controlled environment (tunnels, greenhouse and shades) in South Africa. However, in other parts of the world, there is information. A study conducted in Turkey by Ayas (2013) illustrated that low water supply in potato production under unheated greenhouse significantly affects plant height, yield, and a number of tubers per plant, diameter, weight, dry matter and starch matter. In a similar study in Japan, it was revealed that different water regimes increased potato plant height, shoot and biomass with an increase of the amount of irrigation water but specific leaf weight declined (Yuan *et al*., 2013). Both studies suggested the importance of maintaining irrigation using a pan evaporation factor above 0.75 ($K > 0.75$) as a guideline because lower factors could negatively affect potato yield (Yuan *et al*., 2013). Alsharari *et al*., (2007) evaluated drought tolerance of different potato genotypes under greenhouse conditions. They reported that most genotypes were highly affected during the vegetative stage, consequently, it decreased tuber yield as water stress increased. Therefore, looking at the tuber yield and number produced in relation to days after treatment and irrigation regimes, drought tolerance and drought-sensitive genotypes were identified. Such information could be useful in addressing the issue of the ongoing drought problem in South Africa.

2.8.7 Water use efficiency

Water use efficiency is defined as the yield of marketable crop produced per unit of water used in evapotranspiration (Boutraa, 2010; Badr *et al*., 2012). Hussain *et al*. 2015 reported that water use efficiency focuses on the total yield produced over water used to produce that yield. It also involves the loss of water from the soil surface and crop through the evapotranspiration process (De Pascale *et al*., 2011). This is a parameter used to measure how crops use water applied during the growing season. The concept involves the capacity of the soil to store water and the crop's ability to access stored water in soil pores and then after the crop's ability to go through metabolic processes, conversion until biomass or yield produced (Masango, 2014). Water use efficiency aimed to improve crop yield and quality at low water supply (Boutraa, 2010). Therefore, it is important to understand the soil or environment and crop to be used its water status. Fereres and Soriano. (2006) stated that applying water below the evapotranspiration requirements is described as deficit irrigation, and that reduces crop production. On the other hand, deficits irrigation may beneficially improve water use efficiency by crop when imposed to less sensitive growth stages (i.e. late vegetative and late tuber bulking) (De Pascale *et al*., 2011; Begum *et al*., 2018).

The majority of the plant's physiological processes depend on water supply for adequate growth. Water deficit may inhibit either of the physiological processes such as photosynthesis, transpiration, enzymatic activities and cell enlargement (Aliche *et al*., 2018). Even though potato is known as water use efficiency compared to cereal crops, but it is sensitive to water scarcity (Birch *et al*., 2012; Daryanto *et al*., 2016). Badr *et al*. (2012) conducted research looking at how different irrigation levels (100, 80, 60 and 40 %) affects yield and results reveal that the highest tuber yield obtained under full irrigation (100 and 80 %) and reduced as irrigation decreases. Scheduling irrigation based on soil and crop requirement remains vital for the potato crop. This can be attained by estimating soil moisture using relevant instruments such as HS2 HydroSense II, neuron probes and tensiometer. Moreover, improving water use efficiency can be done through the correct selection of specific genotype, planting date as well as a specific location.

2.7 Summary and conclusions

The short durations and uneven distribution of precipitation which is related to prolonged dry periods result in complete yield loss. This has been demonstrated for the past decades where potato production has declined significantly due to climatic extremes. Yet, there is a high demand for potatoes of high quality for processing and other different usages. Potato genotypes require careful management to guarantee optimal tuber development since tubers are sensitive to water deficit throughout the growing season. Also, poor post-harvest handling practices can compromise quality if not fully considered. The current literature review has revealed that reducing water at certain growth stages of potato has an impact on the growth, yield and quality, but, there is little information on the responses of different potato genotypes to water deficit at critical stages of growth and development. Secondly, we do not know for how long and by how much we can impose water deficit and which stages are most sensitive to water deficit and third we need to describe the variability among current potato genotypes in relation to the imposition of water deficit, the recovery process and effect on yield performance.

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Chapter 3: Drought tolerance assessment of potato (*Solanum tuberosum* L.) genotypes at different growth stages based on morphological and physiological traits

3.1 Abstract

Cultivation of drought-tolerant potato (*Solanum tuberosum* L.) genotypes is key to improving complementary morphological and physiological traits tuber yield and quality for food and processing. The objective of this study was to assess drought tolerance of diverse potato genotypes. Physiological and morphological responses of eight potato varieties were assessed under well-watered (Ww) and water-deficit (Wd) conditions across four different growth stages namely: (i.e. vegetative (VG), tuber initiation (TI), tuber bulking (TB) and maturity (MAT) stages using an 8×4×2 factorial treatment with three replications. Data was collected on morphological traits such as plant height (PH), leaf number (LN), tuber yield (TY) and total above-ground biomass (TAG), and physiological traits including stomatal conductance (*gs*), transpiration rate (Tr), rate of photosynthesis (*A*), instantaneous water use efficiency (IWUE), chlorophyll content index (CCI) and relative water content (RWC). Significant ($p < 0.05$) genotype x water condition x growth stage effect were observed for *A*, Tr, IWUE, RWC, CCI, PH, LN, TY and TAG indicating varied response of genotypes to water condition across growth stages. This is useful to recommend growth-stage specific and tolerant potato genotypes for production. Correlation analysis revealed significant and negative associations between *gs* and IWUE with TY (r = -0.81; r = -0.77) at VG stage, PH, Tr, *A* and IWUE with TY (r = 0.92; (r = 0.65; r = 0.95; r = 0.88 at TI stage. Also, CCI with TY (r = 0.71) at MAT stage and negative association between TAG with TY (r = -0.85) at MT stage under Wd condition. Principal component bi-plot identified drought-tolerant potato genotypes such as Bikini and Challenger with high tuber yield across growth stages and recommended for cultivation in water-restricted environments.

Keywords: Abiotic stress, potato genotypes; water deficit; growth stages; physiological traits

3.2 Introduction

Potato (*Solanum tuberosum* L.) is an economically important tuber crop widely cultivated for food and various industrial applications globally after cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), and yam (*Dioscorea alata*) (FAOSTAT, 2019). The starchy tuber are valuable sources of health-promoting phyto-nutrients including carbohydrates, minerals (i.e. iron, zinc, magnesium, phosphorus and potassium), vitamins (i.e. Vit C, B3, B5, B6 and fibre) and protein content ranging from 1 to 1.5%, and 8 to 9 % for fresh and tubers, respectively (Singh and Raigond, 2014; Wassu, 2017). The crop is also valuable source of phenolic compound such as phenolic acids and flavonoids including flavonols and anthocyanins, alkaloids such as glycoalkaloids which are health-promoting possessing antioxidant and anti-cancer properties (Singh and Raigond, 2014; Akyol *et al*., 2016). Potato is largely produced under rainfed conditions and production is affected by abiotic stress factors mainly drought and heat (Chauvin *et al*., 2012; El-Wahab *et al*., 2016) resulting in low yield output and unsuitable for marketing (Adhikari *et al*., 2015; Kiptoo *et al*., 2018). Efforts to develop well-adapted and drought-tolerant potato genotypes are required to improve yield gains and overall production, and quality end-user potato-derived products by processing industries.

Agronomic traits are key determinant of potato tuber yield under water-stress environments and useful indicators for drought tolerance assessment. Traits such as plant height, leaf number and total-above ground biomass are widely used for selection of drought-tolerant potato genotypes (Tourneux *et al*., 2003a). Agronomic traits well correlated with yield serving as an indirect selection criterion for cultivar development (Mahmud *et al*., 2017). Physiological traits including chlorophyll content index (CCI), rate of photosynthesis (A), stomatal conductance (gs), transpiration (T_r), relative water content (RWC) which measures plant water status, and water-use efficiency (WUE) are also useful indicators of drought tolerance. These traits can be targeted in breeding programs to select and identify promising genotypes for production in targeted environments (Tourneux *et al*., 2003b; Ramirez *et al*., 2014). Therefore, the integration of agronomic and physiological traits is useful to improving identification and selection of drought tolerant genotypes.

Growth of potato occurs in various stages including vegetative, tuber initiation, tuber bulking and maturity stages (Ayas and Korukcu, 2010). All potato growth stages are sensitive to water deficit; however, the most drought-sensitive are tuber initiation and bulking stages, whereas early vegetative and maturity stages are regarded as tolerant to drought stress (Ayas and Korukcu, 2010; Hirut *et al*., 2017). Water deficit reduce total yield in all potato growth stages (Abbas and Ranjan, 2015; Al-Mahmud *et al*., 2015). As a result, the interactive effects genotype, developmental stage, and the environment influence the response of potato to drought stress. This is important to identify growth-stage specific or “all-stage” adaptation of genotypes for specific cultivation in dry environments to improve yield potential.

In South Africa, drought stress is the leading factor for reduced potato yields and quality (DAFF, 2017). In the country, potato yield output has slowly increased from 1.2 to 2.5 million tonnes from the period 1990 to 2015 (Potato South Africa, 2017). In addition, production is insufficient due to the high demand of the crop by neighbouring countries such as Botswana, Lesotho, Namibia, Swaziland, Zambia and Zimbabwe (Kapuya and Sihlobo, 2015). There has been very limited efforts in the country concerning developing potato genotypes with high-levels of drought tolerance across all growth stages for recommendation to growers. The currently and widely grown genotypes in the country could serve as useful germplasm for developing specific and across-stage tolerance potato genotypes for improving yield output and quality under water-constrained production environments.

Although extensive research has been carried out determining the response of potato genotypes to different water regimes (Alsharari *et al*., 2007; Haverkort *et al*., 2013; Elzner *et al*., 2018), there is limited information on potato response at different growth stages and how this influence yield performance. Therefore, the objective of this study was to determine the drought tolerance of diverse potato genotypes based on physiological and morphological responses to identify for recommendation or breeding.

3.3 MATERIAL AND METHODS

3.3.1 Plant materials

Certified seed (i.e. generation 1-3) of eight potato genotypes namely: Bikini (G1), Challenger (G2), Electra (G3), Mondial (G4), Panamera (G5), Sababa (G6), Sifra (G7), and Tyson (G8) were sourced from Wes grow Pretoria, South Africa and used for the study. This are highly demanded and newly introduced genotypes for potato the industry in South Africa, hence selected for evaluation.

3.3.2 Description of a controlled environment

An experiment was conducted at the University of KwaZulu-Natal's Controlled Environment Research Unit (CERU), Pietermaritzburg, South Africa. The environmental conditions inside the tunnel were semi-controlled with the average day and night temperatures of 38 °C and 18 °C, respectively, whereas relative humidity ranged between 45 % - 55 %. Temperature and relative humidity were monitored electronically using a data logger (HOBO 2K logger, Onset Computer Corporation, Bourne, USA). The experiment was planted on the 16th of December 2018 and terminated on the 14th of April 2019.

3.3.3 Experimental design and trial establishment

The study was conducted using an 8×4×2 factorial treatment structure arranged in randomized complete blocks design with three replications resulting in 192 experimental units (i.e. 10 L drained polyethylene pots). The experiment comprised of the following factors: potato genotypes- 8 levels (Bikini, Challenger, Electra, Mondial, Panamera, Sababa, Sifra, and Tyson); growth stages - 4 levels (vegetative stage, tuber initiation, tuber bulking and maturity) and watering regimes -2 levels (Well-watered [Ww] and Water deficit [Wd] conditions). A loamy soil with known chemical (Table 1) and physical properties (Table 1) collected from Ukulinga Research Farm (29° 39′48.82″S; 30° 24′19.89″E), Pietermaritzburg, South Africa was used for the study.

One sprouted potato tuber was sown in each pot half-filled with 2.5 kg of sieved soil and after two weeks another 2.5 kg of sieved soil was re-added. Nitrogen (N), phosphorus (p) and potassium (K) were supplied using automated drip irrigation at a rate of 200 kg N ha^{-1} (ha^{-1}), 80 kg P ha^{-1} and 90 kg K ha^{-1} based on soil fertility analysis using potato nutrient requirements as a reference. For the first two weeks, all pots were watered to field capacity after planting to ensure fully establishment. The studied genotypes were exposed to water deficit at the beginning of each growth stage (i.e. vegetative growth, tuber initiation, tuber bulking and maturity) for the entire growth stage and re-irrigated at the end of each growth stage. The crop duration in growing degree days (beginning and end-stage of each growth stage) was monitored using the BBCH developmental scale (Table 2) (Meier, 2001). Soil water content was monitored daily by a Hydro-Sense II (HS2) Handheld Soil Moisture Sensor, carefully inserted in the pot to a depth of 12 cm. The H2S uses a battery capacitance to estimate the volumetric soil moisture content (VSC). Soil moisture content was maintained at 32 % at field capacity (throughout the growing period) under well-watered condition. Under water deficit treatment, soil moisture was allowed to decline from 32 % to approximately 10% after irrigation was withheld throughout all the crop growing period. Weeds were removed by hand while pests and diseases were chemically controlled.

Table 3.1: Soil chemical composition

Sample density (g/ml)	N (%)	P (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Exch.Acidity (cmol/L)	Total cations (cmolmg/L)	pH (KCL)	Zn (mg/L)	Mn (mg/L)	Cu (mg/L)	Organic C (%)
1.46	0.13	30	108	844	314	1.14	8.21	3.94	5.9	110	8.9	1.5

N = nitrogen, P = phosphorus, K = phosphorus, Ca = calcium, Mg = magnesium, Zn = zinc, Mn = manganese, Cu = copper, C = carbon.

Table 3.2: Phonological development stages of potato (*Solanum tuberosum* L.) according to the BBCH scale (Meier, 2001).

Code	Description	Stage no.	dd/mm/Year	DAP
00	Planting	0	16 December 2018	0
11	Emergence	I	02 January 2019	17
21	Vegetative stage	II	19 January 2019	34
40	Tuber initiation	III	27 January 2019	42
51	Flowering	-	04 February 2019	50
69	End of flowering	-	17 February 2019	63
70	Tuber bulking	IV	01 March 2019	75
95	Maturity	V	30 March 2019	104
99	Yellow leaves and Harvest	N	13-14 April 2019	119

N= Terminal, dd-Date, mm-Month, y-Year, DAP-Days after planting

3.3.4 Data collection

3.3.4.1 Physiological traits

The LI-6400 XT Portable Photosynthesis System (Licor Bioscience, Inc. Lincoln, Nebraska, USA) was used to measure leaf gas exchange parameters: stomatal conductance (*gs*), the rate of photosynthesis (*A*) and transpiration rate (Tr). Measurements were performed at the termination of the stressing period for each growth stage for all genotypes under Ww and Wd conditions. Data was collected at the mid-morning during sunny conditions between 9:00-11:00 am on three young fully expanded leaves second from the top for each combination genotype and water regime, to avoid potential stomatal closure during the middle of the day. Instantaneous water-use efficiency was calculated as the ratio of *A*/Tr (de Santana *et al*., 2015). Chlorophyll content index (CCI) was measured on abaxial surface using the chlorophyll content meter (CCM-200 PLUS, Opti-Sciences, USA). The average of CCI was determined from three.

Relative leaf water content (RWC) was measured from three plants randomly selected plants per genotype under Ww and Wd conditions across growth stages according to Kalina *et al*. (2016) using the formula by:

$$\mathrm{RWC}\ (\%) = \frac{(\mathrm{FW}\ (\mathrm{g}) - \mathrm{DW}\ (\mathrm{g}))}{(\mathrm{TW}\ (\mathrm{g}) - \mathrm{DW}\ (\mathrm{g}))} \times 100$$

Where: FW-Fresh water; DW-Dry weight; TW-Turgid weight

3.3.4.2 Morphological traits

Data were collected on the following morphological traits: plant height (PH) in cm measured from the base of the plant to the terminal point or last growth using a meter ruler, the leaf number was physically counted. Plant fresh weights (sum of stem and leaf of the plants) were determined for both well-watered and water deficit conditions. Samples were oven-dried at 75 °C for 48 hours to determine plant dry weight. Total above-ground biomass (TAG) or shoot dry weight was calculated. Plant biomass was calculated as follows:

$$\mathrm{Total\ above-ground\ biomass}\ (\%) = \frac{\mathrm{Plant\ dry\ weight\ (g)}}{\mathrm{Plant\ fresh\ weight\ (g)}} \times 100$$

Number of tubers per plant were counted and fresh tuber yield determined by weighing all tubers and expressing values in grams/plant.

3.3.5 Data analysis

The data collected was subjected to analysis of variance (ANOVA) using GenStat® 18th Edition (VSN International, Hemel Hempstead, UK). The means were separated with the LSD test at 5% probability level. Correlation analysis was performed on studied traits to determine their level of association. Principal component analysis (PCA) based on the correlation matrix was used to derive bi-plots showing the relationship between genotypes and assessed traits under well-watered and water deficit conditions.

3.4 Results

3.4.1 Effect of genotype, water condition and growth stages on physiological and morphological traits

Analysis of variance showing mean squares and significance tests for physiological and morphological traits among eight selected potato genotypes under well-watered and water deficit conditions is shown in Table 3. Genotypic differences were observed with regards to *A*, Tr, IWUE, CCI, RWC, PH, NL, TY and TAG. Highly significant ($p < 0.001$) effects of water condition and growth stages were observed for assessed traits. Genotype x water condition and genotype x growth stage were significant ($p < 0.05$) for most assessed traits. A significant ($p < 0.001$) genotype × water condition × growth stages interaction was observed for *A*, Tr, CCI, RWC, NL, TAG and TY (Table 3).

Table 3.3. Analysis of variance showing mean squares and significance test for assessed physiological and morphological traits among eight potato genotypes tested under well-watered and water deficit conditions at four different growth stages.

Source of variation	df	*A*	*gs*	Tr	IWUE	CCI	RWC	PH	NL	TY	TAG
Genotypes (G)	7	31***	0.01ns	119.7***	3.22**	91.0***	381.3***	1422***	130***	26737***	1754***
Water condition (WC)	1	1174***	0.33***	540.0***	10.59**	213.4***	3069***	2567***	2938***	603649***	448.4***
Growth Stage (GS)	3	3694***	0.17***	562.6***	66.61***	1385***	2326***	15854***	5383***	60766***	2195***
G × WC	7	27***	0.02ns	38.6***	0.79ns	63.08***	288.2***	205ns	7ns	671.9***	7804***
G × GS	21	50***	0.04***	79.5***	2.46***	25.5***	251.0***	243*	48***	623.9***	9397***
WC × GS	3	57***	0.02ns	37.5**	2.23ns	17.4***	45.2ns	320ns	220***	139.7***	34832***
G × WC × GS	21	38***	0.01ns	32.2***	1.15ns	39.3***	177.4***	60ns	18***	4116***	424.1***
Residual	68	6	0.01	7.2	0.99	1.5	24.1	122	5	358	21.6

df = degree of freedom; * = significance at $p < 0.05$; ** = significance at $p < 0.01$; *** = significance at $p < 0.001$; ns = non-significant. *A* = Rate of photosynthesis; *gs* = stomatal conductance; Tr = Transpiration rate; IWUE = instantaneous water-use efficiency; CCI = Chlorophyll content index; RWC = Relative water content; PH = Plant height; NL = Number of leaves; TY= Yield; TAG = Total above-ground biomass.

3.4.2 Physiological response of potato genotypes under well-watered and water deficit conditions across different growth stages

The mean values comparing for stomatal conductance (*gs*) and transpiration (Tr) rates of studied potato genotypes under Ww and Wd conditions are presented in Figures 1a and 1b. Non-significant ($p > 0.05$) genotypic differences were observed among potato genotypes for *gs* at the vegetative and tuber bulking stages (Figure 1a). All genotypes under Ww condition recorded higher *gs* than under Wd conditions in all growth stages (vegetative stage, tuber initiation, tuber bulking and maturity stage). During vegetative and maturity stages genotypes Panamera and Sababa recorded lowest *gs* (<2.18 and 2.16 molH$_2$O m^{-2}s^{-2} respectively) under Wd condition, whereas Electra had lowest *gs* at tuber initiation (2.24 molH$_2$O m^{-2}s^{-2}) and Panamera (2.14 molH$_2$O m^{-2}s^{-2}) at the tuber bulking stage. Under Ww condition, Challenger 2.27 molH$_2$O m^{-2}s^{-2} and Mondial 2.28 molH2O m-2s-2 at the vegetative stage, Bikini 2.25 molH$_2$O m^{-2}s^{-2} at tuber initiation, Panamera 2.17 molH$_2$O m^{-2}s^{-2} and Sababa 2.12 molH$_2$O m^{-2}s^{-2} recorded lowest *gs* at the maturity stage.

Significant ($p < 0.05$) differences were observed among potato genotypes with respect to Tr under Ww and Wd conditions across growth stages (Figure 1b). Sababa had a significantly lower Tr (9.16 mmol H$_2$O m^{-2} s^{-2}) compared to Bikini which recorded higher Tr of >20 mmol H$_2$O m^{-2} s^{-2} under Wd condition at the vegetative stage. A lower rate of Tr (<17 mmol H$_2$O m^{-2} s^{-2}) was observed for Sababa and Panamera, whereas Electra, Tyson and Bikini recorded higher Tr of >21 mmolH$_2$O m^{-2} s^{-2} under Ww condition at the vegetative stage. Mondial and Sababa recorded low Tr (<9 mmolH$_2$O m^{-2} s^{-2}) compared to genotypes Sifra and Tyson which recorded higher Tr (>15 mmolH$_2$O m^{-2} s^{-2}) under Wd condition at the tuber initiation stage. Under Ww condition at the tuber initiation stage, Sifra recorded significantly higher Tr (>20 mmolH$_2$O m^{-2} s^{-2}), whereas lower Tr (<13 mmolH$_2$O m^{-2} s^{-2}) were observed for Mondial and Challenger.

During the tuber bulking stage all genotypes recorded higher Tr (>20 mmolH$_2$O m^{-2} s^{-2}) except Electra recording slightly low Tr rate of 18.91 mmolH$_2$O m^{-2} s^{-2} under Ww condition. Bikini, Sababa and Mondial recorded higher Tr (>20 mmolH$_2$O m^{-2} s^{-2}) under Wd condition at the tuber bulking stage, Panamera and Sababa showed a similar trend at maturity stage under Wd condition. At maturity stage, Panamera, Sababa, Sifra and Tyson recorded the highest Tr rate of >30.5 mmolH$_2$O m^{-2} s^{-2}, whereas Electra, Mondial, Bikini and Challenger recorded lowest Tr rate of <24 mmol H$_2$O m^{-2} s^{-2} under Ww condition.

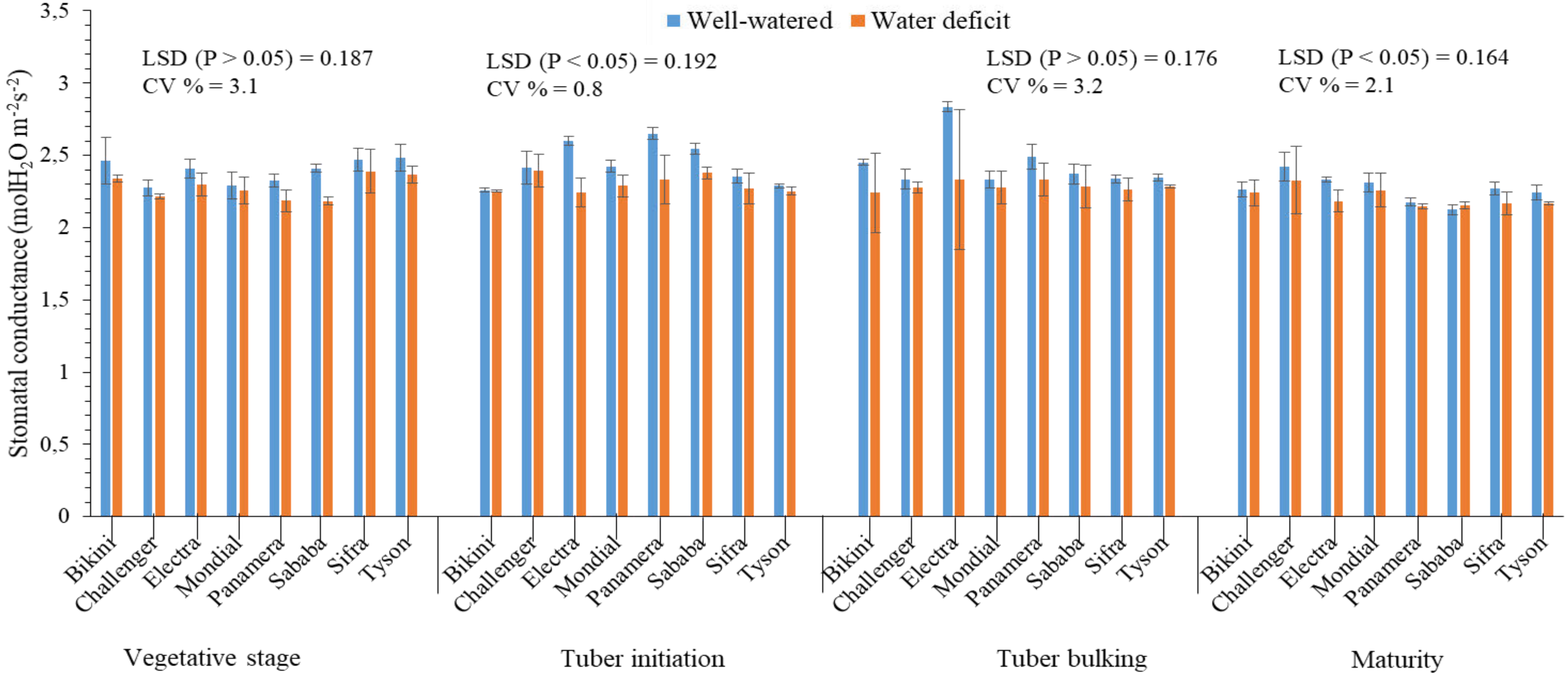


Figure 3.1a: The effect of water deficit imposed at different growth stages on stomatal conductance (*gs*) of eight potato genotypes.

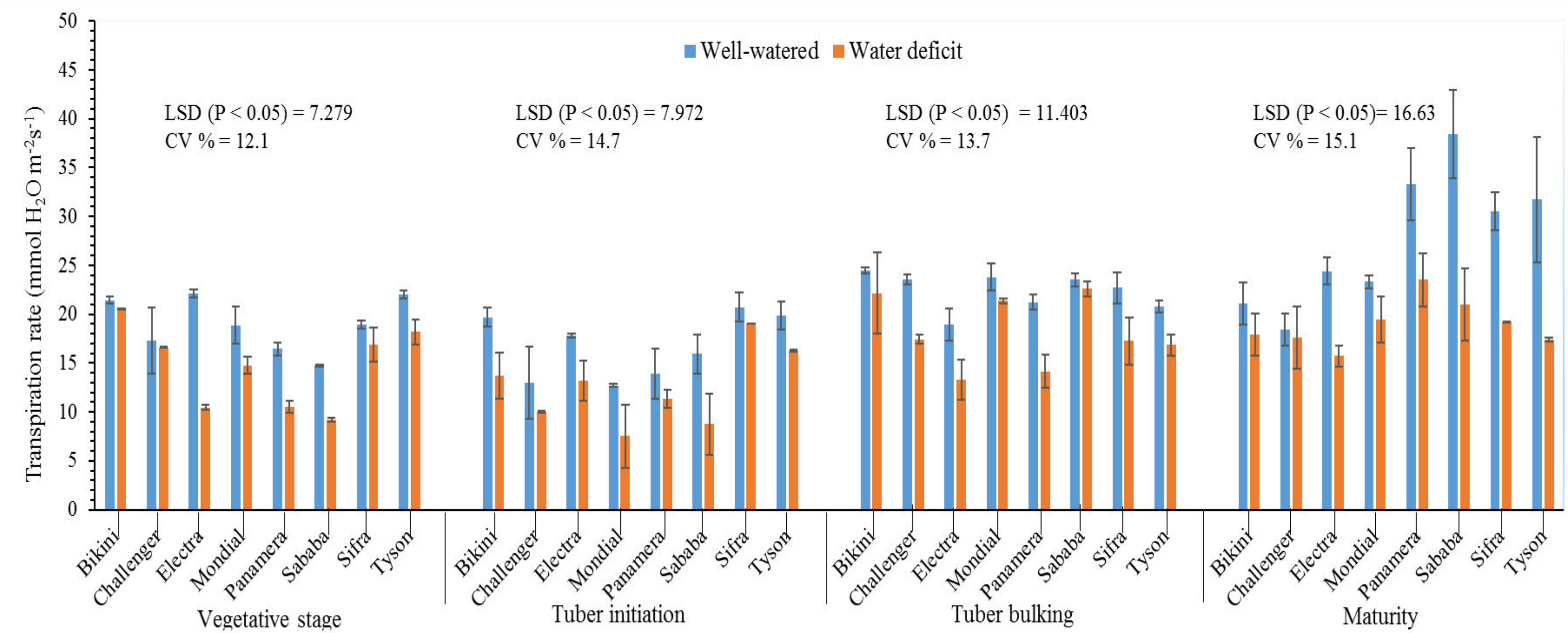


Figure 3.1b: Effect of water deficit imposed at four different growth stages on transpiration rate (Tr) of eight potato genotypes.

Genotypic differences ($p < 0.05$) were observed for *A* under Ww and Wd conditions across growth stages (Figure 2). Water deficit during the vegetative stage significantly reduced *A* rate of Sababa (32.13 µmol CO_2 m^{-2} s^{-1}) compared to Sifra, Bikini and Tyson which recorded higher *A* rate (>40 µmol CO_2 m^{-2} s^{-1}). Tyson, Electra and Mondial recorded highest *A* rate (i.e., 47.21, 46.86 and 46.01 µmol CO_2 m^{-2} s^{-1}, respectively) under Ww condition at the vegetative stage. Under Wd condition during the tuber initiation stage, Tyson recorded a significantly higher *A* rate of 48.67 µmol CO_2 m^{-2} s^{-1} compared to other test genotypes. Under Ww condition during the tuber initiation stage, most genotypes recorded *A* rate >53 µmol CO_2 m^{-2} s^{-1}. At the tuber bulking stage, all genotypes recorded *A* rates <29 µmol CO_2 m^{-2} s^{-1} except Mondial which had a higher *A* rate of 30.07 µmol CO_2 m^{-2} s^{-1} under Wd condition. Under Ww condition during the tuber bulking stage, Electra recorded a higher *A* rate (42.74 µmol CO_2 m^{-2} s^{-1}), whereas Panamera recorded the lowest A rate of 30.01 µmol CO_2 m^{-2} s^{-1}. Water deficit during the maturity stage reduced *A* rate of genotypes Sifra and Electra (<21 µmol CO_2 m^{-2} s^{-1}), whereas Challenger and Panamera recorded a high *A* rate (>24 µmol CO_2 m^{-2} s^{-1}). The lowest *A* rate under Ww condition was recorded for Sifra (21 µmol CO_2 m^{-2} s^{-1}) compared to the highest *A* rates of 27.57 and 27.63, µmol CO2 m^{-2} s^{-1} were recorded Panamera and Bikini at maturity stage, respectively.

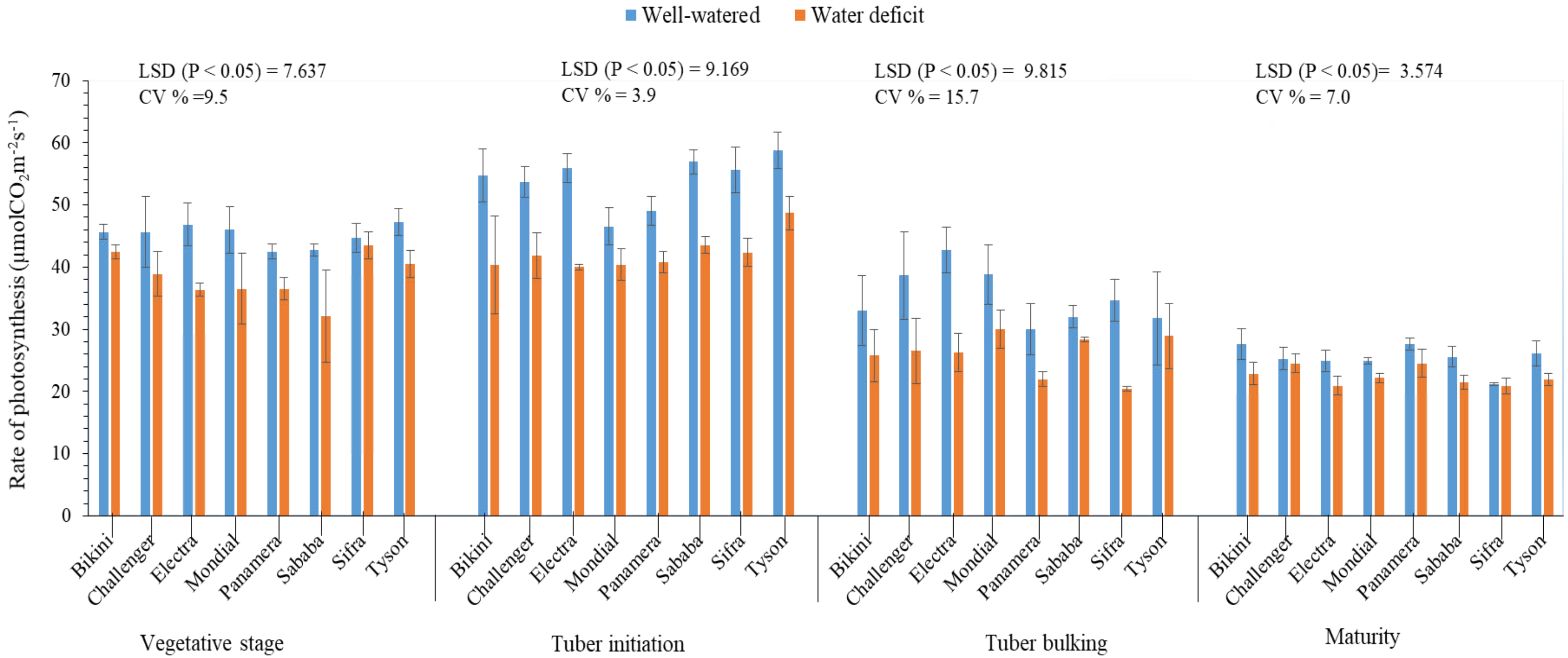


Figure 3.2: The effect of water deficit on the rate of photosynthesis at different growth stages of potato genotypes evaluated under well-watered and water deficit conditions.

For IWUE, significant differences ($p < 0.05$) were observed among potato genotypes across some growth stages under Ww and Wd conditions (Figure 3). Sababa, Challenger and Panamera showed significantly higher IWUE (>2.50 µmolCO_2 mmol^{-1} H_2O) compared to genotypes Bikini and Tyson which showed lower IWUE values (< 2.10 µmolCO_2 mmol^{-1} H_2O) under Wd condition at the vegetative stage. Under Ww condition, Sababa, Panamera and Electra recorded higher IWUE values (>3.50 µmolCO_2 mmol^{-1} H_2O), whereas Bikini and Tyson displayed lower IWUE values of < 2.3 µmolCO_2 mmol^{-1} H_2O during the vegetative stage. At the tuber initiation stage, IWUE of genotypes Mondial and Challenger were higher (>4 µmolCO_2 mmol^{-1} H_2O) compared to Bikini, Sifra and Tyson which (< 4µmolCO_2 mmol^{-1} H_2O) under Wd condition. Mondial, Bikini and Sababa recorded significantly higher IWUE (> 5.09 µmolCO_2 mmol^{-1} H_2O) whereas genotype Sifra recorded a lower IWUE (2.7 µmolCO_2 mmol^{-1} H_2O) under Ww condition.

Non-significant differences were observed among tested potato genotypes at the bulking stage. At the maturity stage under Wd condition, Bikini, Mondial, Challenger and Electra recorded higher IWUE values (>1.0 µmolCO_2 mmol^{-1} H_2O), whereas Panamera, Sababa, Sifra and Tyson recorded lower IWUE values (<0.9 µmolCO_2 mmol^{-1} H_2O). The lowest value of IWUE of 1.09 µmolCO_2 mmol^{-1} H_2O was recorded for Panamera compared to other genotypes under Ww condition at the maturity stage.

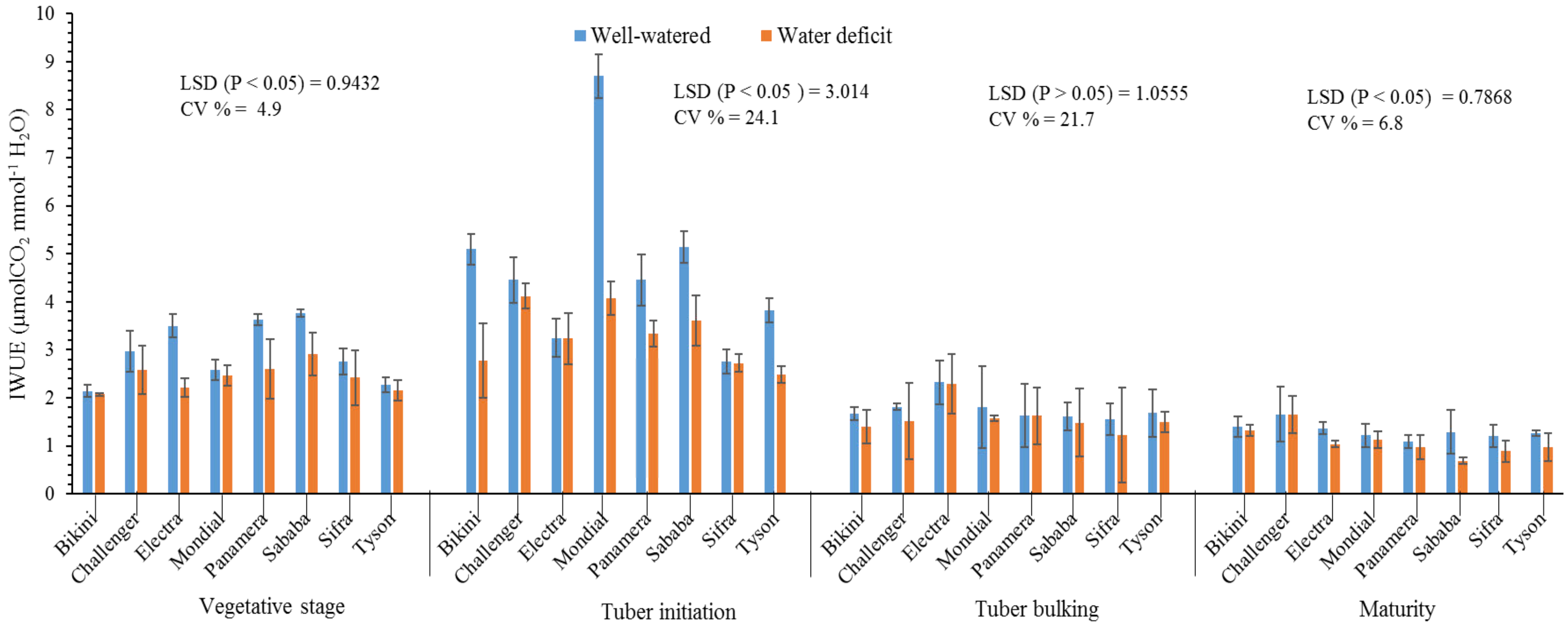


Figure 3.3: Effect of water deficit on the instantaneous water use efficiency (IWUE) at different growth stages of potato genotypes tested under well-watered and water deficit conditions.

Genotypic differences ($p < 0.05$) were observed among genotypes across all growth stages for CCI (Figure 4). Under Wd condition at the vegetative stage, Bikini, Challenger, Mondial, Sifra and Tyson recorded higher CCI (> 42 %) compared to Sababa and Panamera which recorded lower CCI (<37 %). Tyson recorded lower CCI of 31.40 % whereas Electra recorded higher CCI (43.70 %) under Ww condition at the vegetative stage. At the tuber initiation stage, Electra, Mondial, Challenger and Tyson recorded higher CCI of > 35%, whereas other test genotypes recorded CCI (<27 %) under Wd condition. Genotypes Bikini, Electra, Mondial and Sifra recorded CCI >30 % compared to genotypes such as Challenger, Panamera, Sababa and Tyson which recorded lower CCI (<29 %) under Ww condition.

At the tuber bulking stage, the water deficit significantly increased CCI of Bikini (34.95 %). Mondial and Challenger recorded CCI (<29 %) compared to other studied genotypes. Bikini recorded lowest CCI of 25% compared to Sifra and Panamera, which recorded higher CCI of 30.43 % and 30.25 % under Ww condition, respectively. At the maturity stage, Mondial and Tyson showed significantly higher CCI of 38.68 and 35.3%, compared to Sifra and Panamera, which recorded 21.40 and 21.20% under Wd condition, respectively. Challenger, Mondial and Panamera recorded a higher CCI of 29 % whereas Sifra and Bikini recorded lower CCI of 22.05 and 22.95 % under Ww condition at the maturity stage, respectively.

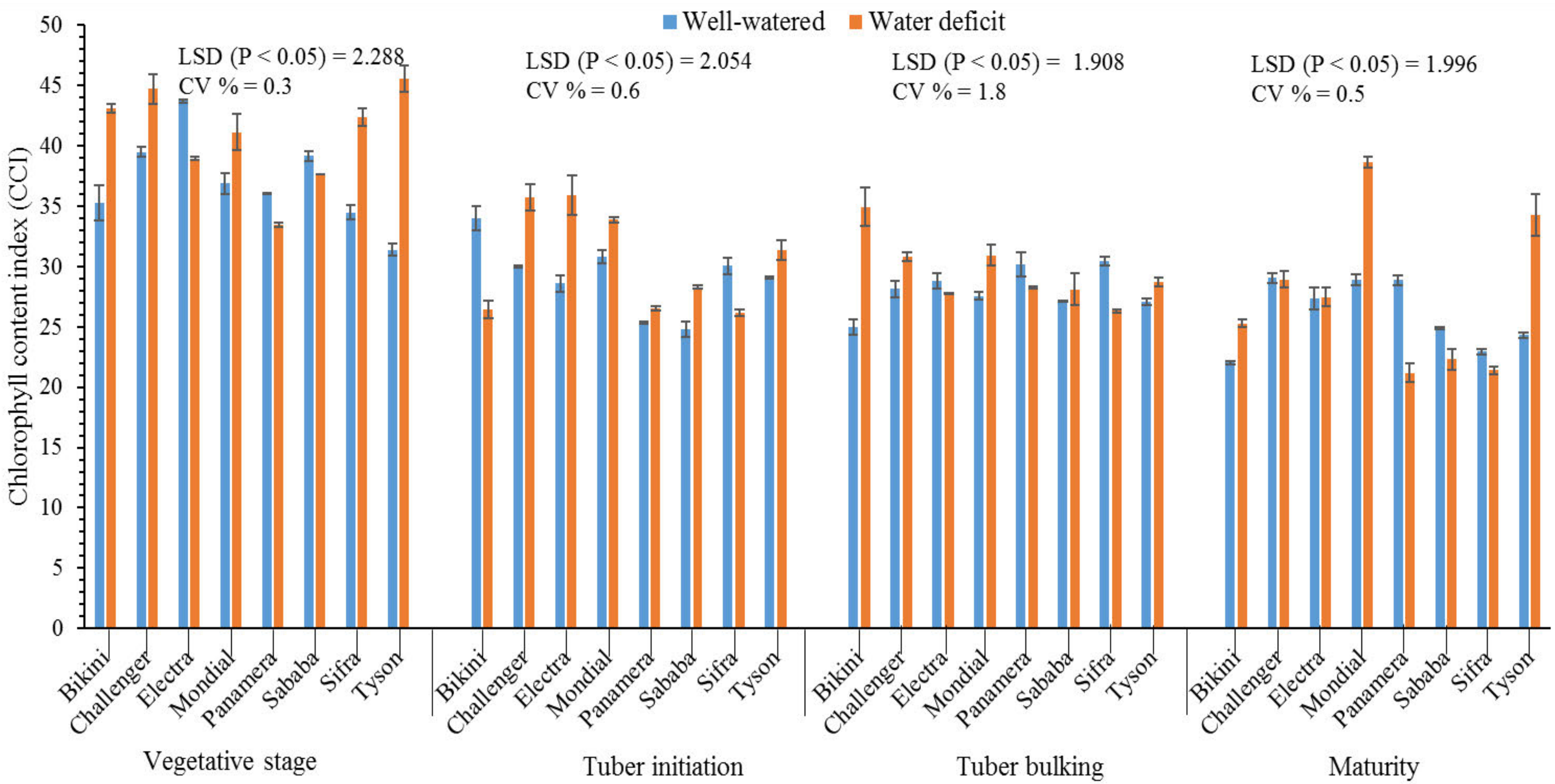


Figure 3.4: Effect of water deficit on chlorophyll content index (CCI) of eight potato genotypes imposed at four growth stages.

For RWC, genotypic differences were observed among genotypes across growth stages and water conditions (Figure 5). Sifra and Tyson recorded RWC > 80% under Ww and Wd conditions at the vegetative stage. Significantly, low RWC was observed for Bikini under Ww condition (67.06%), whereas Bikini and Panamera recorded high RWC of 59.51 and 53.95% under Wd condition at the vegetative stage. High RWC of > 70% was recorded for Sifra, Tyson, and Electra at the tuber initiation, tuber bulking and maturity stages under Ww condition, whereas Bikini recorded lower RWC of < 67% under Ww condition across all growth stages. During the vegetative stage under Wd condition genotype Panamera and Bikini attained the lowest RWC of 53.95 and 59.51 % compared to other genotypes whereas Sifra (88.86) and Tyson (85.66) recorded higher RWC%, also at the tuber initiation Bikini, Sifra and Tyson recorded RWC < 53.34 %, while Sababa recorded higher RWC of 67.65% under Wd condition. Challenger and Mondial recorded lowest RWC of 49.32 and 49.63% respectively, during tuber bulking whereas Challenger, Electra, Sifra and Tyson recorded RWC > 50% compared to other genotypes who recorded less than 50% during maturity stages under Wd condition.

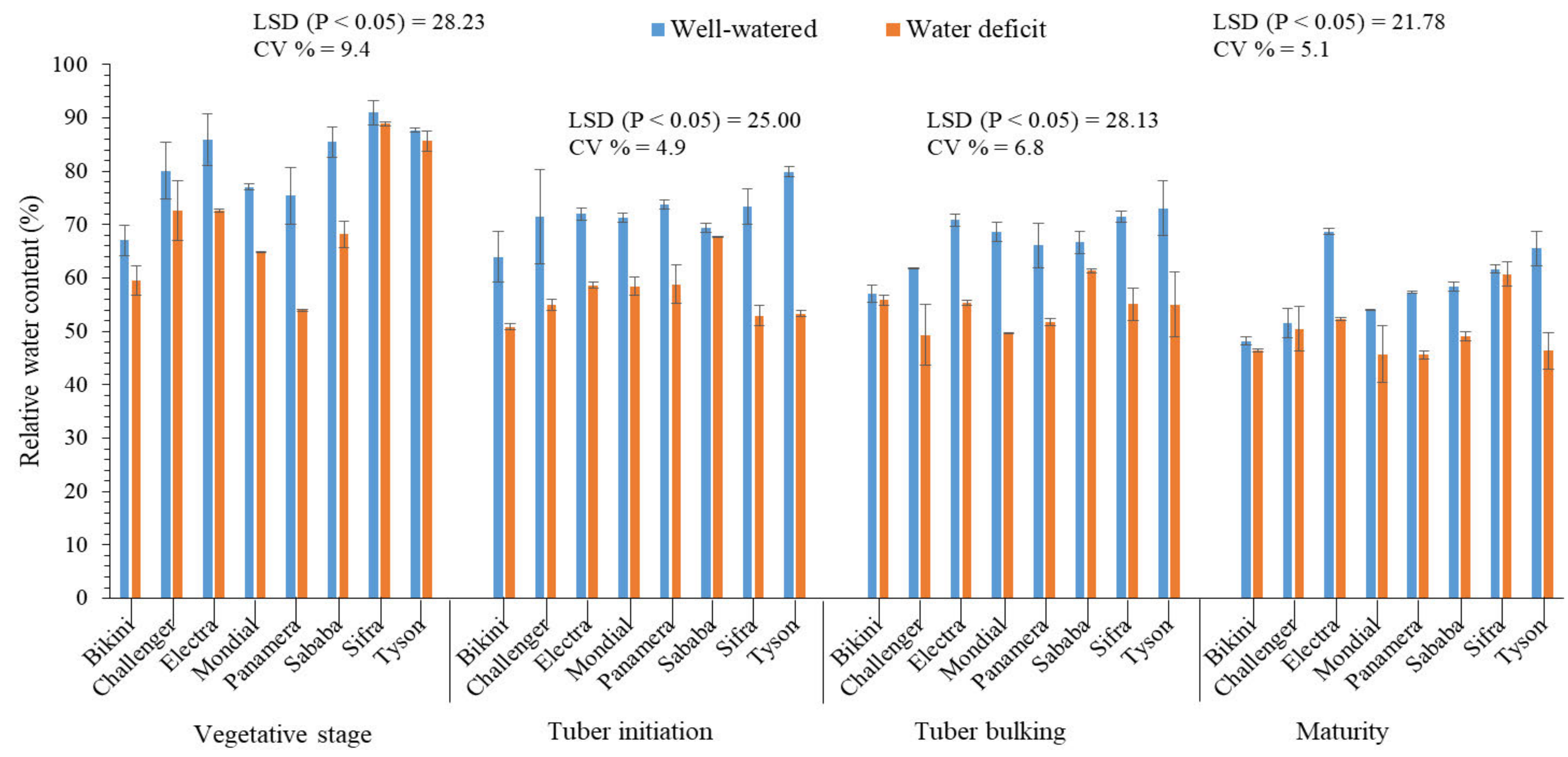


Figure 3.5: The influence of water deficit imposed at four different growth stages on relative water content (RWC) of eight potato genotypes.

3.4.3 Morphological response of potato genotypes under well-watered (Ww) and water deficit (Wd) conditions across different growth stages

Mean values of PH and NL of studied potato genotypes evaluated under Ww and Wd conditions are presented in Figures 6a and 6b. Non-significant genotypic differences were observed at vegetative and tuber initiation stages under both Ww and Wd conditions (Figure 6a). Significant differences ($p < 0.05$) were observed for PH among potato genotypes at tuber bulking and maturity growth stages. Genotypes Panamera, Mondial and Challenger recorded taller plants of 83.30, 79.90 and 67.70 cm, in that order whereas Sifra and Bikini recorded shorter plants of 49.30 and 53.30 cm under Ww during tuber initiation stage, respectively. Under Wd condition, taller plants of 72.50 and 72.30 cm were recorded for Mondial and Panamera compared to Sifra and Sababa which attained the lowest PH of 47.30 and 50.3 cm, in the order. During the tuber bulking stage under Wd condition, the shortest plant height was observed for genotypes Bikini (54.7 cm), Sifra (55.00 cm) and Sababa (56.00 cm). Genotypes with taller plants under Wd condition at the tuber initiation stage were Panamera (74.7 cm), Mondial (72.70 cm) and Tyson (70.70 cm). Under Ww condition, tallest plants were observed for genotypes Mondial (99.00 cm) and Panamera (88.00 cm); whereas Tyson (59.30 cm) and Sifra (61.00 cm) recorded lowest PH during tuber bulking stage. At the maturing stage, the highest PH of 102.3, 110.00 and 82.30 cm was recorded for genotypes Panamera, Mondial and Challenger, in that order compared to the low PH of 66.70, 72.00 and 73.30 cm for Bikini, Tyson and Sifra under Ww condition, respectively. Genotypes Panamera (78.70 cm), Mondial (78.00 cm) and Tyson (74.30 cm) recorded highest PH under Wd condition compared with Sababa (60.3 cm), Electra (60.70 cm) and Sifra (61.30 cm).

The number of leaves per plant differed significantly ($p < 0.05$) among studied potato genotypes under Ww and Wd conditions across all growth stages (Figure 6b). Under Ww condition, genotypes Mondial and Panamera produced the highest number of leaves per plant during vegetative (> 17), tuber initiation (> 29), tuber bulking (> 39) and maturity stages (> 50). While under Wd condition, genotypes Mondial and Panamera and Tyson recorded a higher number of leaves per plant during tuber initiation (> 24), tuber bulking (> 35) and maturity stages (> 40), during vegetative stage Challenger, Mondial, Panamera and Tyson had (> 13).

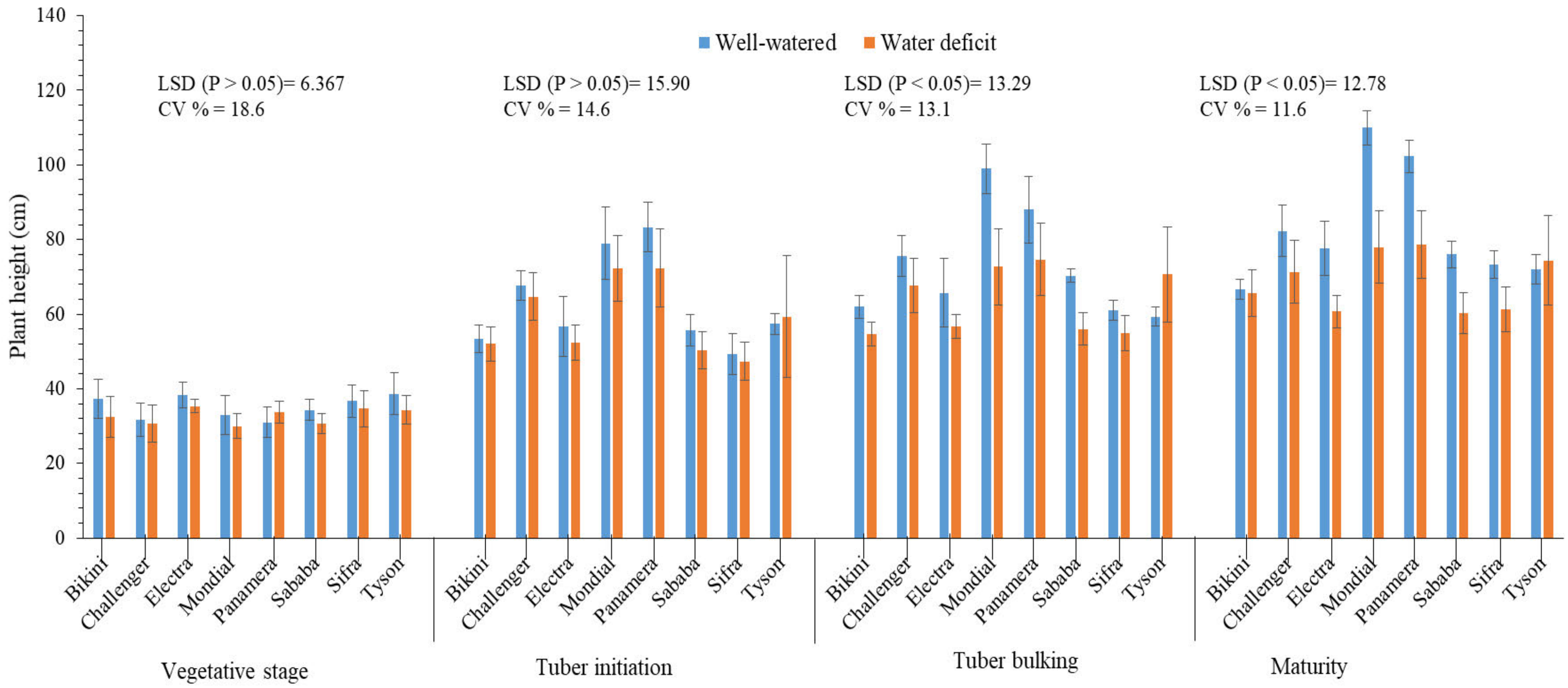


Figure 3.6a: The effect of water deficit on plant height of eight potato genotypes imposed at the vegetative stage, tuber initiation, tuber bulking and maturity growth stages.

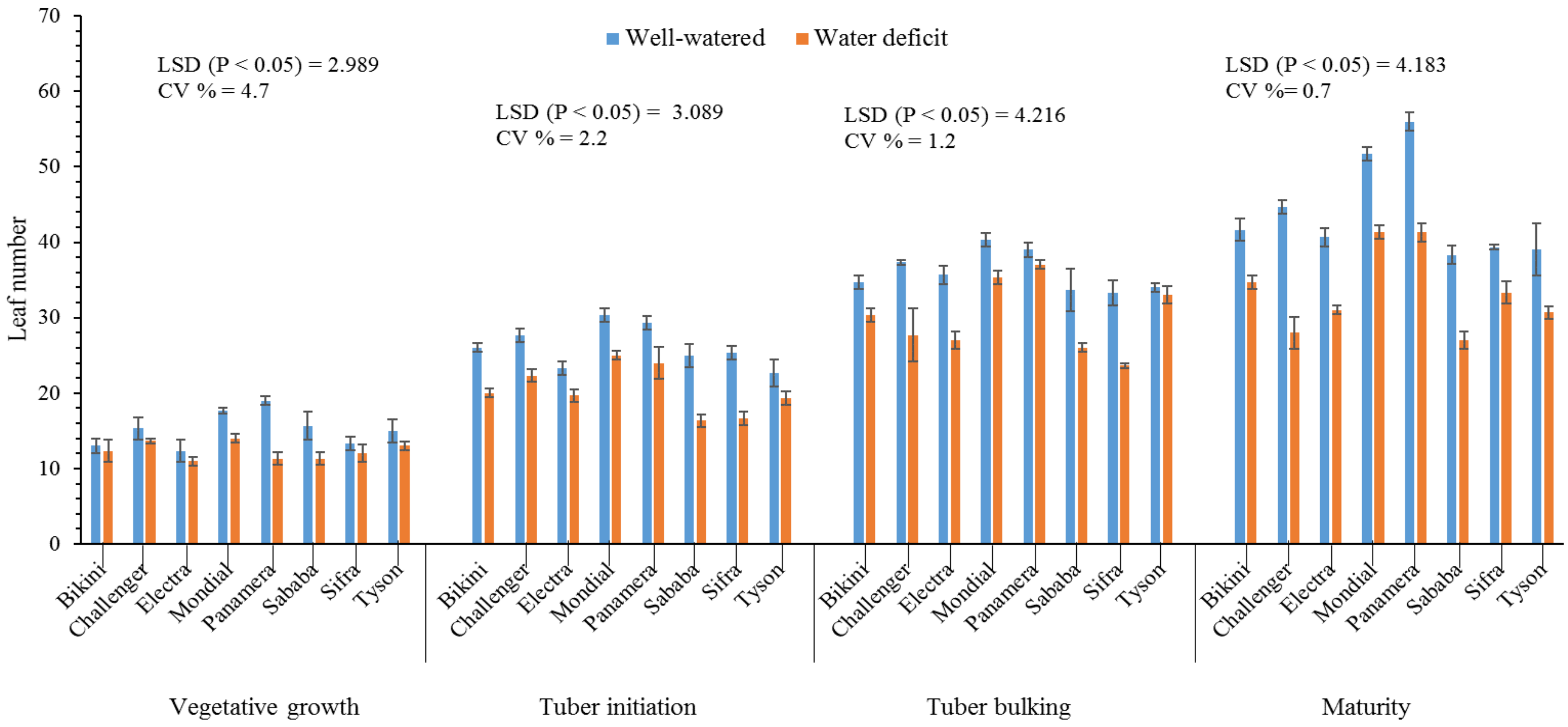


Figure 3.6b: Effect of water deficit imposed at four different growth stages on the number of leaves per plant of eight potato genotypes.

Across all growth stages, genotypes differed significantly ($p < 0.05$) for tuber yield under Ww and Wd conditions (Figure 7). Genotypes Electra, Challenger and Mondial recorded significantly higher tuber yields (> 430 g) under Ww condition at the vegetative stage. Genotypes Bikini Challenger, Electra, Mondial and Tyson produced higher fresh yield (>310 g) compared to Sababa (203.0 g), Sifra (266.0 g) and Panamera (254.0 g) which produced lower tuber yields under Wd condition at the vegetative stage. During the tuber initiation stage, Mondial and Sifra were high-yielding (> 450 g) under Ww condition, whereas Challenger and Sifra recorded significantly higher yields of 181 and 217.4 g under Wd condition. Under Ww condition, genotypes Challenger, Mondial, Sifra and Tyson recorded higher tuber yields during tuber bulking (> 430 g) and maturity stages (> 390 g). Genotype Tyson produced the highest tuber yield while the lowest obtained for Bikini, Mondial and Panamera under Wd condition during tuber bulking and maturity stages.

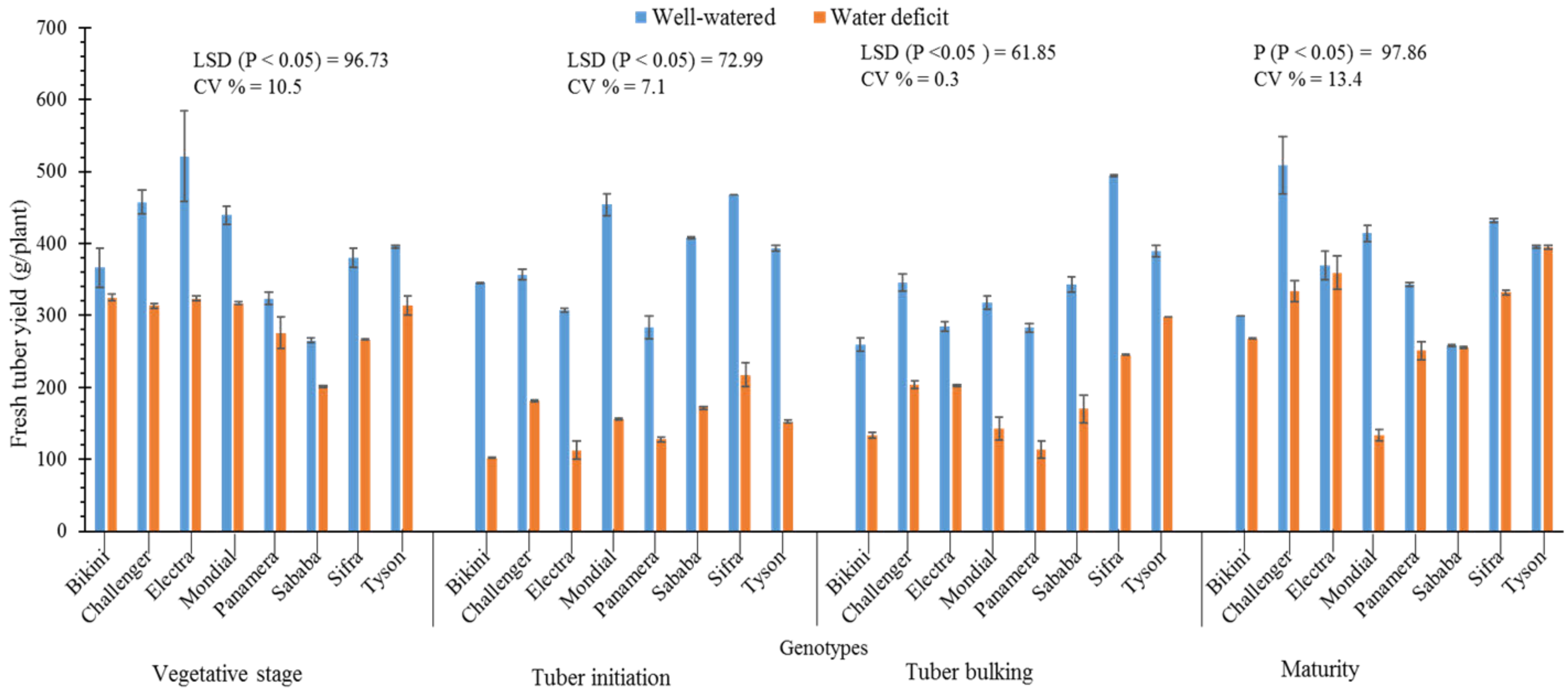


Figure 3.7: Effect of water deficit on tuber yield of eight potato genotypes under well-watered and water deficit conditions at different growth stages.

The mean values of total above-ground biomass (TAG) of evaluated potato genotypes under Ww and Wd conditions are presented in Figure 8. Genotypes differed significantly ($p < 0.05$) for TAG across water treatments and growth stages for TAG. Under Ww condition at the vegetative stage, genotypes Electra and Panamera recorded significantly higher TAG (>45 g), whereas genotypes Sifra and Tyson recorded lower TAG (< 27 g). Under Wd condition at the vegetative stage higher TAG of > 35 g was recorded for Sifra and Electra compared to lower TAG of < 20 g recorded for Mondial and Challenger. Under Ww condition during the tuber initiation stage, the highest TAG (> 63 g) was recorded for Bikini, Panamera and Sababa compared to other test genotypes. Under Wd condition during the tuber initiation stage, Bikini recorded the highest TAG of 44.19 g compared to other test genotypes.

At the tuber bulking stage, the highest TAG was recorded for genotype Bikini and Sifra under both Ww (64.86 and 41.10 g, respectively) and under Wd conditions (i.e., 57.42 and 61.63 g, respectively). At the maturity stage, the highest TAG was recorded for genotypes Bikini, Electra and Panamera under both Ww (57.35, 76.47 and 71.93 respectively) and Wd (50.61, 72.20 and 68.99, respectively) conditions compared to other test genotypes.

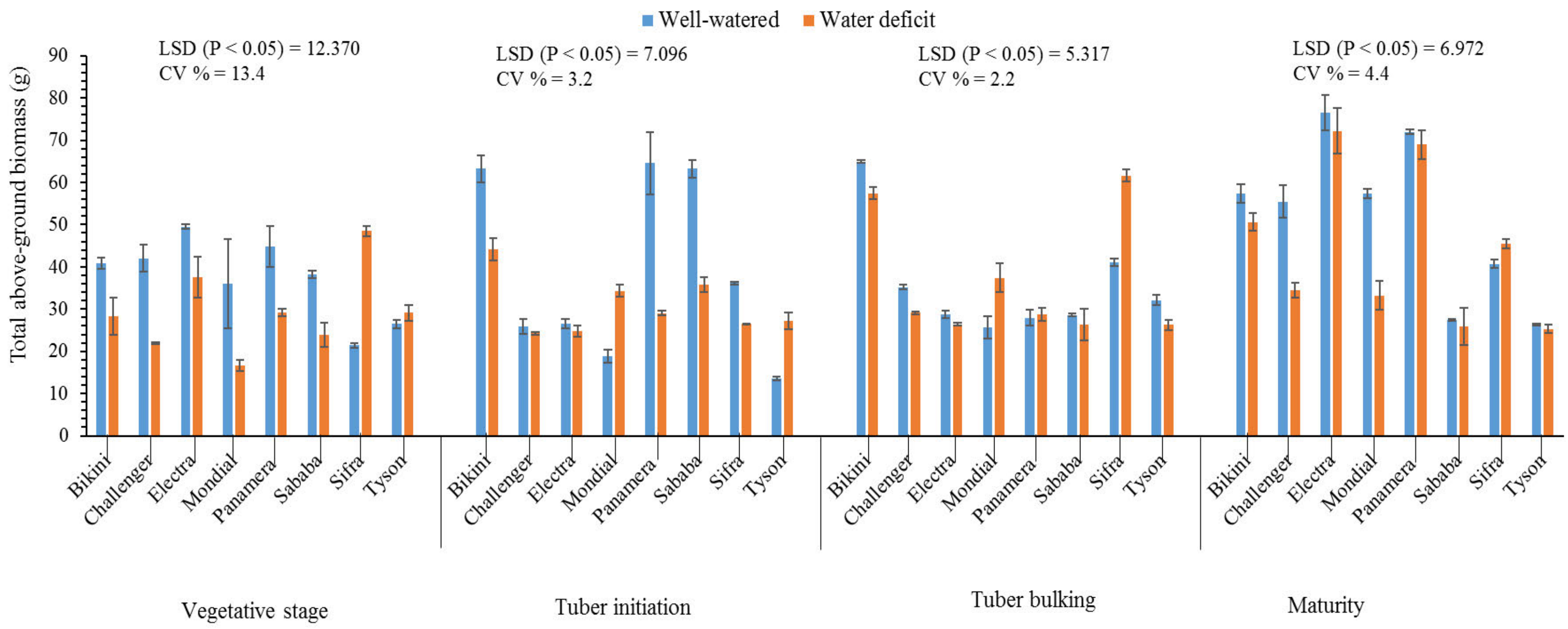


Figure 3.8: The influence of water deficit on total above-ground biomass (TAG) of eight potato genotypes imposed at the vegetative stage, tuber initiation, tuber bulking and maturity growth stages.

3.4.4 Correlations coefficients among morphological and physiological traits under well-watered and water-deficit conditions across growth stages

Pearson's correlation coefficients (r) revealing the level of associations for studied traits of among potato genotypes under well-watered and water deficit conditions at different growth stages are presented in Table 5. TY was significantly and negatively correlated with *gs* (r = -0.81; p = 0.05) and IWUE (r = -0.77; p = 0.05) at the vegetative stage under Wd condition. Under Ww condition, TY positively and significantly correlated with IWUE (r = 0.94 p = 0.001) at the vegetative stage. At tuber initiation stage under Wd condition, TY negative and significantly correlated with RWC (r = -0.87; p = 0.01) and CCI (r = -0.89; p = 0.01) but positively correlated with PH (r = 0.91; p = 0.001), Tr (r = 0.63; p = 0.001), *A* (r = 0.94; p = 0.01) and IWUE (r = 0.87; p = 0.01). Non-significant and poor correlations were observed between TY with other traits observed at the tuber bulking stage under both conditions. TY negatively and significantly correlated with CCI (r = -0.71; p = 0.05) and TAG (r = -0.85; p = 0.01) under Wd condition at the maturity stage.

Table 3.4: Pearson correlation coefficients (r) showing associations of morphological and physiological traits of 8 selected potato genotypes under well-watered (lower diagonal) and water deficit (upper diagonal) conditions at different growth stages.

Vegetative stage

Traits	PH	NL	TAG	*gs*	Tr	*A*	IWUE	RWC	CCI	TY
PH		0.14ns	0.66ns	0.52ns	-0.19ns	-0.09ns	0.60ns	0.20ns	0.01ns	-0.66ns
NL	0.81*		0.01ns	0.75*	0.57ns	0.24ns	0.37ns	0.78*	0.73*	-0.34ns
TAG	-0.40ns	-0.17ns		0.55ns	0.11ns	0.45ns	0.63ns	0.49ns	0.43ns	-0.69ns
gs	0.83**	0.67*	-0.01ns		0.51ns	0.43ns	0.60ns	0.87**	0.73*	-0.81*
Tr	0.78*	0.55ns	-0.21ns	0.80**		0.88**	-0.19ns	0.65ns	0.63ns	-0.10ns
A	-0.11ns	0.11ns	0.06ns	0.12ns	0.21ns		-0.10ns	0.60ns	0.60ns	-0.22ns
IWUE	0.29ns	0.43ns	-0.39ns	-0.05ns	0.17ns	0.27ns		0.58ns	0.54ns	-0.77*
RWC	0.11s	0.25ns	-0.41ns	-0.22ns	0.12ns	0.36ns	0.93***		0.96***	-0.66ns
CCI	0.22ns	0.45ns	-0.27ns	0.01ns	0.22ns	0.57ns	0.93***	0.87**		-0.50ns
TY	0.03ns	0.28ns	-0.34ns	-0.33ns	-0.06ns	0.30ns	0.94***	0.93***	0.89**	

Tuber initiation

Traits	PH	NL	TAG	*gs*	Tr	*A*	IWUE	RWC	CCI	TY
PH		0.97***	0.51ns	-0.62ns	0.33ns	0.96***	0.92***	-0.97***	-0.98***	0.91***
NL	0.97***		0.58ns	-0.63ns	0.51ns	0.96***	0.94***	-0.96***	-0.96***	0.96ns
TAG	0.65**	0.69**		-0.22ns	0.45ns	0.68*	0.67ns	-0.47ns	-0.57ns	0.59ns
gs	-0.19ns	-0.23ns	-0.30ns		-0.39ns	-0.61ns	-0.51ns	0.60ns	0.60ns	-0.64ns
Tr	0.36ns	0.43ns	0.63**	-0.75***		0.41ns	0.46ns	-0.39ns	-0.27ns	0.63***
A	0.89***	0.92***	0.68**	-0.43ns	0.48*		0.91***	-0.91***	-0.96***	0.94**
IWUE	0.69**	0.77***	0.44ns	-0.16ns	0.11ns	0.77***		-0.92***	-0.93***	0.87**
RWC	-0.68**	-0.76***	-0.48*	0.27ns	-0.32ns	-0.73***	-0.78***		0.94***	-0.87**
CCI	-0.47ns	-0.49*	-0.04ns	0.27ns	0.04ns	-0.66**	-0.76***	0.54*		-0.89**
TY	-0.02ns	0.09ns	0.01*	-0.67**	0.36ns	0.36ns	0.38ns	-0.44ns	-0.60***	

Tuber bulking

Traits	PH	NL	TAG	*gs*	Tr	*A*	IWUE	RWC	CCI	TY
PH		0.49ns	-0.83**	-0.59ns	-0.84*	-0.92***	0.87*	-0.16ns	0.70*	0.27ns
NL	0.57ns		-0.74*	0.24ns	-0.21ns	-0.62*	0.74*	0.42ns	0.19ns	0.09ns
TAG	-0.46ns	-0.15ns		0.42ns	0.63*	0.79**	-0.90***	-0.00ns	-0.64ns	0.03ns
gs	0.67ns	0.14ns	-0.50ns		0.62ns	0.42ns	-0.34ns	0.77*	-0.78*	-0.08ns
Tr	0.60ns	0.72*	0.08ns	0.46ns		0.78*	-0.72*	0.24ns	-0.71*	-0.06ns
A	0.82**	0.89**	-0.32ns	0.39ns	0.80**		-0.95***	0.10ns	-0.59ns	-0.43ns
IWUE	-0.12ns	-0.32ns	-0.51ns	-0.25ns	-0.81**	-0.32ns		0.03ns	0.55ns	0.25ns
RWC	0.86**	0.12ns	-0.62ns	0.79**	0.24ns	0.46ns	0.13ns		-0.63ns	-0.27ns
CCI	-0.92***	-0.57ns	0.53ns	-0.84**	-0.61ns	-0.76*	0.17ns	-0.83**		0.14ns
TY	-0.22ns	0.50ns	0.61ns	-0.42ns	0.48ns	0.21ns	-0.63*	-0.63*	0.24ns	

Maturity

Traits	PH	NL	TAG	*gs*	Tr	*A*	IWUE	RWC	CCI	TY
PH		0.87**	-0.63*	0.60ns	-0.68*	-0.88*	0.44ns	0.40ns	0.01ns	0.38ns
NL	-0.76*		-0.78*	0.33ns	-0.81**	-0.99***	0.79**	0.203ns	0.44ns	0.63ns
TAG	0.65*	-0.84**		-0.25ns	0.40ns	0.79*	-0.53ns	-0.31ns	-0.67*	-0.85**
gs	0.14ns	-0.30ns	-0.20ns		-0.03ns	-0.30ns	-0.16ns	0.75*	-0.41ns	0.33ns
Tr	-0.89**	0.53ns	-0.57ns	0.01ns		0.79**	-0.82*	0.29ns	-0.28ns	-0.22ns
A	-0.65ns	0.18ns	-0.36ns	0.25*	0.90**		-0.76*	-0.21ns	-0.44ns	-0.61ns
IWUE	-0.63ns	0.83**	-0.44ns	-0.67ns	0.33ns	-0.00ns		-0.20ns	0.63*	0.48ns
RWC	-0.12ns	-0.18ns	0.56ns	-0.58ns	0.07ns	0.09ns	0.29ns		-0.26ns	0.33ns
CCI	-0.69*	0.45ns	-0.44ns	-0.18ns	0.87**	0.77*	0.32ns	0.04ns		0.70*
TY	0.71*	-0.67ns	0.47ns	0.26ns	-0.54ns	-0.22ns	-0.59ns	0.07ns	-0.60ns	

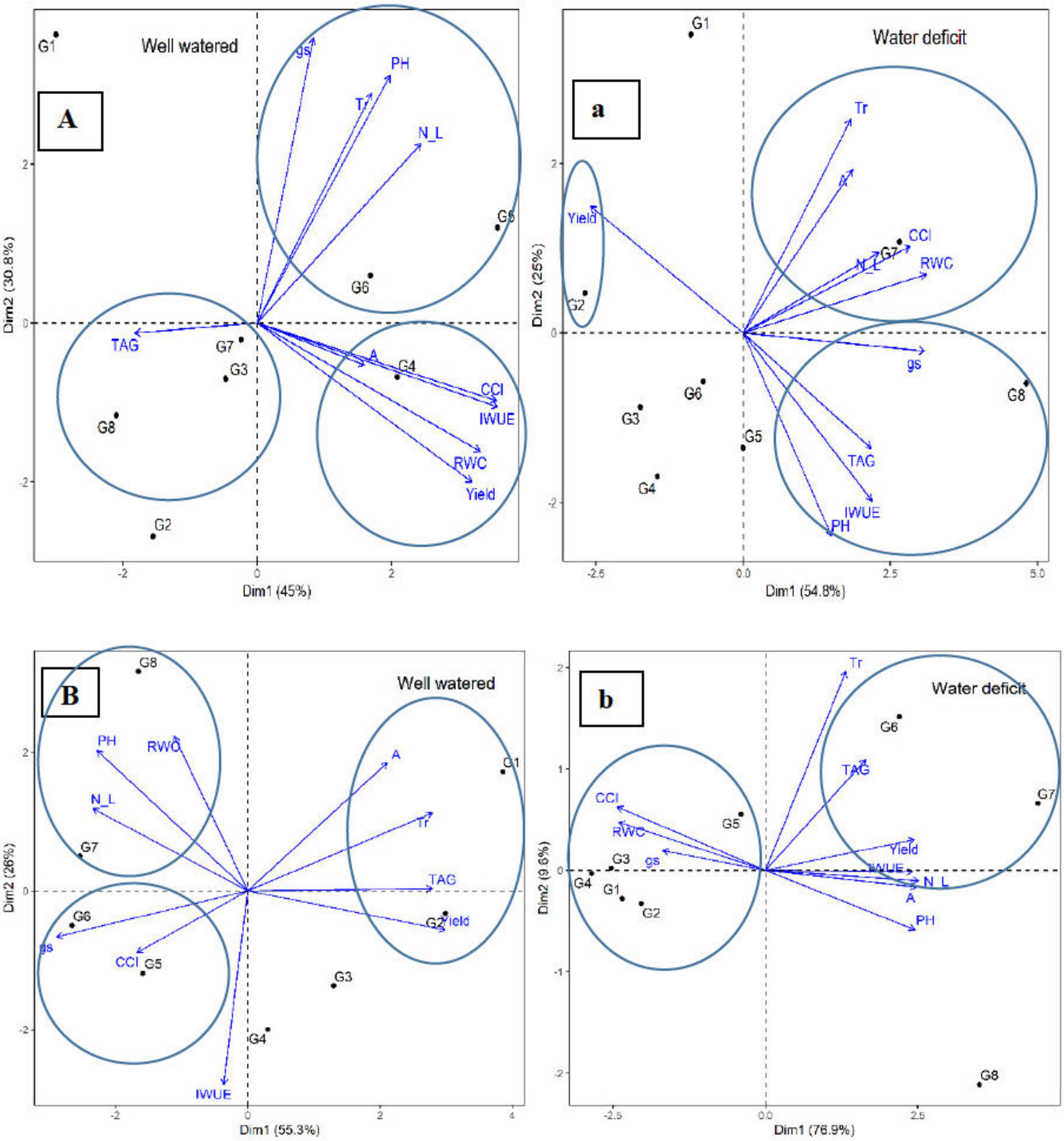
A = Rate of photosynthesis; *gs* = stomatal conductance; Tr = Transpiration rate; IWUE = instantaneous water-use efficiency; CCI = Chlorophyll content index; RWC = Relative water content; PH = Plant height; NL = Number of leaves; TY = tuber yield; TAG = Total above-ground biomass.* = significance at $p < 0.05$; ** = significance at $p < 0.01$; *** = significance at $p < 0.001$; ns = non-significant

3.4.5 Principal component biplot analysis for assessed agronomic and physiological traits under well-watered and water-deficit conditions across growth stages

Principal component analysis (PCA) biplot analysis showing percent variance for PC1 and PC2 measured morphological and physiological traits for studied genotypes under Ww and Wd conditions across four growth stages is shown in Figure 9.

All evaluated genotypes that performed better in a specific measured trait were grouped nearby and furthest to the vector line. Under Wd condition, Bikini and Challenger were differentiated from the other genotypes based on high tuber yield at the vegetative stage (Figure 9a). Under Wd condition at the vegetative stage, Tyson and Sifra are far apart from other genotypes based on NL, CCI, RWC and *gs*. At tuber initiation (Figure 9b) under Wd condition Bikini, Challenger, Mondial and Electra were grouped together based on high CCI, RWC and *gs*. No distinctive grouping was observed for genotypes under Wd condition at the tuber bulking stage (Figure 9c). Panamera, Sababa, Sifra and Tyson grouped displaying high Tr, *A* and TAG under Wd condition during the maturity stage (Figure 9d).

Under Ww condition during vegetative stage (Figure 9A) genotypes Electra, Sababa and Tyson were grouped together based on high values for TAG. At the tuber initiation stage (Figure 9B), no clear grouping patterns were observed for genotypes and assessed traits. During the tuber bulking (Figure 9C) Electra, Mondial and Panamera were grouped together recording higher values for *A*, Tr and NL. At the maturity stage (Figure 9D) Challenger, Electra and Tyson were grouped together recording higher CCI, IWUE and NL (Figure 9D).


A
Well watered
Dim1 (45%)
Dim2 (30.8%)
a
Water deficit
Dim1 (54.8%)
Dim2 (25%)
B
Well watered
Dim1 (55.3%)
Dim2 (26%)
b
Water deficit
Dim1 (76.9%)
Dim2 (9.6%)
G1
G2
G3
G4
G5
G6
G7
G8
gs
PH
Tr
N_L
TAG
A
CCI
IWUE
RWC
Yield

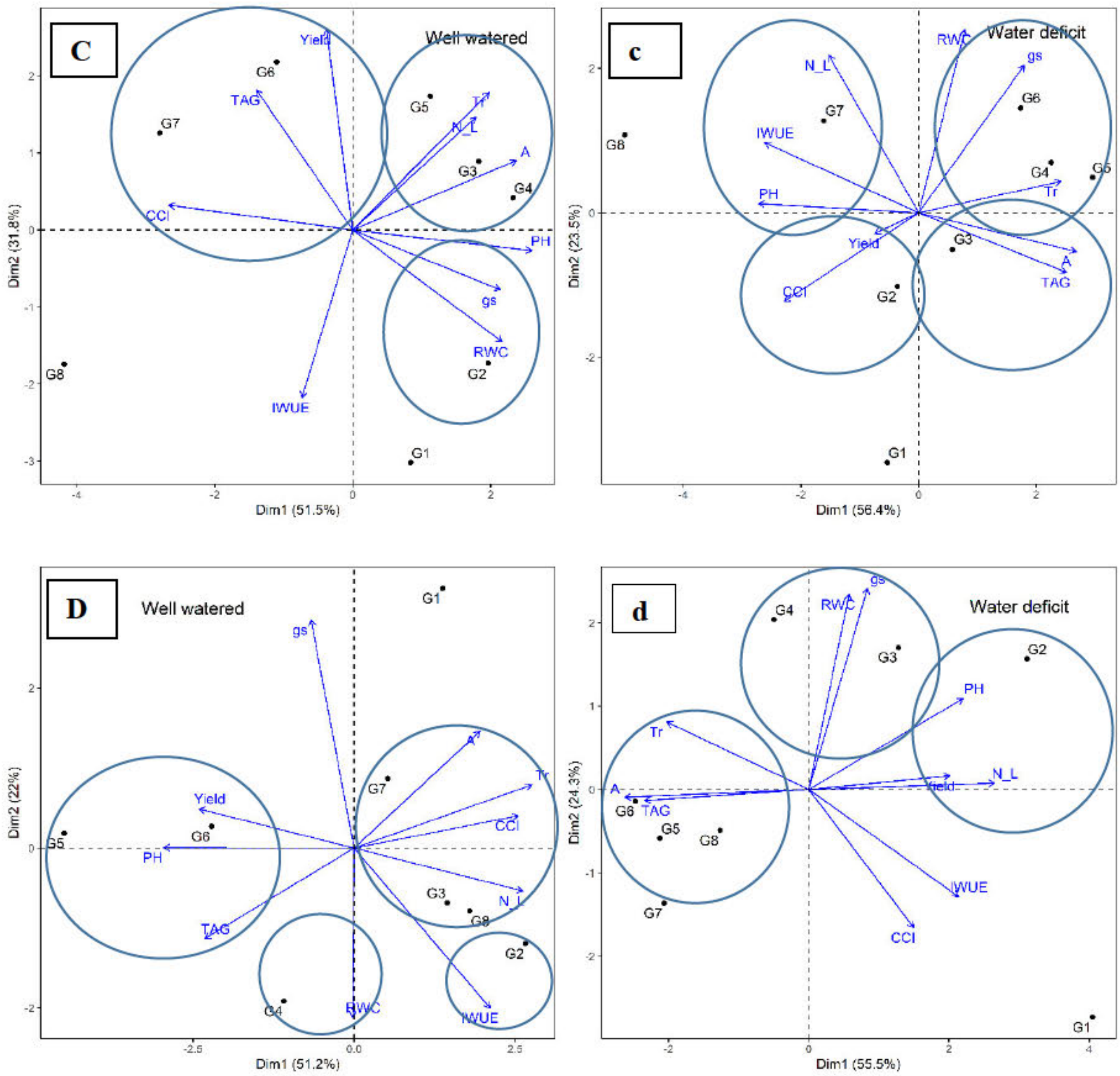


Figure 3.9: Principal component bi-plot scores of PC1 vs PC2 showing groupings of potato genotypes based on morphological and physiological traits evaluated under well-watered (Ww) and water deficit (Wd) conditions. A = vegetative stage under Ww; a = vegetative stage under Wd, B = tuber initiation under Ww; b = tuber initiation under Wd; C = tuber bulking under Ww; c = tuber bulking under Wd and D = maturity under Ww; d = maturity under Wd. PH = Plant height; NL = Leaf number; RWC = Relative water content; CCI = Chlorophyll content index; *A* = Photosynthetic rate; *gs* = stomatal conductance; Tr = Transpiration rate; IWUE = instantaneous water-use efficiency; TAG = Total above-ground biomass and TY = Yield. G1-Bikini, G2-Challenger, G3-Electra, G4-Mondial, G5-Panamera, G6-Sababa, G7-Sifra and G8-Tyson.

3.5 Discussion

Drought stress occurring during critical growth stages in potato results in low yield potential under water-stress conditions. Developing potato genotypes with tolerance to crop growth stages such as vegetative stag, tuber initiation, tuber bulking and maturity expand terms, is key to improving potato yield outputs and gains (Hassan *et al*., 2002; Alsharari *et al*., 2007; Al-Mahmud *et al*., 2015). The current study evaluated drought tolerance of potato (*Solanum tuberosum* L.) genotypes at different growth stages based on physiological and morphological traits assessed under well- and water-deficit conditions. The significant interaction between genotypes x water deficit x growth stage for studied traits indicated genotypes performed differently across different growth stages (Table 3). This is useful to identify and select potato genotypes with specific growth stage adaptation for a recommendation for cultivation. For example, genotypes such as Bikini, Electra and Mondial with high-yield potential under water deficit conditions at the vegetative stage are useful for breeding or cultivation (Figure 7). Water deficit significantly reduced yield at tuber initiation and tuber bulking stage. Tuber initiation drought tolerant genotypes including Sifra and Challenger while Tyson and Sifra were high at tuber bulking. Tyson, Challenger and Electra had good yield performance at the maturity stage under water deficit are useful for cultivation under a low water supply environment.

Physiological and morphological traits are widely targeted in potato enhancement programmes to develop high-yielding genotypes with improved levels of abiotic stress tolerance (Tourneux *et al*., 2003a; b; Alsharari *et al*., 2007; Mahmud *et al*., 2016; Ramirez *et al*., 2016; Hirut *et al*., 2017; Elzner *et al*., 2018). The current study revealed positive and significant correlations between rates of photosynthesis with transpiration at the vegetative stage (Table 4). Total-above ground, plant height and number of leaves can be selected to improve the rate of photosynthesis during the tuber initiation under water deficit. However, at the tuber bulking and maturity stage, negative but significant correlations between the rate of photosynthesis with plant height and number of leaves were observed.

The negative or poor correlations between agronomic traits such as plant height, number of leaves and total above-ground biomass with tuber yield at the vegetative and the tuber bulking stages suggest that studied genotypes consist of unique genes. This means they are capable of manipulating potato yields regardless of the high total above ground. This also explains the reason why plant height and a number of leaves were unaffected by water deficit at the tuber initiation, however, the total yield was reduced (Figure 7). The traits, such as plant height, transpiration, photosynthesis and instantaneous water-use efficiency during the tuber initiation and chlorophyll content index at maturity are positively correlated with total yield, which can be used as selection conditions to improve yield genotype under water deficit.

3.6 Conclusion

The present study evaluated drought response of potato genotypes to water deficit imposed at different growth stages to select drought-tolerant genotypes that best suited to be cultivated in environments with restricted water. Genotypes with a higher water use efficiency and high yield were identified as the most tolerant genotypes since they responded consistently at various stages under water deficit. Therefore, it can be proposed from the assessed genotypes that Bikini and Tyson were tolerant to water deficit at the vegetative stage. Electra and Tyson were tolerant to water deficit at tuber initiation. Electra and Panamera were tolerant at tuber bulking while Bikini and Challenger were tolerant to water deficit at the maturity stage. These genotypes can be recommended in environments with water stress and still produce optimum yields. Meanwhile Sababa, Sifra and Tyson were identified as most sensitive genotypes.

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Chapter 4: The effect of water deficit on yield performance and tuber quality of different potato genotypes

4.1 Abstract

Selection of drought-tolerant (*Solanum tuberosum* L.) genotypes is essential to enhance tuber yield and quality for food and processing. The aim of the study was to evaluate effect of water deficit on tuber yield and quality and drought-tolerant varieties and growth stages. Tuber quality of eight potato genotypes were evaluate under well-watered (Ww) and water-deficit (Wd) conditions through four different growth stages namely: (i.e. vegetative (VG), tuber initiation (TI), tuber bulking (TB) and maturity (MAT) stages using an 8×4×2 factorial treatment with three replications. Data was collected on yield traits such as tuber yield (TY), number of tubers (NT), tuber size distribution (TSD) and dry matter content (DMC). Significant (p < 0.05) genotype x water condition x growth stage effect were observed for TY, NT, TSD and DMC indicating varied response of genotypes to water condition across growth stages. This is useful to recommend tolerant potato genotypes at growth-stage specific for processing industry. Correlation analysis shown significant and positive associations among medium tubers and yield (r = 0.76; p = 0.05) also between large tubers and number of tuber (r = 0.42; p = 0.05) at VG stage, DMC and yield (r = 0.79; p = 0.010) at TI stage and highly significant negatively correlated with NT (r = -0.94; p = 0.001) at TB stage. Mondial and Sifra produced high percentage of medium (35-55 mm) and large tubers (>55 mm) across growth stages. Genotypes Bikini, Mondial, Sababa and Sifra were identified as tolerance genotypes to water deficit due to high yield potential and suitable for processing industry.

Keywords: Potato; genotypes; growth stages; water deficit; yield; quality.

4.2 Introduction

The production of the potato (*Solanum tuberosum* L.) guarantees that it has the potential for contributing significantly to the alleviation of hunger and to the world's food requirement (Dreyer, 2017; Ayyub *et al*., 2019). It is one of the important vegetables which is known for playing a vital role in food and nutrition security in South Africa (van Niekerk *et al*., 2016; Dreyer, 2017). It rich in nutrients such as copper, iron, magnesium, manganese, potassium, phosphorous and zinc (Ngobese *et al*., 2017; Gultekin and Ertek, 2018). The crop known to be source of energy, highly in carbohydrate, proteins and amounts of vitamin C (Ayyub *et al*., 2019). The global production of potato is approximately 374 million tonnes (Obidiegwe *et al*., 2015), of which comes from five leading producing countries which include Chine (26.3%), India (12.5%), Russia (7.62%), Ukraine (5.72%) and United States of America (5.15%) (FAOSTAT, 2019). It is mostly used for mashed potatoes, chips, French fries, croquettes or soups (VIB Facts Series, 2019). Potato comes third after maize and wheat among crops produced in the country (Ngobese *et al*., 2017; Cavalcante *et al*., 2019). The production of potatoes in South Africa occurs in 16 different geographic regions (van Niekerk *et al*., 2016). However, the production has been threaten by various factors such as drought leading in poor tuber quality produced unsuitable for processing (Levy *et al*., 2013; Kiptoo *et al*., 2018). The product's demand is increasing at a high rate and that have driven the expansion of the processing industry and the necessity to evaluate a number of newly introduced genotypes that can be used for production in South Africa.

Drought stand-out as one of the factors affecting potato tuber quality (Monneveux *et al*., 2013). Traits including tuber size distribution, dry matter content, reducing sugar and specific gravity are important characteristics of potato tuber internal quality that are intended for the processing industry (Tabatabaeefar, 2002; Muthoni and Kabira, 2016). Tuber size distribution is very important for processing and fresh markets that have specific preferences. Irregular tuber size distribution might not satisfy the desires of the consumer and that might be costly to the producer (Denner *et al*., 2012). Water deficit reduce number of tubers during the vegetative stage, and number of tubers during tuber initiation stage; whereas at tuber bulking and maturity stages affects tuber size and quality (Obidiegwu *et al*., 2015). Available information does not specify or identify the growth stage that produced smaller and irregular tuber size when exposed to water deficit. Thus, it is necessary to know which potato growth stage is likely to give smaller, medium or bigger tuber size after imposing water deficit at different growth stages. This information would assist in understanding the target market or consumers' desires in terms of size distribution and internal quality.

The impact of water deficit on potato yield and quality differs from developmental stages (Stark *et al*. 2013). Various field studies have reported that limited water during the vegetative stage and tuber initiation adversely affect potato yield (Abbas and Ranjan, 2015; Al-Mahmud *et al*., 2015). Although the literature has shown that water deficit at vegetative stage and tuber initiation results in lower yield and poor quality, the impact of water deficit on potato genotypes imposed at the vegetative stage, tuber initiation, tuber bulking and maturity has never been assessed in South Africa. There is very little available information on the actual potato yield loss due to moisture stress.

The South Africa research attempts on potato production under limited water have focussed on growth and yield quality (Steyn *et al*., 1998). Scant information is available about the effects of water deficit on different potato tuber quality, size distribution and nutritional status. It is crucial to examine and also identify less sensitive potato growth stages and genotypes where water can be withheld, hence improving yield. This would assist potato growers in decision making and planning when to increase or decrease irrigation. It is hypothesized that drought tolerance may be linked to genotype and environmental conditions. Hence, the specific objective of this study was to determine the effect of water deficit imposed at different growth stages on yield performance and tuber quality of different potato genotypes.

4.3 MATERIAL AND METHODS

4.3.1 Plant materials

Certified seed (i.e. generation 1-3) of eight potato genotypes namely: Bikini (G1), Challenger (G2), Electra (G3), Mondial (G4), Panamera (G5), Sababa (G6), Sifra (G7), and Tyson (G8) were sourced from Wes grow Pretoria, South Africa and used for the study. This are highly demanded and newly introduced genotypes for potato the industry in South Africa, hence selected for evaluation.

4.3.2 Description of a controlled environment

An experiment was conducted at the University of KwaZulu-Natal's Controlled Environment Research Unit (CERU), Pietermaritzburg, South Africa. The environmental conditions inside the tunnel were semi-controlled with the average day and night temperatures of 38 °C and 18 °C, respectively, whereas relative humidity ranged between 45 % - 55 %. Temperature and relative humidity were monitored electronically using a data logger (HOBO 2K logger, Onset Computer Corporation, Bourne, USA). The experiment was planted on the 16th of December 2018 and terminated on the 14th of April 2019.

4.3.3 Experimental design and trial management

The study was conducted using an 8×4×2 factorial treatment structure arranged in randomized complete blocks design with three replications resulting in 192 experimental units (i.e. 10 L drained polyethylene pots). The experiment comprised of the following factors: potato genotypes- 8 levels (Bikini, Challenger, Electra, Mondial, Panamera, Sababa, Sifra, and Tyson); growth stages - 4 levels (vegetative stage, tuber initiation, tuber bulking and maturity) and watering regimes -2 levels (Well-watered [Ww] and Water deficit [Wd] conditions). A loamy soil with known chemical (Table 1) and physical properties (Table 1) collected from Ukulinga Research Farm (29° 39′48.82″S; 30° 24′19.89″E), Pietermaritzburg, South Africa was used for the study.

One sprouted potato tuber was sown in each pot half-filled with 2.5 kg of sieved soil and after two weeks another 2.5 kg of sieved soil was re-added. Nitrogen (N), phosphorus (p) and potassium (K) were supplied using automated drip irrigation at a rate of 200 kg N ha^{-1} (ha^{-1}), 80 kg P ha^{-1} and 90 kg K ha^{-1} based on soil fertility analysis using potato nutrient requirements as a reference. For the first two weeks, all pots were watered to field capacity after planting to ensure fully establishment. The studied genotypes were exposed to water deficit at the beginning of each growth stage (i.e. vegetative growth, tuber initiation, tuber bulking and maturity) for the entire growth stage and re-irrigated at the end of each growth stage. The crop duration in growing degree days (beginning and end-stage of each growth stage) was monitored using the BBCH developmental scale (Table 2) (Meier, 2001). Soil moisture content was monitored daily by a Hydro-Sense II (HS2) Handheld Soil Moisture Sensor, carefully inserted in the pot to a depth of 12 cm. The H2S uses a battery capacitance to estimate the volumetric soil moisture content (VSC). Soil moisture content was maintained at 30% (throughout the growing period) under well-watered condition. Under water deficit treatment, soil moisture was allowed to decline from 30% to approximately 10% after irrigation was withheld throughout all the crop growing period. Weeds were removed by hand while pests and diseases were chemically controlled.

Table 4.1: Soil chemical composition

Sample density (g/ml)	N (%)	P (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Exch.Acidity (cmol/L)	Total cations (cmolmg/L)	pH (KCL)	Zn (mg/L)	Mn (mg/L)	Cu (mg/L)	Organic C (%)
1.46	0.13	30	108	844	314	1.14	8.21	3.94	5.9	110	8.9	1.5

N = nitrogen, P = phosphorus, K = phosphorus, Ca = calcium, Mg = magnesium, Zn = zinc, Mn = manganese, Cu = copper, C = carbon.

Table 4.2: Phonological development stages of potato (*Solanum tuberosum* L.) according to the BBCH scale (Meier, 2001).

Code	Description	Stage no.	dd/mm/Year	DAP
00	Planting	0	16 December 2018	0
11	Emergence	I	02 January 2019	17
21	Vegetative stage	II	19 January 2019	34
40	Tuber initiation	III	27 January 2019	42
51	Flowering	-	04 February 2019	50
69	End of flowering	-	17 February 2019	63
70	Tuber bulking	IV	01 March 2019	75
95	Maturity	V	30 March 2019	104
99	Yellow leaves and Harvest	N	13-14 April 2019	119

N= Terminal, dd-Date, mm-Month, y-Year, DAP-Days after planting

4.3.3.1 Application of water deficit treatments

- T_X (00000); Water deficit
- T_Y (11111); Well-watered
- T_1 (11111); Well-watered at stage I
- T_2 (10111); Water deficit at stage II
- T_3 (11011); Water deficit at stage III
- T_4 (11101); Water deficit at stage IV
- T_5 (11110); Water deficit at stage V

Where 0-Water deficit, 1-Well-watered, stage I-Emergency, stage II-Vegetative stage, stage III-Tuber initiation, stage IV-Tuber bulking, stage V-Maturity.

4.3.4 Data collection

4.3.4.1 Tuber yield

The number of tubers and weight (g) were determined according to Lihlou *et al*. (2003) with some modifications. The number of tubers per plant was determined by physically counting tubers produced per plant and taking the average (three plants) for each treatment and growth stage. At maturity, the weight of fresh tuber yield was taken from three pots of each treatment and growth stage. Thereafter, the average representing treatment output per block was determined.

4.3.4.2 Tuber size

Tuber size category was determined according to Khan *et al*. (2011); Bekele and Haile (2019) with some modification. Tuber yield samples were washed and six tubers in each genotype randomly selected from both conditions (well-watered and water deficit) and categorized into three groups size of tubers: small (< 35 mm), medium (35-55 mm) and large (>55 mm) using Vernier caliper after categorizing was done tubers in each grade were counted.

4.3.4.3 Determination of dry matter content

Washed potato tubers with a diameter range of 30 to 40 mm from each treatment combination were selected and used to determine tuber dry matter content. The standard of 150 g fresh sample tubers was weighed, chopped into small pieces to accelerate the oven drying process. Dry weights were determined by oven dry chopped samples at 70 ^{o} C for 24 hours to determine the dry weight and then 60 ^{o}C re-weighed till constant weight was obtained. The dry matter content was calculated as a percentage of dry weight over fresh weight (g) (Abbas *et al*., 2011; Bekele and Haile, 2019). Dry matter content (%) was determined using Equation (1).

$$\text{Dry matter content (\%)} = \frac{\text{Dry weight}}{\text{Fresh weight}} \times 100$$

4.3.5 Data analysis

The data collected was subjected to analysis of variance (ANOVA) using GenStat® 18th Edition (VSN International, Hemel Hempstead, UK). The means were separated with the LSD test at 5% probability level. Correlation analysis was performed on measured traits to determine the level of association. Principal component analysis (PCA) based on the correlation matrix was used to derive bi-plots showing the relationship between genotypes and assessed traits for both well-watered and water deficit conditions.

4.4 Results

4.4.1 Effect of genotype, water condition and growth stages on total yield and tuber quality

Analysis of variance showing mean squares and significance tests for total yield and tuber quality traits between eight selected potato genotypes under well-watered and water deficit conditions is shown in Table 3. Genotypic differences were observed with regards to Yield, NT, small tubers and DMC. Highly significant ($p < 0.001$) effects of water condition and growth stages were observed for assessed traits. Genotype x water condition and genotype x growth stage were significant ($p < 0.05$) for most assessed traits. A significant ($p < 0.001$) genotype × water condition × growth stages interaction was observed for DMC only, whereas a significant ($p < 0.001$) interaction between water condition × growth stages was observed for Yield, NT, small tubers and DMC (Table 3).

Table 4.3. Analysis of variance showing mean squares and significance test for evaluated potato quality traits among eight potato genotypes tested under well-watered and water deficit conditions at four different growth stages.

Source of variation	Df	Yield	NT	Small	Medium	Large	DMC
Genotypes (G)	7	36531***	22.97***	1461***	706*	479**	17.5***
Water condition (WC)	1	769006***	126.75***	26759***	7239***	7500***	856.8***
Growth Stage (GS)	3	92860***	26.19***	187ns	129ns	27ns	20.4***
G × WC	7	6640ns	1.32ns	966***	216ns	446*	13.6***
G × GS	21	11527***	2.15ns	443**	224ns	189ns	6.7***
WC × GS	3	57608***	16.69***	2172***	1024*	413ns	24.7***
G × WC × GS	21	3670***	0.76ns	294ns	393ns	127ns	4.4***
Residual	128	3292	2.09ns	214ns	318ns	162ns	0.6***

df = degree of freedom; * = significance at $p < 0.05$; ** = significance at $p < 0.01$; *** = significance at $p < 0.001$; ns = non-significant. Yield = Total yield NT = Number of tubers; Small = Small tubers; Medium = Medium tubers; Large = Large tubers; DMC = Dry matter content.

4.4.2 Yield performance of potato genotypes under well-watered and water deficit conditions across different growth stages

The interactions between water treatments and genotypes had significant ($p < 0.05$) effect on fresh tuber yield among genotypes (Figure 1a). Genotypes Tyson, Electra and Bikini (327.0, 326.5 and 320.0 g, respectively) produced higher TY compared to Sababa, Sifra and Panamera (203.0, 266.0 and 254.0 g, respectively) that produced low TY when Wd were imposed at VG. Genotypes Electra, Challenger and Mondial recorded significantly higher tuber yields (> 430 g) under Ww condition at the VG. All genotypes were affected by Wd at TI and TB stage where Sifra, Challenger and Sababa (200.0, 180.0 and 173.5 g, respectively) were less affected while Panamera and Electra (124.0 and 125.0 g, respectively) were highly affected during TI stage. Under Ww condition Mondial, Sababa and Sifra recorded higher TY > 400 g compared to other genotypes at the TI. During TB and MAT under Wd condition Tyson produced the highest tuber yield while the lowest obtained for Bikini, Mondial and Panamera. Under Ww condition, Challenger, Mondial, Sifra and Tyson recorded higher tuber yields during TB (> 430 g) and MAT (> 390 g).

Genotypic differences ($p < 0.05$) were observed among genotypes across all growth stages for NT (Figure 1b). When Wd was imposed at VG it affected Sababa and Panamera NT while Electra and Sifra were unaffected. Under Ww condition Electra, Mondial and Sifra produced high NT compared to other genotypes. During TI, TB and MAT stage under Wd condition, genotypes Sababa and Panamera produced lower NT. Electra recorded high NT at VG, TI and MAT, whereas Mondial had higher NT at TB and MAT under Wd condition. Bikini, Electra, Mondial and Sifra produced high NT than other genotypes under Ww condition throughout stages.

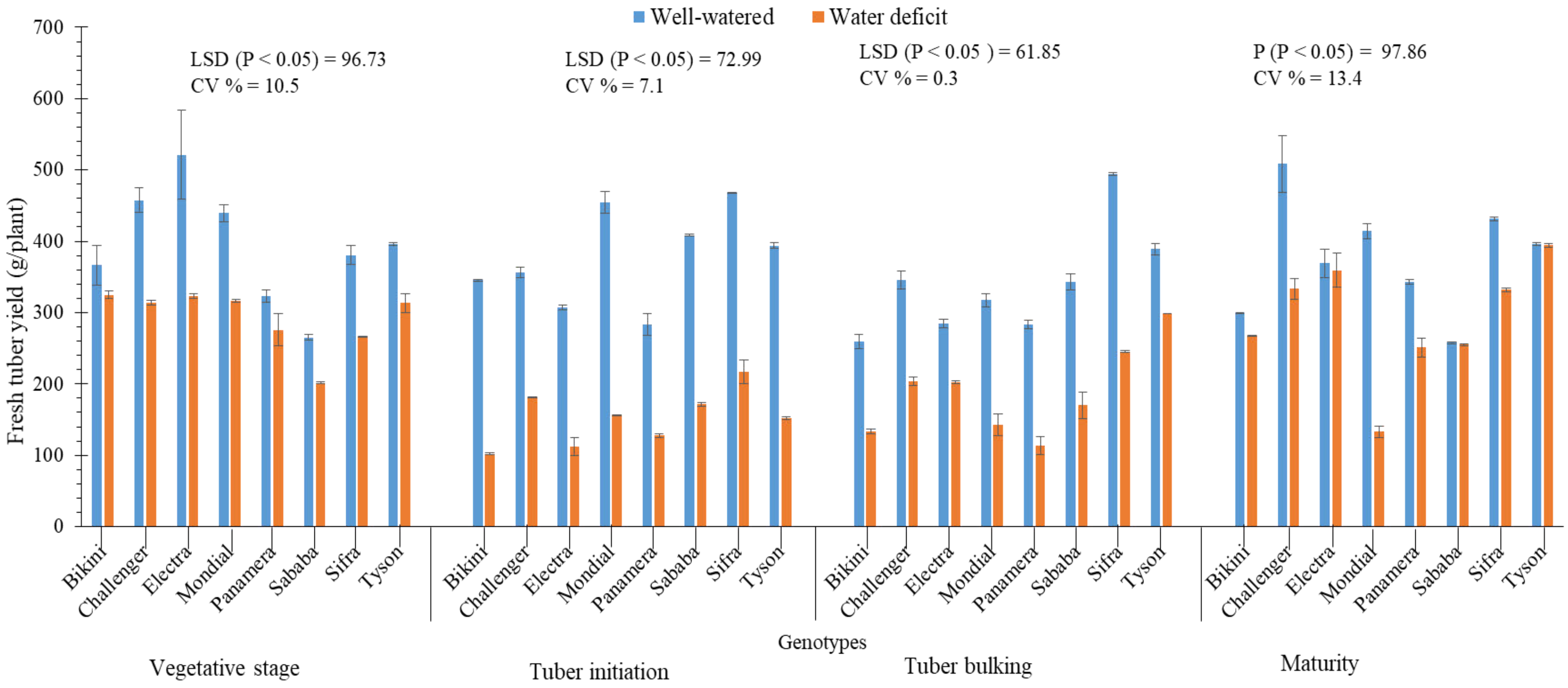


Figure 4.1a: Yield performance of eight potato genotypes under well-watered and water deficit conditions at different growth stages.

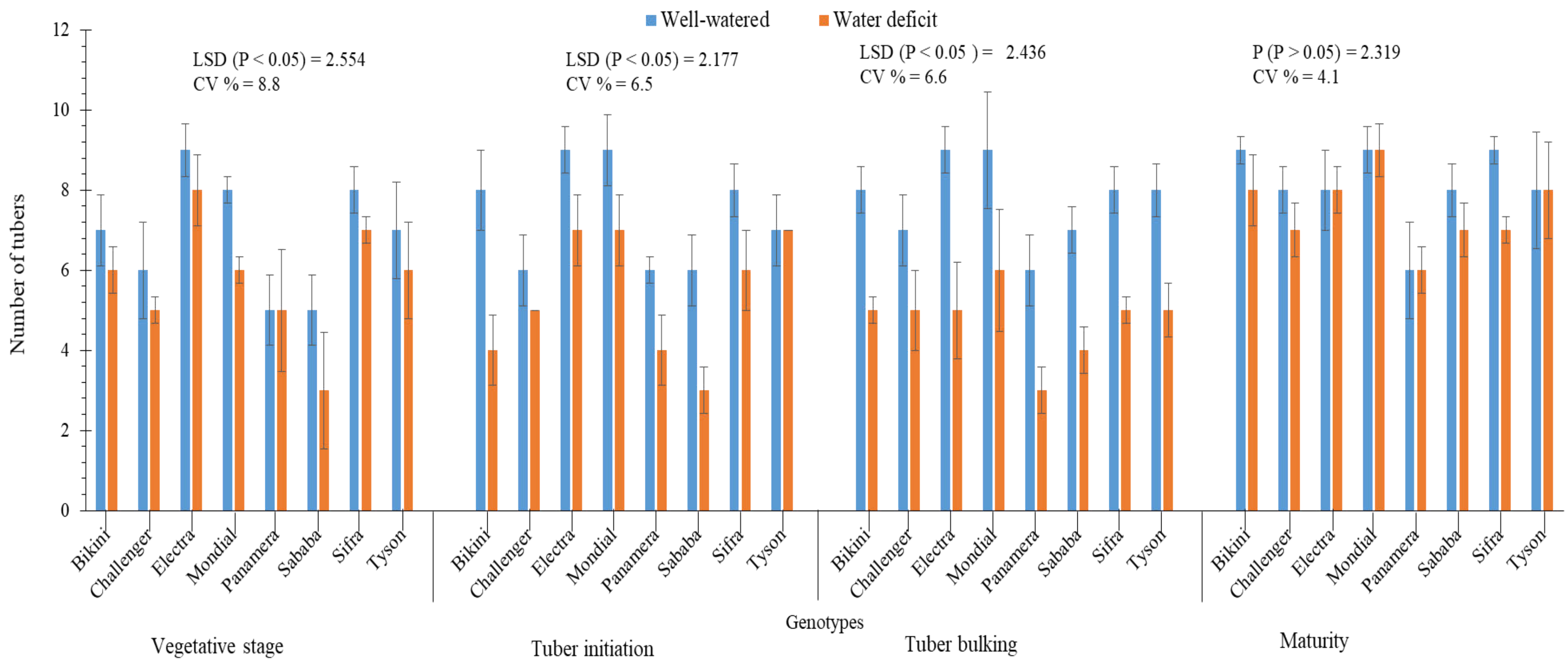


Figure 4.1b: The effect of water deficit imposed at different growth stages on the number of tubers of potato genotypes.

4.4.3 The effect of water deficit on potato genotypes tuber size distribution and dry matter content across different growth stages

A significant difference ($p < 0.05$) in tuber size among tested genotypes concerning the number of small size tuber in percentage was observed (Table 3a). During VG stage Wd resulted in the highest percentage of small tubers from Tyson, Sababa (both 66.67%), Bikini and Challenger (both 61.11%). Under Ww condition at VG stage Sababa recorded high percentage of small tubers (77.78%) while Sifra produced lowest percentage (11.11%) of small size tuber. On the other hand, Sifra, Panamera and Mondial (55.55, 50 and 50%, respectively) dominated with medium size tubers whereas the highest percentage of large tubers were obtained from Sifra, Mondial and Sababa (16.67, 11.11 and 11.11%, respectively) at VG stage under Wd condition. Under Ww condition at VG stage Panamera, Tyson and Mondial produced many medium size tuber >50% whereas Sifra and Sababa produced less than 30% of medium size tubers. Many large size tubers were obtained from Sifra (61.11%) while other genotypes recorded fewer large tubers < 11.11% under Ww condition.

Genotypic differences ($p < 0.05$) were observed among genotypes at TI for small size tubers under Ww and Wd condition (Table 3b). Under Wd condition at TI stage a high percentage of small size tubers were produced by Bikini and Challenger (both 11.11%) compared to other genotypes. Only Tyson produced many small size tubers (44.44%) whereas Sifra produced fewer under Ww condition. Panamera, Sababa and Tyson recorded higher medium size tuber of 44.44% also large size tubers (Sababa and Tyson) at TI stage under Wd condition. Under Ww condition Sababa and Tyson produced lesser percentage of medium size tubers while other genotypes produced more than 50%. High percentage of large size tubers were obtained from Sifra (22.22%).

Table 4.4a: Tuber size distribution (small, medium and large) of potato genotypes at vegetative stage evaluated under well-watered (Ww) and water deficit (Wd) conditions.

Tuber size category at Vegetative stage						
Genotypes	Small (< 35mm)		Medium (35-55mm)		Large (> 55 mm)	
	Ww	Wd	Ww	Wd	Ww	Wd
Bikini	55.55[cde]	61.11[cde]	33.33[abc]	33.33[abc]	11.11[a]	5.56[a]
Challenger	50.00[bcde]	61.11[cde]	44.44[abcd]	33.33[abc]	5.56[a]	5.56[a]
Electra	44.44[bcd]	50.00[bcde]	44.44[abcd]	44.44[abcd]	11.11[a]	5.56[a]
Mondial	22.22[ab]	38.89[abcd]	66.67[d]	50.00[abcd]	11.11[a]	11.11[a]
Panamera	33.33[abc]	44.44[bcd]	55.56[bcd]	50.00[abcd]	11.11[a]	5.56[a]
Sababa	77.78[e]	66.67[de]	16.67[a]	22.22[a]	5.56[a]	11.11[a]
Sifra	11.11[a]	27.78[ab]	27.78[ab]	55.55[cd]	61.11[b]	16.67[a]
Tyson	38.89[abcd]	66.67[de]	50.00[abcd]	27.78[a]	11.11[a]	5.56[a]
P-value	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p > 0.05$	$p > 0.05$
LSD	25.14	25.14	26.77	26.77	18.84	18.84
S.e.d	12.31	12.31	13.11	13.11	9.23	9.23
CV (%)	5.6	5.6	14.6	14.6	31	31

Note: Means in a column and treatment group followed by the same letter are not significantly different from each other using the LSD test at 5% probability level; Ww, Well-watered (control); Wd, Water deficit; *p*-value = Significance of interaction between treatment x genotype; LSD, Least significant difference; S.e.d, standard error deviation; CV, Coefficient of variation.

Table 4.4b: Tuber size distribution (small, medium and large) of potato genotypes at tuber initiation evaluated under well-watered (Ww) and water deficit (Wd) conditions.

Tuber size category at Tuber initiation						
Genotypes	Small (< 35mm)		Medium (35-55mm)		Large (> 55 mm)	
	Ww	Wd	Ww	Wd	Ww	Wd
Bikini	33.33[abc]	61.11[de]	55.56[b]	33.33[ab]	11.11[a]	5.56[a]
Challenger	33.33[abc]	61.11[de]	50.00[ab]	33.33[ab]	16.67[a]	5.56[a]
Electra	38.89[bcd]	55.56[cde]	50.00[ab]	38.89[ab]	11.11[a]	5.56[a]
Mondial	22.22[ab]	55.56[cde]	61.11[b]	38.89[ab]	16.67[a]	5.56[a]
Panamera	33.33[abc]	50.00[cde]	50.00[ab]	44.44[ab]	16.67[a]	5.56[a]
Sababa	38.89[abc]	44.44[bcd]	44.44[ab]	44.44[ab]	16.67[a]	11.11[a]
Sifra	11.11[a]	72.22[e]	66.67[b]	22.22[a]	22.22[a]	5.56[a]
Tyson	44.44[bcd]	44.44[bcd]	44.44[ab]	44.44[ab]	11.11[a]	11.11[a]
P-value	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p > 0.05$	$p > 0.05$
LSD	20.64	20.64	30.07	30.07	21.70	21.70
S.e.d	10.10	10.10	14.72	14.72	10.63	10.63
CV (%)	6.0	6.0	14.5	14.5	39.6	39.6

Note: Means in a column and treatment group followed by the same letter are not significantly different from each other using the LSD test at 5% probability level; Ww, Well-watered (control); Wd, Water deficit; *p*-value = Significance of interaction between treatment x genotype; LSD, Least significant difference; S.e.d, standard error deviation; CV, Coefficient of variation.

At the TB stage, significant differences ($p < 0.05$) with respect to small size distribution among genotypes imposed in Wd were found (Table 3c). During TB under Wd all genotypes produced high number of small size tubers >50% except Sababa and Tyson. Genotype Challenger produced >50% of smaller size tubers and Sifra produced less (11.11%) under Ww condition. A high percentage of medium-sized tubers under Wd condition were observed from Sababa, Panamera and Tyson (>50%). On the other hand, Sifra produced a lower percentage of medium-sized tubers (<30%) under Wd condition. Under Ww condition Mondial and Panamera produced high percentage of medium sized tubers >55% while Challenger recorded lowest (<33.33%). Electra, Panamera and Sababa produced non-large size tubers while Tyson produced higher of 16.67% under Wd condition. However, under Ww condition Sifra followed by Panamera and Mondial produced >20% of large size tubers and <10% observed for Challenger. At MAT stage under Ww condition only Panamera produced high percentage of medium size tubers, while under Wd condition Challenger produced high percentage of small size tubers.

Table 4.4c: Tuber size distribution (small, medium and large) of potato genotypes at tuber bulking stage evaluated under well-watered (Ww) and water deficit (Wd) conditions.

	Tuber size category at Tuber bulking					
Genotypes	Small (< 35mm)		Medium (35-55mm)		Large (> 55 mm)	
	Ww	Wd	Ww	Wd	Ww	Wd
Bikini	38.89[bcde]	61.11[de]	50.00[a]	33.33[a]	11.11[a]	5.56[a]
Challenger	61.11[de]	61.11[de]	33.33[a]	33.33[a]	5.56[a]	5.56[a]
Electra	44.44[bcde]	55.56[de]	44.44[a]	44.44[a]	11.11[a]	0.00[a]
Mondial	16.67[ab]	50.00[cde]	61.11[a]	38.89[a]	22.22[ab]	11.11[a]
Panamera	22.22[abc]	50.00[cde]	55.56[a]	50.00[a]	22.22[ab]	0.00[a]
Sababa	44.44[bcde]	44.44[bcde]	38.89[a]	55.56[a]	16.67[ab]	0.00[a]
Sifra	11.11[a]	66.67[e]	50.00[a]	27.78[ab]	38.89[b]	5.56[a]
Tyson	33.33[abcd]	33.33[abcd]	50.00[a]	50.00[a]	16.67[ab]	16.67[ab]
P-value	$p < 0.05$	$p < 0.05$	$p > 0.05$	$p > 0.05$	$p < 0.05$	$p < 0.05$
LSD	24.53	24.53	30.53	30.53	22.00	22.00
S.e.d	12.01	12.01	14.95	14.95	10.77	10.77
CV (%)	7.7	7.7	7.0	7.0	42.3	42.3

Note: Means in a column and treatment group followed by the same letter are not significantly different from each other using the LSD test at 5% probability level; Ww, Well-watered (control); Wd, Water deficit; *p*-value = Significance of interaction between treatment x genotype; LSD, Least significant difference; S.e.d, Standard error deviation; CV, Coefficient of variation.

Table 4.4d: Tuber size distribution (small, medium and large) of potato genotypes at maturity stage evaluated under well-watered (Ww) and water deficit (Wd) conditions.

Tuber size category at Maturity						
Genotypes	Small (< 35mm)		Medium (35-55mm)		Large (> 55 mm)	
	Ww	Wd	Ww	Wd	Ww	Wd
Bikini	33.33[bcde]	50.00[defg]	44.44[abcd]	44.44[abcd]	22.22[abde]	5.56[abcd]
Challenger	38.89[bcdef]	77.78[g]	44.44[abcd]	22.22[a]	16.67[abcde]	0.00[abc]
Electra	16.67[abc]	66.67[fg]	66.67[cd]	33.33[abc]	16.67[abcde]	0.00[abc]
Mondial	22.22[abcd]	66.67[fg]	55.56[bcd]	33.33[abc]	22.22[abde]	0.00[a]
Panamera	0.00[a]	66.67[fg]	72.22[d]	33.33[ab]	27.78[e]	0.00[a]
Sababa	44.44[cdef]	55.56[efg]	44.44[abcd]	27.78[ab]	11.11[abcde]	16.67[abcde]
Sifra	11.11[ab]	61.11[efg]	61.11[bcd]	38.89[abcd]	27.78[e]	0.00[ab]
Tyson	11.11[ab]	66.67[fg]	55.56[bcd]	33.33[abc]	33.33[e]	0.00[a]
P-value	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
LSD	26.87	26.87	30.95	30.95	19.10	19.10
S.e.d	13.16	13.16	15.16	15.16	9.35	9.35
CV (%)	12.4	12.4	2.4	2.4	40.8	40.8

Note: Means in a column and treatment group followed by the same letter are not significantly different from each other using the LSD test at 5% probability level; Ww, Well-watered (control); Wd, Water deficit; *p*-value = Significance of interaction between treatment x genotype; LSD, Least significant difference; S.e.d, Standard error deviation; CV, Coefficient of variation.

For dry matter content (DMC), genotypic differences were observed among genotypes across growth stages and water conditions (Figure 2). Challenger and Tyson recorded higher DMC across stages while Electra, Panamera and Sababa recorded lower DMC % under Wd at the VG, TI, TB and MAT stages. Genotypes Electra recorded higher DMC% during VG stage followed by Sababa and Tyson higher > 17% at both VG and TI stage under Ww condition. Bikini and Sababa produced higher DMC > 19% at TB whereas Sifra and Tyson were higher > 18% at MAT stage under Ww condition. Lower DMC under Ww condition was observed from Mondial and Panamera (14 and 14%, respectively) at VG stage. Electra, Mondial and Panamera were lower at TI, Mondial at TB and Sababa was lower < 16% at MAT stage under Wd condition.

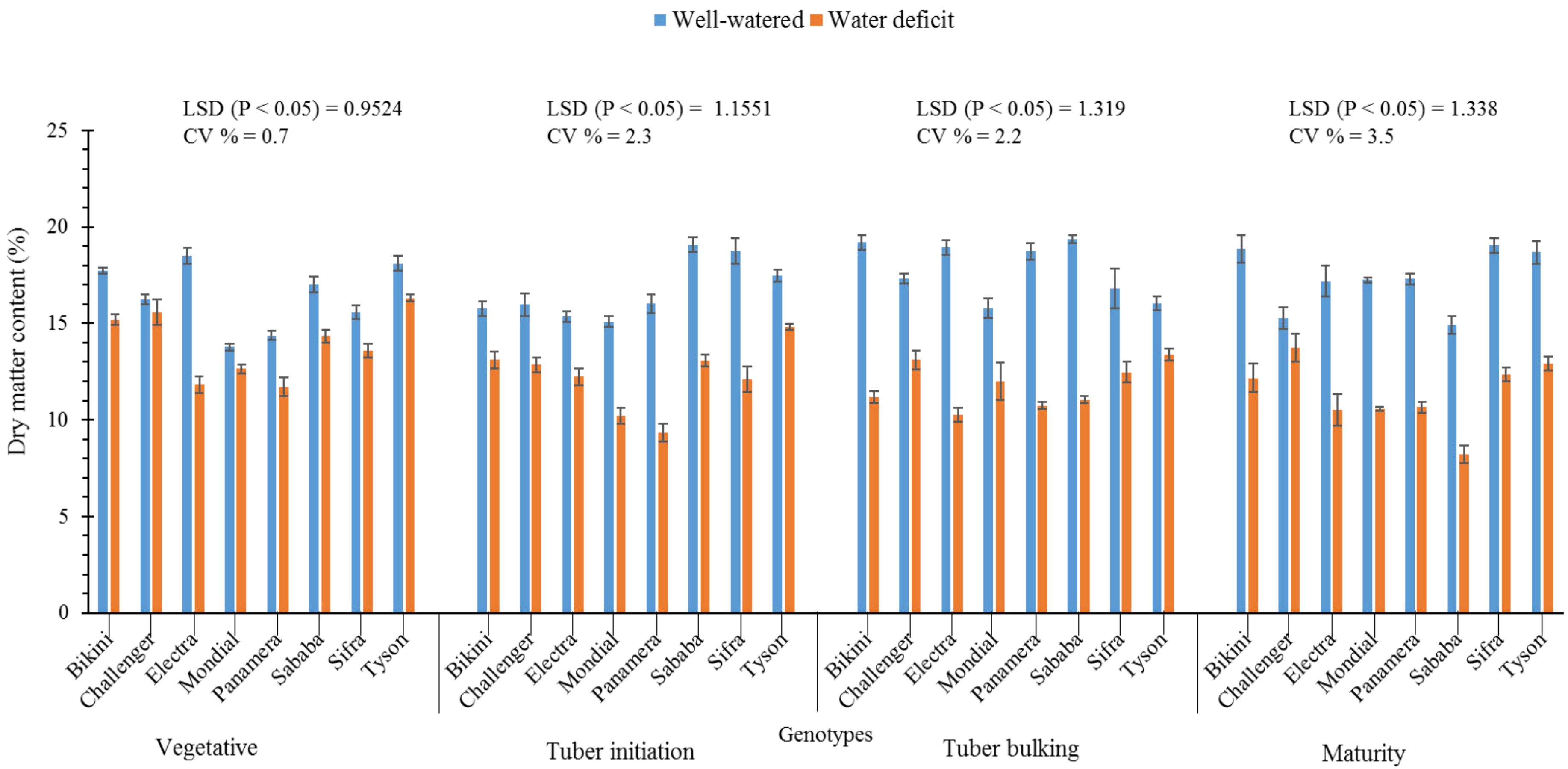


Figure 4.2: Effect of water deficit imposed at different growth stages on tubers dry matter content of eight potato genotypes.

4.4.4 Correlations among yield and quality traits under well-watered and water-deficit conditions across growth stages.

Pearson's correlation coefficients (r) revealing the level of associations of yield and quality traits among potato genotypes under well-watered and water deficit conditions at different growth stages are presented in Table 5. On the upper diagonal, under Wd condition, medium tubers were significant and positively correlated with yield (r = 0.76; *p* = 0.05) at vegetative stage, (r = 0.88; *p* = 0.010) at tuber bulking however, at tuber initiation it was significant and negatively correlated with yield (r = -0.08; *p* = 0.05). Medium tubers were highly significant and negatively correlated with small tubers (r = -0.95; *p* = 0.001) at vegetative stage, (r = -0.95; *p* = 0.001) at tuber initiation also significant and negatively correlated with small tubers (r = -0.75; *p* = 0.05) at tuber bulking and (r = 0 -0.69; *p* = 0.05). During tuber initiation on the upper diagonal under Wd condition medium tubers were significant and positively correlated with NT (r = 0.75; *p* = 0.05). Small tubers were significant and negatively correlated with yield (r = -0.81; *p* = 0.010) during tuber bulking on the upper diagonal.

Large tubers were significant and positively correlated with NT (r = 0.42; *p* = 0.05) at vegetative stage however during tuber initiation and tuber bulking it was significant and negatively correlated with yield (r = -0.68; *p* = 0.05) and (r = -0.09; *p* = 0.05), respectively. During vegetative stage under Wd condition on upper diagonal DMC was significant and positively correlated with large tubers (r = 0.71; *p* = 0.05) while during tuber initiation it was significant and negatively correlated with large tubers (r = -0.64; *p* = 0.05). DMC was significant and positively correlated with yield (r = 0.79; *p* = 0.010) during tuber initiation and highly significant negatively correlated with NT (r = -0.94; *p* = 0.001) at tuber bulking.

Table 4.5: Pearson correlation coefficients (r) showing associations of quality traits of 8 selected potato genotypes under well-watered (lower diagonal) and water deficit (upper diagonal) conditions at different growth stages.

Vegetative stage						
Traits	Yield	NT	Small	Medium	Large	DMC
Yield		0.4266ns	-0.6021ns	0.764*	-0.5068ns	-0.4688ns
NT	-0.0971ns		-0.4384ns	0.4132ns	0.3337*	0.2543ns
Small	-0.1634ns	-0.6939*		-0.9539***	0.1823ns	0.4778ns
Medium	0.177ns	0.5923ns	-0.9742ns		-0.4275ns	-0.5618ns
Large	-0.5618ns	0.4725ns	-0.17ns	-0.0173ns		0.7158*
DMC	-0.0657ns	-0.1495ns	0.7531*	-0.8544**	0.2228ns	
Tuber initiation						
Traits	Yield	NT	Small	Medium	Large	DMC
Yield		0.5697ns	0.3137ns	-0.0886*	-0.6816*	0.7959**
NT	0.8569**		-0.5465ns	0.748*	-0.1259ns	0.2553ns
Small	-0.8304**	-0.6154ns		-0.9499***	-0.6344*	0.454ns
Medium	0.6955*	0.3454ns	-0.811**		0.4088ns	-0.3459ns
Large	0.4779ns	0.5841ns	-0.6112ns	0.0327ns		-0.6386*
DMC	-0.7646*	-0.3815ns	0.7908**	-0.9674***	-0.0423ns	
Tuber bulking						
Traits	Yield	NT	Small	Medium	Large	DMC
Yield		0.3283ns	-0.8189**	0.8893**	-0.0912*	-0.542ns
NT	0.3159ns		-0.2218ns	0.3818ns	-0.2257ns	-0.9411***
Small	-0.5033ns	-0.8669**		-0.7559*	-0.3592ns	0.3223ns
Medium	0.3119ns	0.128ns	0.1329ns		-0.3394ns	-0.5148ns
Large	0.3302ns	0.7187*	-0.9318***	-0.4835ns		0.2707ns
DMC	0.8429**	0.1067ns	-0.2262ns	0.5159ns	0.0109ns	
Maturity						
Traits	Yield	NT	Small	Medium	Large	DMC
Yield		-0.1089ns	0.5335ns	-0.5489ns	-0.43ns	0.2604ns
NT	-0.1089ns		-0.4154ns	0.4663ns	0.1843ns	-0.8282ns
Small	0.5335ns	-0.4154ns		-0.9957*	-0.9341ns	0.8035ns
Medium	-0.5489ns	0.4663ns	-0.9957ns		0.8971ns	-0.8285ns
Large	-0.43ns	0.1843ns	-0.9341***	0.8971**		-0.6406ns
DMC	0.2604ns	-0.8282**	0.8035**	-0.8285**	-0.6406*	

Yield = total yield; NT = Number of tubers; Small = small tubers; Medium = medium tubers; Large = large tubers; DMC = dry matter content.* = significance at $p < 0.05$; ** = significance at $p < 0.01$; *** = significance at $p < 0.001$; ns = non-significant.

4.4.5 Principal component analysis for assessed quality traits under well-watered and water-deficit conditions across growth stages.

Principal component analysis (PCA) showing percent variance and correlation among the measured quality traits for studied genotypes under Ww and Wd conditions across four growth stages (Table 5). For vegetative, tuber initiation, tuber bulking and maturity stages, PCA revealed two principal components (PC's) which accounted for a total variation of Figure Aa, Bb, Cc and Dd. Medium tubers, DMC and small tubers correlated with PC1 which accounted for 51.6 % of the total variation while large tubers and yield correlated with PC2 which accounted for 30.1 % of the total variation under Ww condition at the vegetative stage. Under Wd condition PC1 correlated with small tubers, DMC, yield and medium tubers which accounted for 56 % of the total variation whereas only NT correlated with PC2 which accounted for 28.8 % of the total variation at the vegetative stage. At the tuber initiation under Ww condition yield, medium tubers, NT, DMC and small tubers correlated with PC1 and large tubers correlated with PC2 which accounted for 67.6 and 23.2 % of the total variation, respectively. On the other hand of Wd condition small tubers, DMC, medium tubers and large tubers correlated with PC1 which accounted for 52.6 % of total variation whereas only NT correlated with PC2 which accounted for 38.1 % of the total variation. Large tubers, NT and small tubers correlated with PC1 which accounted for 50.6 % of total variation while medium tubers and DMC correlated with PC2 during tuber bulking which accounted for 34 % of the total variation. But during Wd condition medium tubers, yield, small tubers and DMC correlated with PC1 which accounted for 55.7 % of total variation and only large tubers correlated with PC2 which accounted for 25.8 % of the variation. At maturity stage under Ww condition medium tubers, large, DMC and small tubers correlated with PC1 whereas only NT correlated to PC2 which accounted for 68.7 and 19.4 % of the total variation, respectively. Under Wd condition yield and small tubers were correlated with PC1 which accounted for 40 % whilst medium tubers correlated with PC2 which accounted for 73 % of the total variation.

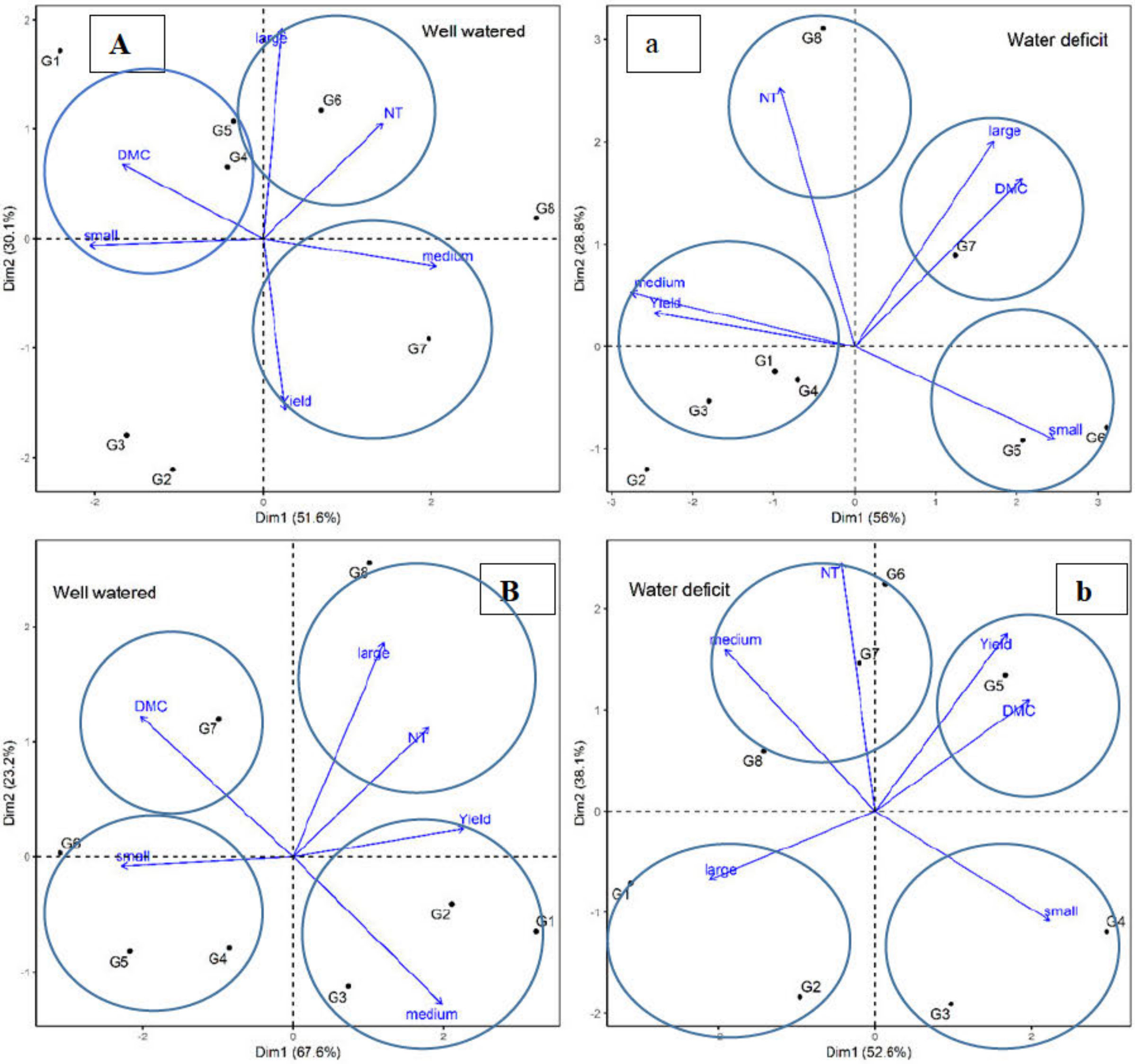
The evaluated genotypes that performed best in a particular assessed trait were gathered nearby and furthest to the vector line (Figure 3). Under Wd condition (Figure 3a) at the vegetative stage, G1-Bikini, G3-Electra and G4-Mondial were grouped together based on high yield of medium tubers while G5-Panamera and G6-Sababa were grouped together on small tubers produced. G8-Tyson was characterised with high NT and G7-Sifra with large tubers and DMC under Wd condition. During the tuber initiation under Wd condition (Figure 3b), G6-Sabab and G7-Sifra were grouped together based on high medium NT. G1-Bikini and G2-Challenger were grouped together based on high large tubers produced while G4-Mondial and G3-Electra produced small tubers, under Wd condition at the tuber initiation stage. G2-Challenger, G3-Electra and G4-Mondial grouped together by producing large tubers with high DMC while G7-Sifra had high yield of medium size tubers under Wd condition during the tuber bulking (Figure 3c). Under Wd condition (Figure 3d) at the maturity stage, G1-Bikini and G6-Sababa were grouped together based on high large NT whereas G4 and G5 were clustered together by producing medium tubers with high DMC.

Under Ww condition during vegetative stage (Figure 3A) genotypes G5- Panamera and G4-Mondial were grouped together based on many small tubers with a high DMC. Meanwhile G6-Sababa was characterised with high large NT and G7-Sifra with high yield of medium tubers (Figure 3A) also high DMC at tuber initiation (Figure 3B) under Ww condition. At the tuber initiation stage (Figure 3B) G1-Bikini, G2-Challenger and G3-Electra were grouped together with high yield of medium tubers while G4-Mondial, G5-Panamera and G6-Sababa were grouped together based on high small tubers produced. G8-Tyson at Figure 3B and G2-Challenger at Figure 3C (tuber bulking) was characterised with high large NT under Ww condition. During the tuber bulking under Ww condition (Figure 3C) G3-Electra and G4-Mondial were grouped together based on high medium and large tubers with DMC produced whereas G5-Panamera, G6-Sababa and G8-Tyson were grouped together based on small tubers produced. At the maturity stage (Figure 3D) under Ww condition G1-Challenger and G2-Electra were grouped together recording higher DMC. G3-Electra and G4-Mondial were grouped together based on high yield of small tubers while G6-Sababa, G7-Sifra and G8-Tyson were grouped together by producing medium and large tubers under Ww condition at the maturity stage.

Table 4.6: Principal component analysis showing eigenvalues and cumulative percent variance of all measured traits of eight potato genotypes under Ww and Wd conditions at different growth and Bi-plot.

Traits	Vegetative stage				Tuber initiation				Tuber bulking				Maturity			
	Ww		Wd		Ww		Wd		Ww		Wd		Ww		Wd	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Yield	0.12	-0.75	-0.85	0.11	0.95	0.10	0.66	0.69	0.69	0.59	0.89	0.31	-0.55	0.52	0.86	0.03
NT	0.68	0.51	-0.32	0.87	0.75	0.47	-0.17	0.97	0.84	-0.16	0.68	-0.53	0.58	0.75	0.66	0.35
Small	-0.99	-0.03	0.85	-0.31	-0.95	-0.03	0.88	-0.43	-0.96	0.22	-0.74	-0.64	-0.97	0.15	-0.79	0.40
Medium	0.98	-0.12	-0.95	0.18	0.83	-0.53	0.76	0.63	0.005	0.82	0.90	0.14	0.98	-0.11	0.27	-0.89
Large	0.10	0.92	0.59	0.69	0.50	0.78	-0.83	-0.26	0.85	-0.50	-0.21	0.72	0.86	-0.31	0.65	0.62
DMC	-0.80	0.32	0.71	0.57	-0.84	0.51	0.78	0.43	0.44	0.82	-0.80	0.45	-0.89	-0.42	0.26	-0.39
Eigenvalues variance %	51.62	30.07	56.01	28.81	6.75	2.31	52.62	38.05	5.06	3.40	5.57	2.58	6.86	1.94	4.00	2.72
Cumulative variance %	51.62	81.69	56.01	84.81	67.55	90.73	52.62	90.68	50.64	84.66	55.71	81.54	68.67	88.08	40.00	67.27

Yield = total yield; NT = Number of tubers; Small = small tubers; Medium = medium tubers; Large = large tubers; DMC = dry matter content.


A
Well watered
a
Water deficit
B
Well watered
b
Water deficit
Dim1 (51.6%)
Dim2 (30.1%)
Dim1 (56%)
Dim2 (28.8%)
Dim1 (67.6%)
Dim2 (23.2%)
Dim1 (52.6%)
Dim2 (38.1%)
large
NT
DMC
small
medium
Yield
G1
G2
G3
G4
G5
G6
G7
G8

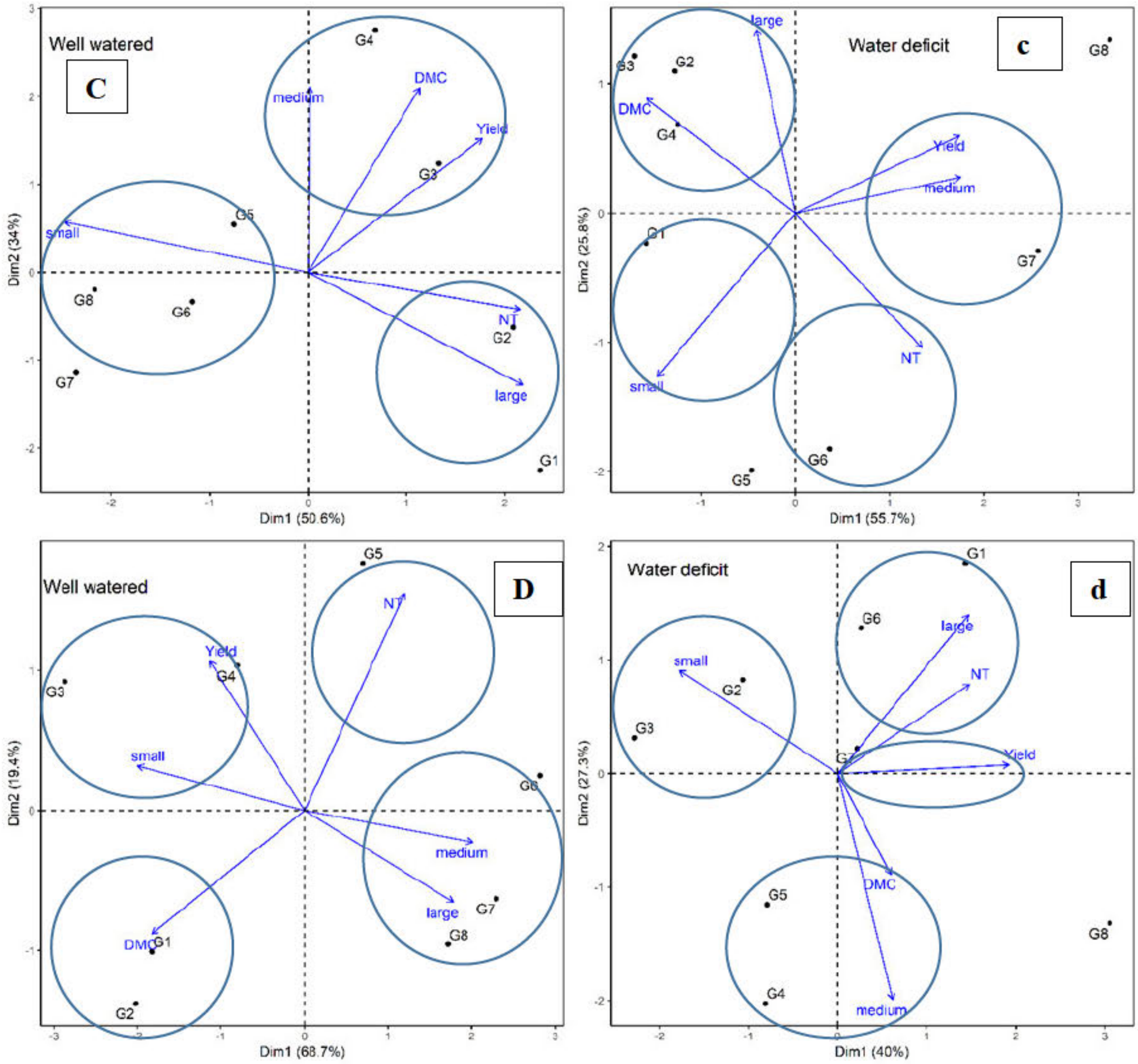


Figure 4.3: Principal component bi-plot scores of PC1 vs PC2 showing groupings of potato genotypes based on quality traits evaluated under well-watered (Ww) and water deficit (Wd) conditions. A = vegetative stage under Ww; a = vegetative stage under Wd, B = tuber initiation under Ww; b = tuber initiation under Wd; C = tuber bulking under Ww; c = tuber bulking under Wd and D = maturity under Ww; d = maturity under Wd. Yield = total yield; NT = number of leaves; Small = small tubers; Medium = medium tubers; Large = large tubers; DMC = dry matter content. G1-Bikini, G2-Challenger, G3-Electra, G4-Mondial, G5-Panamera, G6-Sababa, G7-Sifra and G8-Tyson.

4.5 Discussion

Understanding potato quality traits that play an important role in improving adaptation to low water environments is critical in the identification of drought tolerant genotypes for breeding programmes and marking industry (Carputo *et al*., 2005). Therefore, the current study assessed the response of drought tolerant potato (*Solanum tuberosum* L.) genotypes by means of quality traits under well- and water-deficit conditions to select favourable for processing industry. Genotype x water condition x growth stage interaction effect were significant for the evaluated traits signifying difference response of genotype across studied growth stages. This is useful to identify exact growth stage and select potato genotypes with better adaptation for a recommendation for processing industry (Table 3).

Quality traits such as total yield, number of tubers produced per plant, tuber size distribution (small, medium and large), dry matter content and specific gravity have been extensively used in assessing potato quality (Patel *et al*., 2008; Abong and Kabira, 2011; Al-Mahmud *et al*., 2015; Cavalcante *et al*., 2019). Reducing water supply during tuber initiation stage and tuber bulking negatively affect tuber size and number produced (Alsharari *et al*., 2007; Hirut *et al*., 2017; Rudack *et al*., 2017). Despite extensive number of tubers observed for the studied genotypes, most of them were small tubers under water deficit condition. In the current study, water deficit affected quality traits of the studied potato genotypes to various degrees (Figure 1(a–b), 2 and Table 3(a-d)). Low water supply at the tuber initiation and tuber bulking significantly reduced all studied genotype total yield and negligible effect on maturation stage across the tested potato genotypes (Figure 1(a–b)). The observation that water deficit significantly affected total yield on both tuber initiation and tuber bulking stage but not affected at vegetative stage and maturity stage, is contained in studies by Lahlou *et al*. (2003); Alsharari *et al*. (2007); Khan *et al*. (2011) and Aya (2013). These results are consistent with the findings of Alsharari *et al*. (2007) who found that water deficit imposed at 30th and 60th day after planting reduced both number and fresh tuber yield of tested genotypes.

This suggests that exposing genotypes to water deficit at the maturity stage has no much impact on total yield except tuber quality. Overall, Tyson, Electra and Sifra produced high yield throughout the growth stage, they can, therefore, be identified as tolerant genotypes to a low water supply (Figure 1(a–b). Panamera and Sababa cannot be recommended under a low water supply environment because of their sensitive response. The pot experiment during watering pots period below field capacity could have contributed to the yield reduction genotypes. Also, high soil evaporation accelerated by high temperatures (Rebetzke and Richards, 1999; Rykaczewska, 2013). According to Geofrey *et al*. (2014) when soil water drops below 65 % of the field capacity, tuber yield and quality are reduced. Metabolic imbalance of photosynthesis rate due to stomatal closure and low transpiration rate caused by water deficit at tuber initiation and tuber bulking probably contributing to low yield and fewer number of tubers (Onder *et al.*, 2005). Also, during stolon formation, water deficit restrained vegetation which resulted in a reduction of tuber numbers with effects on final yield (Deblonde and Ledent, 2001 and Tourneux *et al*., 2003b).

In the present study, dry matter content was poorly correlated with tuber size distribution (small, medium and large) under water deficit conditions, suggesting this trait contributed very little to tuber size distribution among the tested potato genotypes. A significant and positive correlation observed between dry matter content and large tubers (Table 4) under water deficit condition suggests low dry matter allocation. A negative correlation between dry matter content and large tubers (Table 4) suggested rapid accumulation rates of dry matter content in large tubers than other tuber size among the studied potato population at tuber initiation. Based on the tubers' dry matter percentage of each genotype obtained, it seems like Panamera was the most sensitive genotype whereas Tyson and Challenger were tolerant in water deficit in all growth stages (Figure 2). These results corroborate those of Solaiman *et al*. (2015); Elfnesh *et al*. (2011) who reported that dry matter content increased with the maturity of the tuber. Further reported that more time to mature means a high percentage of dry matter content provided that there's an adequate amount of water. Based on the results obtained in this study, it can be concluded that withholding water at the tuber bulking and maturity stage is detrimental to the dry matter content. It is at these stages (bulking stage and maturity) where the partitioning of sugars and dry matter content occurs (Sharma and Singh, 2009; Solaiman *et al*., 2015). High temperatures contributed to the significant decreased dry matter content in tested genotypes. Struik *et al*. (1991) stated that the thickness and the number of stems compete for assimilates and that affects tuber size distribution. Genetic and environmental factors alter the partitioning of dry matter, consequently, tuber size is also affected.

In this study, it was observed that potato genotypes responded differently in different growth stages to water deficit in terms of tuber size distribution (Table 2). Highest percentage of small tubers from Sababa, Bikini and Challenger were observed during vegetative stage and tuber initiation (Table 2a and b). These results were supported by Sharma and Singh (2009) and Abba *et al*. (2012) who reported that the highest percentage of small size tubers may be due to higher vigour of plants at the vegetative stage. Khan *et al*. (2011) indicated that planting the crop later and harvesting early, increased the number of smaller sized tubers, whereas early planting and late harvesting, resulted in a high percentage of large and medium-sized tubers. Tyson, Mondial and Sababa showed a tolerance response by producing large and medium-sized tubers, whereas Bikini and Challenger showed sensitive response by producing a high percentage of the smaller tuber at tuber also referred as baby potatoes at tuber bulking stage (Table 3c). Tuber bulking, and maturity stages were identified as a critical stage for the expansion of tubers. Therefore, factors such as planting date, environmental condition, developmental stages and harvest time attributed to the variation among genotypes in terms of the tuber size distribution of this study. Overall, genotypes such as Bikini, Mondial, Sababa and Sifra were identified and selected possessing yield promoting quality traits such as higher number of tubers per plant, medium-large size tubers and dry matter under water deficit condition (Figure 3(a-b)).

4.6 Conclusion

The study showed that water deficit has a notably effect on the growth, yield and quality of potato genotypes. The amount of irrigation increased the quantity of potato tuber but affected tuber quality. In most cases, potato traits were more affected during tuber initiation and tuber bulking stage, of which it can be identified as critical stages to water deficit. Therefore, potato growers can be advised to pay more attention during these stages when irrigating, as the crop is more prone to yield loss and poor quality. Although the response of other traits such as the number of a tuber, tuber size distribution and dry matter content are important especial for the processing industry (quality control); but genotypes recorded a higher yield are applicable ones to be grown under limited water environments. Therefore, genotypes Tyson, Sifra, Challenger and Electra can be suggested since they appeared as tolerance to water deficit at tuber initiation stage, tuber bulking and maturity stage whereas Panamera and Sababa showed to be the most sensitive water deficit in growth stages all growth stages. It is advised that more studies characterising these genotypes under water deficit are conducted to confirm the result of this study.

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Chapter 5: The effect of production site on growth, physiological and yield responses of potato (*Solanum tuberosum* L.)

5.1 Abstract

The effect of different production sites on growth, physiology and yield performance of eight potato (S*olanum tuberosum L.*) genotypes was investigated. Potato genotypes Bikini, Challenger, Electra, Mondial, Panamera, Sababa, Sifra and Tyson were grown under rain fed conditions at Ukulinga research farm (URF), Pietermaritzburg and eChibini (CB), Bamshela. The field trials, laid in randomized complete block design and replicated three times, were conducted during the summer planting season (2018/19). The studied parameters included tuber emergence percentage (up to 21 days after planting), plant height (PH), stomatal conductance (*gs*), and transpiration (Tr), photosynthesis (*A*), and chlorophyll content index (CCI). Total yield and tuber quality parameters (dry matter content (DMC) and specific gravity (SG)) were determined after harvest. Results indicated a significant difference ($p < 0.05$) among genotype and production sites with regards to emergence. Compared to genotypes that were grown at CB, there was a delayed emergence for plants planted at URF. Stunted growth between 28 and 98 days after planting was observed at URF with a range of 9.67 - 22.25 cm compared to CB with a high range of 24.42 - 41.58 cm. Potato genotypes planted at CB had a significant ($p < 0.05$) lower *gs* and Tr whereas at URF were higher in both stages (tuber initiation and tuber bulking). However, *A* and CCI were significant ($p < 0.05$) higher at tuber initiation but decreased during tuber bulking stage. Moreover, URF had higher yields which ranged from 1.218 to 2.492 t/ha where Challenger and Electra had highest yield, whereas at CB yield ranged from 1.170 to 1.478 t/ha with Tyson being the highest. A higher number of tubers (NT) were also obtained from genotypes planted at URF. Bikini and Electra had the highest DMC of 17.47 and 15.83%, respectively, while Sifra had the lowest (13.60%) at CB. Challenger and Panamera had the highest DMC of 20.66 and 19.18%, respectively, while Electra had the lowest (14.97%) at URF. Tyson, displayed the highest SG in both sites, 1.1348 g ml^{-1} at CB and 1.1043 g ml^{-1} at URF. Overall, Challenger, Tyson, Electra and Mondial showed the best environmental adaptability. Therefore, these genotypes can be recommended to smallholder farmers to their production site.

Keywords: Production sites; potato genotypes; physiological traits; chlorophyll; yield; quality.

5.2 Introduction

Potato is an important perennial, tuberous and leafy crop from the *Solanaceae* family (Zhu *et al*., 2010) and it is the leading tuber crop produced in South Africa (Chauvin *et al*., 2012). The crop plays an important role in alleviating hunger and is highly recommended for food security in most developing countries (Devaux *et al*., 2014; Hirut *et al*., 2017). The crop is nutritionally rich in carbohydrates, vitamin C, zinc, protein and iron (Sanginga and Mbabu, 2015). It also contributes to the South African economy in terms of its (3 %) contribution to the gross domestic product (Strydom *et al*., 2012). Under rain-fed conditions, potato yields are threatened by extreme temperatures, soil moisture and other factors (Hirut *et al*., 2017; Yuan *et al*., 2003).

Being a C_3 crop, potato crop is sensitive to harsh conditions like moisture stress and extreme temperatures. The optimum soil temperature for the tuber development should range between 15 ºC and 18 °C and soil pH of 5.5 to 6.0 in the lower and upper highland regions (FAO, 2018; Nyawade *et al*., 2018). High temperatures are recommended for vegetative growth while low temperature favours tuber initiation. The ideal temperature for net photosynthesis ranges from 16 - 18 ºC (FAO, 2018; Levy and Veilleux, 2007). Temperatures above 21 °C are detrimental to potato growth (Muthoni and Kabira, 2015). Soil moisture defined as the amount of water available in soil pores, which increases and decreases after rainfall or irrigation and drought. Low soil moisture at an early stage (emergence) of the crop growth period is detrimental to the yield (Nyawade *et al*., 2018). As a result, the soil moisture should not drop below 50 % to meet the crop demand (FAO, 2008b). The combination of high temperatures and low soil moisture decreased potato yield and quality (Muthoni and Kabira, 2015).

In South Africa, potatoes are cultivated under both dryland and irrigated conditions in 16 different agronomic regions. It is widely planted in highland tropics and sub-tropics with short summer days, lowland temperate regions with long summer days, and lowland sub-tropics with shorter winter days (Bradshaw *et al*., 2006). Cool temperate regions with humid climate ensure optimum growth whereas insufficient rainfall or inadequate irrigation reduces crop production (Maralian *et al*., 2014). Many factors have led to a decrease in potato production (Kiptoo *et al*., 2018). These factors influence crop physiological mechanisms such as photosynthesis, transpiration and respiration processes. Consequently, low yield and poor tuber quality are produced (Liao *et al*., 2016). Van Zyl and van der Westhuizen (2018) reported that drought significantly reduced potato yield in Eastern Free State and KwaZulu-

Natal (KZN) regions, by 12.5 and 4.5 t/ha, respectively. On the other hand, Mangani *et al*. (2015) reported that different potato spacing in a field affects crop development, tuber yield and quality. Getachew *et al*., (2012) conducted a study on the influence of early and late earthing-up on potato yield. Their findings demonstrated that early earthing-up improves potato yield. A study by Rosen *et al*., (2014) reported that fertilizer plays a vital role in plant growth, cell division, photosynthesis and respiration. Overall, these findings indicate that a combination of cultural practices and environmental conditions have an enormous effect on potato yields. There have been limited studies conducted that identify suitable potato genotypes and cultural practices for different production sites in the KZN region. Therefore, the lack of information may result in potato growers planting inappropriate genotypes to certain production sites.

The province of KwaZulu-Natal is located on the eastern seaboard of the country is a subtropical region, with a summer rainfall of 600 - 2 000 mm/annum (Steyn *et al*., 2009). The province has a diverse climate, topography and soils (Joubert, 2012). Its soils range from sandy loamy, loam to clay-loam soils (Steyn *et al*., 2009). Potato cultivation takes place during August when temperatures range from 12.9 and 24.3 ºC (Steyn *et al*., 2009). Naidoo, (n.d) in association with the department of agriculture and environmental affairs, tested potato genotypes (including Mondial and Sifra among those genotypes) at different sites (Nyangweni and Ndwedwe) in KZN regions to determine their adaptability and potential production under smallholder farmers' management practices. The author reported that uneven irrigation affected potato yields at Nyangweni, especially for Sifrain the 2010 season. But in 2011, the potato yields greatly improved due to reliable irrigation. All genotypes planted at Ndwedwe site had high yield compared to Nyangweni site. The researcher concluded that Mondial and Sifra can be recommended for smallholder farmers because of their adaptability, rapid tuber initiation and high yield.

It is important to evaluate the adaptability of potato genotypes to various production sites. Such information will enable potato growers to select the best suitable genotypes, the production site and management practices that can be employed to ensure high yield. It was hypothesized that location has no effect on potato growth and yield. Hence, the specific objective of this study was to evaluate potato growth, physiological parameters, yield and tuber quality of different potato genotypes grown under different production sites (Ukulinga and eChibini) of KwaZulu-Natal.

5.3 Materials and methods

5.3.1 Potato tuber description

Eight certified potato tubers (i.e. generation 1-3) namely: Bikini (G1), Challenger (G2), Electra (G3), Mondial (G4), Panamera (G5), Sababa (G6), Sifra (G7), and Tyson (G8) were sourced from Wes grow Pretoria, South Africa and used for the study. These are highly demanded and newly introduced genotypes for potato the industry in South Africa, hence selected for evaluation. These genotypes were propagated using sprouting stimulated for three weeks.

Table 5.1: The description of potato genotypes used in this study.

Genotypes	Sourced	Generation	Maturity period
Bikini	Wes grow	G1	Early maturity
Challenger	Wes grow	G3	Medium late
Electra	Wes grow	G1	Early maturity
Mondial	Wes grow	G3	Late maturity
Panamera	Wes grow	G3	Medium
Sababa	Wes grow	G1	Medium
Sifra	Wes grow	G3	Late maturity
Tyson	Wes grow	G2	Medium

G: Generation; Maturation period: early = less than 90, medium = 90-110 and late = 110-150 days (The British Potato Variety Database, 2014; Hettema and ZPC HZPCa,b & c, 2018).

5.3.2 Site descriptions

Field trials were carried out at two different sites, under open field conditions; Ukulinga Research Farm (URF), Pietermaritzburg and eChibini area (CB), Bamshela during the rainy season (December-June, 2018/2019). The trial at URF was planted on the 7th of January 2019 and harvesting was done on the 14th of May 2019. On the other hand, the trial at CB was planted on the 11th of January 2019 and harvested on the 19th of April 2019. The two sites selected for the study were representative of two distinct agro-ecologies (BRGs) of KZN (Table 3.2). Bio-resource group's information general based on different site climate and vegetation dominant species found in the sites (Smith, 2006).

5.3.3 Experimental design and agronomic practices

The two experiments were laid out in a randomized complete block design replicated three times. A total area of 313.1 m^2 field made up of 8.1 m^2 in size (3×2.7 m) single plot with intra-spacing and inter-spacing of 0.3 x 0.9 m, respectively. Each plot had three of 3-meter rows and 10 plants per row. Each plot contained 30 plants which made a total of 720 plants in 24 plots. Sites and potato genotypes were the main factors that were considered.

Prior to land preparation, soil samples were taken for soil fertility and textural analyses. At URF, land preparation involved mowing the weeds, ripping, tilling and discing to achieve fine soil particles. The crop was grown under dryland conditions with no supplementary irrigation. Land preparation at CB only included tilling and disking. The organic fertilizer composed of nitrogen (N), phosphorus (P) and potassium (K) at rate 164:32:16 kg ha^{-1} (N:P:K) was applied based on the results of soil fertility analyses of each site. According to the local (CB) farmers' knowledge, no supplementary irrigation is required for the period of crop growth. Planting rows from both sites were opened with a hand-hoe followed by (NPK) organic fertilizer slightly buried with soil before aligning ten seed tubers in a three-meter row (avoiding tuber being in contact with the fertilizer) and one meter (row) apart. Periodic weeds and earthing-up were done by hand-hoeing.

Table 5.2: Experimental site description for Ukulinga Research Farm and eChibini, Bamshela.

Description	**Ukulinga research farm**	**eChibini**
Geographic sites	29° 29'S, 30° 92' E	29° 29'S, 30° 92' E
Altitude range (m.a.s.l)	1 400 - 1 800 m	900 - 1 400 m
Bio-resource group (BRU)	Moist highland sourveld	Warm moist grassveld
Annual rainfall (mm)	800 - 1 265 mm	800 - 1 280 mm
Mean annual temperature (°C)	14.1 °C	17.1 °C
Frost amount	Moderate frost	Light and occasional
Soil texture	Clay loamy soils	Sandy loam soils
Clay content (%)	32 %	26 %

*Soil Classification, a Taxonomic System for South Africa 1991; y Metres above sea level. z Values of soil water content are in percentage of volumetric water content (Smith, 2006).

5.3.4 Data collection

Plant development and plant physiology data were collected every two weeks in both sites. Data collection included emergence %, plant growth, time to flowering, leaf physiology, total yield, number of tubers, dry matter and specific gravity.

5.3.4.1 Tuber emergence percentage

Potato emergence rate is the percentage of tubers that emerge over the period of time (7, 14 and 21 DAP). Emergence percentage was recorded up to 21 days (Getachew *et al*., 2012). The following formula was used to calculate the emergence rate:

$$\text{Emergence rate (\%)} = \frac{\text{Number of tubers emerged}}{\text{Total number of tubers in a row}} \times 100$$

5.3.4.2 Plant growth and leaf physiological response

Plant height was measured by a ruler from the base to the second youngest fully-formed leaf. This average of randomly selected four plants, from each genotype, was determined. Time to flowering were determined from the beginning of flowering from each genotype to the end. Stomatal conductance, transpiration, photosynthesis and chlorophyll content index (CCI) were determined at two weeks interval. Stomatal conductance, transpiration and photosynthesis were determined simultaneously using the LI-6400 XT Portable Photosynthesis System (Licor Bioscience, Inc. Lincoln, Nebraska, USA) measured from a fully developed leaf. Chlorophyll content index was measured on the adaxial surface of the second youngest fully formed, fully unfolded leaf using a SPAD 502 chlorophyll content meter (Minolta, USA).

5.3.4.3 Determination of total yield and number of tubers per plant

The yield was determined according to Solaiman *et al*. (2015) with some modifications. At physiological maturity, four plants from the middle-center row randomly selected of each 8.1 m^2 plot in each replication and genotype were harvested and the tubers weighed immediately. The following formula was used to calculate the tuber yield.

$$\text{Tuber yield (t ha}^{-1}) = \frac{\text{Yield (kg m}^{-2}) \times 10000\ \text{m2}}{1000\ \text{kg}}$$

At harvest, the average number of tubers per plant was physically counted from four plants in each genotype randomly selected from each plot according to Khan *et al*. (2018) with some modification.

5.3.4.4 Determination of dry matter content

Dry matter content was determined according to Bekele and Haile, (2019) using 200 g of fresh sample tubers. The fresh sample was chopped into small pieces to accelerate the oven drying process. Dry weights were determined by the oven to dry chopped samples at 70 ^{o}C for 72 hours and re-weighed at 65 ^{o}C till constant weight obtained. The dry matter content was calculated as a percentage of dry weight over fresh weight (g). Dry matter content (%) was determined using the following equation.

Dry matter content (%) $= \frac{\text{Dry weight}}{\text{Fresh weight}} \times 100$

5.3.4.5 Determination of specific gravity

The specific gravity was determined according to Steyn *et al*. (2009) with some modifications. Washed potato tubers of 250 g (weighed in the air) were randomly taken from each genotype and plot in both locations. Tubers were measured using weighed in air (Ma) and water (Mw) method. The specific gravity of tubers was determined using the following formula.

Specific gravity (gml^{-1}) $= \frac{\text{Ma}}{\text{Ma}-\text{Mw}}$

5.3.5 Data analysis

Data were subjected to analysis of variance (ANOVA) using GenStat (Version 18, VSN International, UK) and the significance of the difference between means was determined using the Least Significant Difference (LSD) at 5% level of significance. The replications and blocks were treated as fixed factors whereas genotypes, water regimes and their interactions were considered as random factors.

5.4 Results

5.4.1 Emergence percentage

Emergence percentage results showed a highly significant ($p < 0.001$) difference among genotypes, production sites and time to emergence. Interactions between genotypes and emergence; production sites and emergence days were also highly significant ($p < 0.001$). Genotypes and production sites (URF and CB) were significant ($p < 0.05$). Interaction between genotypes, production sites and emergency days did not have a significant influence on emergence percentage (Figure 5.1). There were no significant differences among genotypes at seven days after planting in both sites. There was a delay in genotypes planted at URF while those grown at CB shown a greater emergence % for all genotypes except for Panamera. Emergence percentage at 14 days after planting ranged from 8.82 to 52.22 % at CB while at URF emergence percentage ranged from 16.67 to 52.22 % after 14 days of planting. Genotype Bikini had significantly higher emergence % followed by Tyson and Electra whereas the lowest was recorded for Panamera and Mondial at CB after 14 days of the plantation. At URF both Panamera (16.67 %) and Sifra (18.89 %) recorded the lowest % while Challenger and Sababa had the highest emergence percentage of 52.22 and 48.89 % respectively.

At 21 days after planting, the emergence percentage varied significantly between 22.22 % (Panamera) and 92.22 % (Electra) among genotypes at CB while URF had an emergence percentage ranged from 26.67 % (Panamera) to 66.67 % (Tyson) (Figure 5.1). All genotypes at CB site recorded higher emergence > 60 % (except Panamera). At URF Panamera and Sifra were affected by the site as they had the lowest emergence % compared to other genotypes.

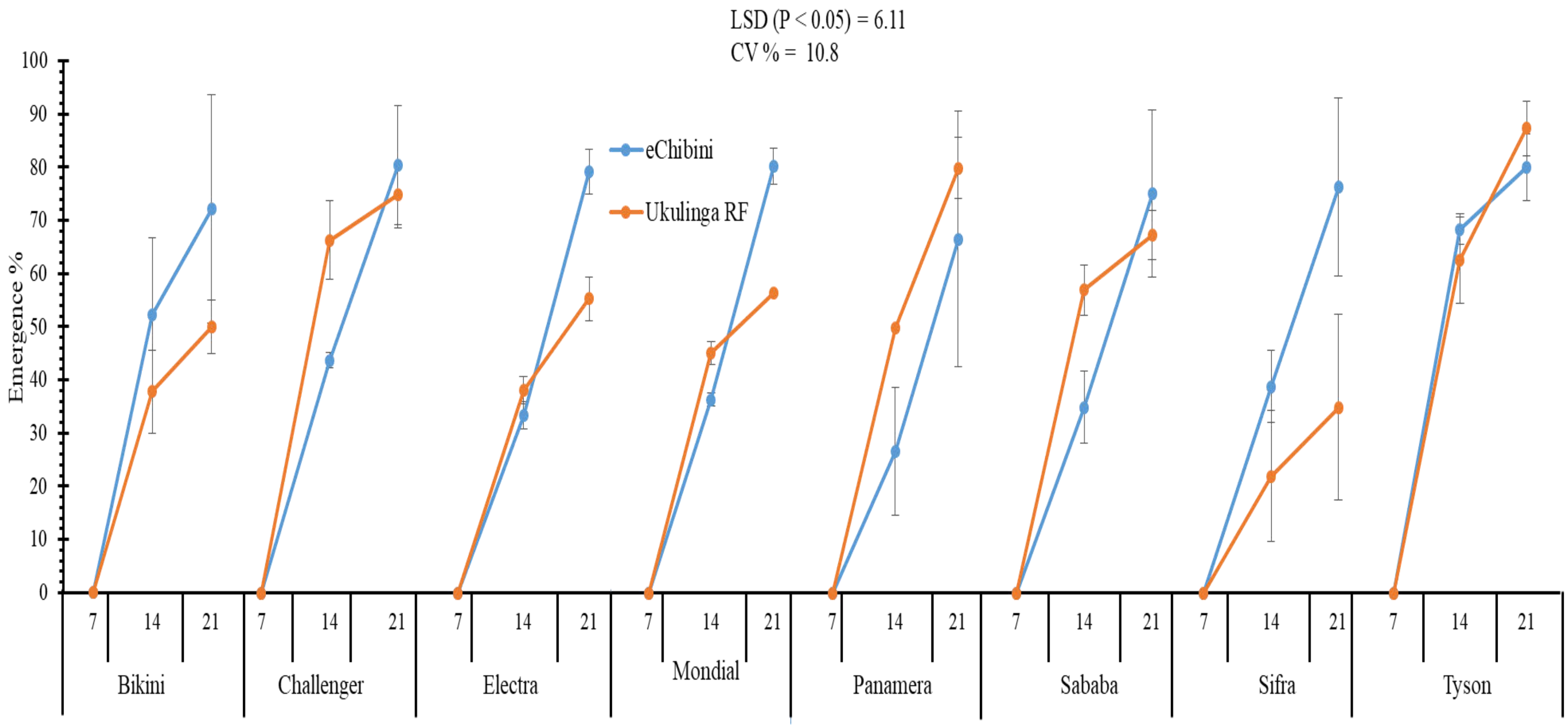

Figure 5.1: Effects of the interactions between genotypes and time to emergence; production sites and emergence days ($p < 0.001$), production sites (Ukulinga Research Farm, URF and eChibini, CB) and genotypes ($p < 0.05$) after 7, 14 and 21 days of planting. The interaction of pooled factors had insignificant ($p > 0.05$) effect on the emergence percentage. Data was analyzed using the Least significant difference (LSD) at 5% level of significance to determine mean values of emergence percentage of eight potato genotypes.

5.4.2 Plant height

The plant height (PH) of potato genotypes was significantly ($p < 0.001$) influenced by the interaction between genotypes, time and production site. Genotypes and time also showed a significant interaction ($p < 0.001$; Table 5.3). The significant interaction between genotypes and production site might be explained by higher PH at CB than at URF after 28 days after planting (DAP). This was expected since CB had a faster emergence percentage compared to genotypes grown at URF. Genotypes Bikini, Sifra and Mondial recorded lower PH while Panamera, Tyson and Electra showed significantly higher PH at URF. The genotypes at CB had significantly higher PH where Tyson and Electra were the tallest while Sifra and Bikini were the shortest. At 98 DAP (Table 5.3) the interaction between genotypes, time and production site influenced genotypes at URF where Sifra and Challenger were highly affected whereas Panamera and Mondial were unaffected. At CB Panamera and Mondial showed stunted growth and the rest of genotypes had >50 cm PH.

Table 5.3: Different production sites (URF and CB) effect on plant height for eight potato genotypes, the pooled data of interaction for genotypes, time and production sites showed significant.

Genotypes	Plant height (cm)			
	28 DAP		98 DAP	
	URF	CB	URF	CB
Bikini	14.58^{b}	24.42^{de}	48.08^{ab}	56.50^{cde}
Challenger	21.58^{c}	28.42^{f}	45.33^{a}	60.17^{de}
Electra	20.83^{c}	35.33^{g}	51.67^{bc}	67.42^{f}
Mondial	9.67^{a}	35.00^{g}	55.00^{cd}	49.17^{ab}
Panamera	14.42^{b}	41.58^{h}	60.58^{e}	48.00^{ab}
Sababa	22.25^{cd}	28.83^{f}	47.67^{ab}	59.33^{de}
Sifra	17.08^{b}	25.58^{e}	45.08^{a}	55.17^{cd}
Tyson	20.75^{c}	35.75^{g}	52.75^{bc}	58.75^{de}
p-value	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
l.s.d	2.560	2.560	4.741	4.741
s.e.d	1.297	1.297	2.402	2.402
c.v	1.5	1.5	1.3	1.3

Note: Means in a column and treatment group followed by the same letter are not significantly different from each other using the Least significant difference (LSD) at 5% level of significance, sites; URF, Ukulinga research farm; CB, Chibini, Bamshela; DAP, Days after planting; *p*-value = Significance of interaction between treatment x genotype; SE, standard error deviation; CV, Coefficient of variation.

5.4.3 Stomatal conductance and transpiration rate

The results showed that the environmental condition (Table 5.2) highly affected potato genotypes stomatal conductance (*gs*) during the initiation and tuber bulking stage (Figure 5.2). Highly significant differences ($p < 0.001$) were observed between production sites. The interaction between genotypes and production sites showed significant differences ($p < 0.05$) also genotypes and production site revealed significant differences, but the interaction between genotypes, the production site and the stage were insignificant ($p > 0.05$). Comparing both production sites genotypes at URF recorded high *gs* than CB during tuber initiation as well tuber bulking stage. Chibini *gs* during tuber bulking it was highly affected by the environmental condition. The high annual temperature during the day and drizzling afternoon could be one of the factors in lowering *gs* at CB. All genotypes maintained similar *gs* ranging from 2.09 to 2.18 molH_2O $m^{-2}s^{-2}$ during tuber initiation but it gradually decreased at the tuber bulking stage where Challenger (1.2768 molH_2O $m^{-2}s^{-2}$) was highly affected followed by Panamera (1.2943 molH_2O $m^{-2}s^{-2}$). Genotypes planted at URF also recorded similar *gs* ranging from 2.18 to 2. 34 molH_2O $m^{-2}s^{-2}$) during tuber initiation but Electra (2.18 molH_2O $m^{-2}s^{-2}$) and Mondial (2.21 molH_2O $m^{-2}s^{-2}$) were affected since they recorded lower values whereas Panamera (2.34 molH_2O $m^{-2}s^{-2}$) followed by Sifra (2.29 molH_2O $m^{-2}s^{-2}$) had higher values.

Highly significant differences ($p < 0.001$) among genotypes and production sites at tuber initiation and tuber bulking were also observed with respect to the transpiration rate (Figure 5.3). Significant differences were also recorded in the interaction between production site, treatment and stage. As expected, genotypes planted at URF recorded a higher Tr throughout compared to those grown at CB due to high *gs*. At tuber initiation, genotypes planted from URF recorded a higher Tr > 24.48 mmol H_2O $m^{-2}s^{-1}$. Electra and Mondial had lower Tr during tuber initiation in both sites. Higher Tr was recorded for Panamera, (32.71 mmol H_2O $m^{-2}s^{-1}$) and Tyson (33.28 mmol H_2O $m^{-2}s^{-1}$) during tuber initiation, Sifra (41.27 mmol H_2O $m^{-2}s^{-1}$) and Sababa (37.05 mmol H_2O $m^{-2}s^{-1}$) during tuber bulking at URF while at CB was observed for Challenger(29.82 mmol H_2O $m^{-2}s^{-1}$) and Sifra (29.61 mmol H_2O $m^{-2}s^{-1}$) during tuber initiation, Sababa (28.55 mmol H_2O $m^{-2}s^{-1}$) and Tyson (27.72 mmol H_2O $m^{-2}s^{-1}$).

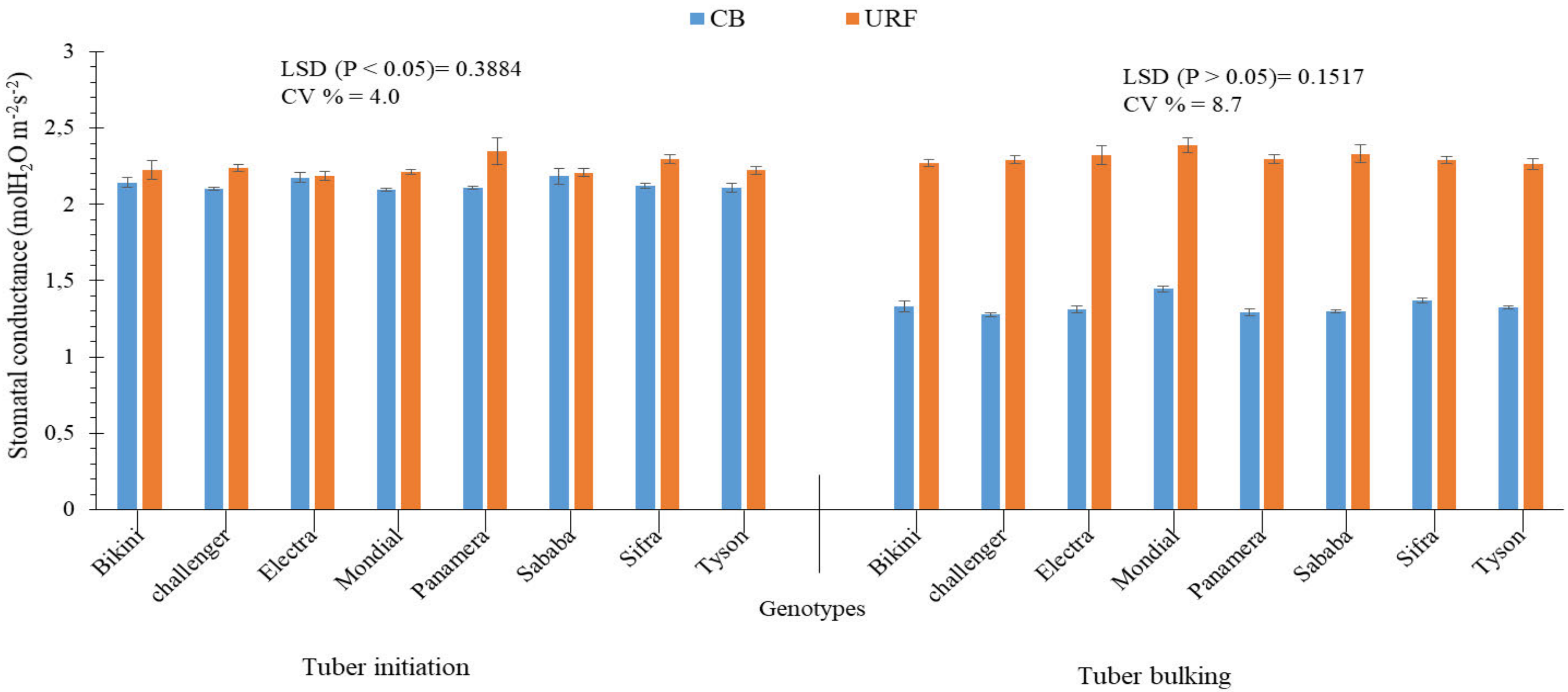

Figure 5.2: The effect of different production sites (CB and URF) on tuber initiation and tuber bulking stage on the stomatal conductance.

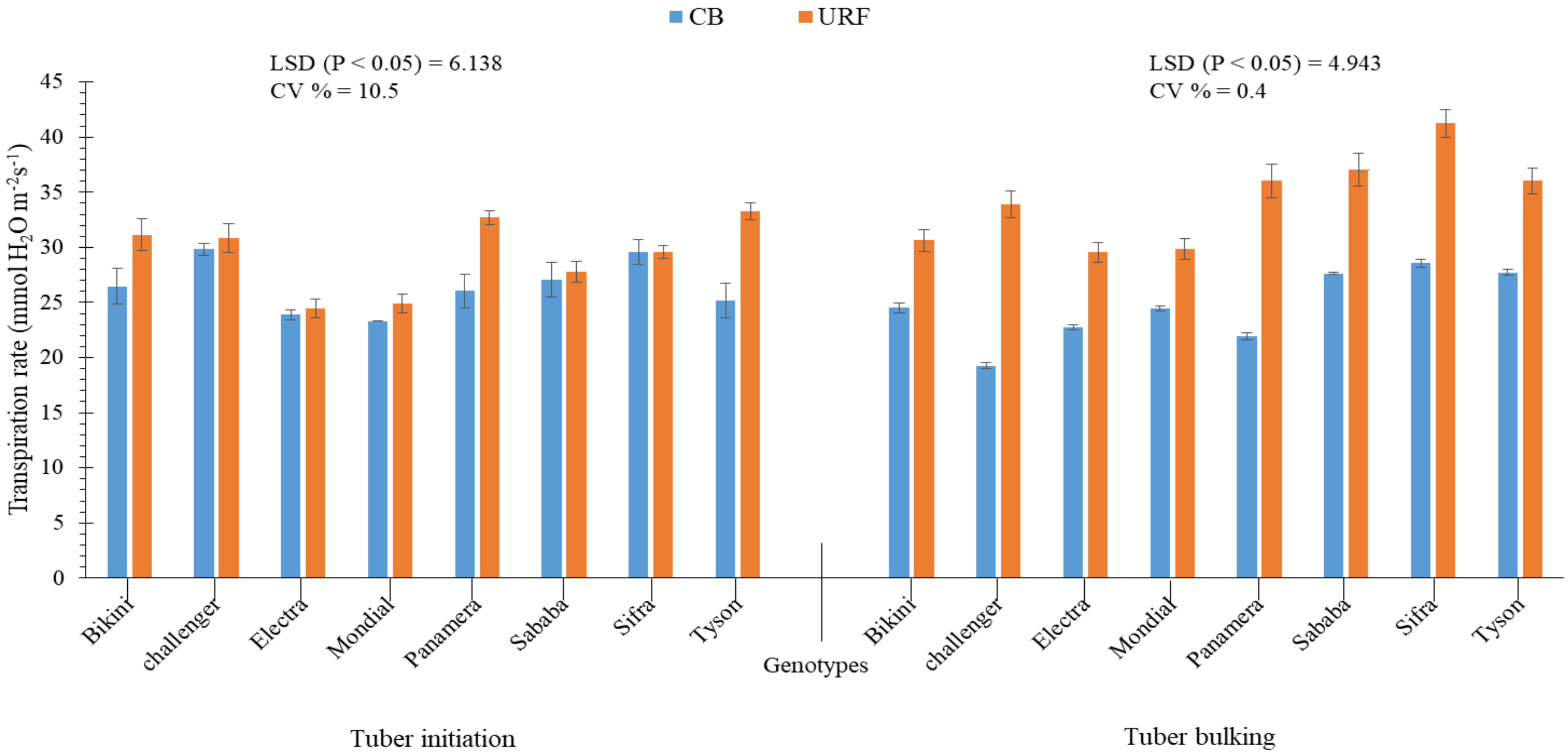

Figure 5.3: The effect of different production sites on potato genotypes transpiration rate during tuber initiation and tuber bulking stage.

5.4.4 Photosynthetic rate (*A*) and Chlorophyll content index (CCI)

Ukulinga research farm (URF) and CB revealed highly significant ($p < 0.001$) differences for both parameters (A and CCI) presented in figure 5.4 and 5.5. The photosynthesis rate (*A*) showed significant ($p < 0.05$) differences among genotypes (Figure 5.4). The interaction between genotypes, time and production sites revealed significant ($p < 0.05$) differences. Highly significant ($p < 0.001$) differences were observed in the interactions between production sites and genotypes. The *A* rate of genotypes at CB recorded high values than others grown at URF during the tuber initiation stage, however, it decreased during tuber bulking while the ones at URF increases. Genotypes at CB Bikini and Sifra showed higher *A* in both stages whereas Challenger (30.86 $\mu molCO_2m^{-2}s^{-1}$) started with higher *A* during tuber initiation and decreased to 19.26 $\mu molCO_2m^{-2}s^{-1}$ at tuber bulking. Mondial (22.59 $\mu molCO_2m^{-2}s^{-1}$) and Electra (22.96 $\mu molCO_2m^{-2}s^{-1}$) at tuber initiation had lower *A* but increased to 24.46 and 24.71 $\mu molCO_2m^{-2}s^{-1}$ respectively, during tuber bulking at CB. Genotypes at URF during tuber initiation recorded *A* ranging from 13.74 to 19.65 where Challenger had the lowest value while Panamera recorded the highest value. During tuber bulking all genotypes recorded $A > 30$ $\mu molCO_2m^{-2}s^{-1}$ except Electra (28.60 $\mu molCO_2m^{-2}s^{-1}$).

Chlorophyll content index (CCI) differed significantly ($p < 0.05$) among potato genotypes presented in Figure 5.5. The interactions between the production site and genotypes were highly significant ($p < 0.001$). Genotypes planted at CB recorded the highest CCI compared to genotypes at URF at tuber initiation (Figure 5.5). However, during tuber initiation at CB Sifra (38.32 %), Sababa (38.15 %) and Panamera (37.25 %) also at URF Sifra (24.33 %), Bikini (25.65 %) and Tyson (25.95 %) recorded lower CCI. The higher CCI at CB was obtained for Bikini (45.37 %) and Mondial (45.6 %) while at URF was recorded for Panamera (33.08 %) and Electra (33.53 %) during tuber initiation. During the tuber bulking stage, the CCI for Panamera and Tyson was slightly lower at URF while Sababa and Tyson were affected at CB. Genotypes Electra and Mondial had lower CCI at URF while at CB Sifra and Mondial recorded higher CCI. It was notable that, both sites reduced CCI for Sifra's during tuber initiation, while Tyson affected during tuber bulking. Panamera was affected in both sites (URF and CB) since they showed lower CCI while Challenger, Mondial and Sababa appeared to be sensitive to CB environment.

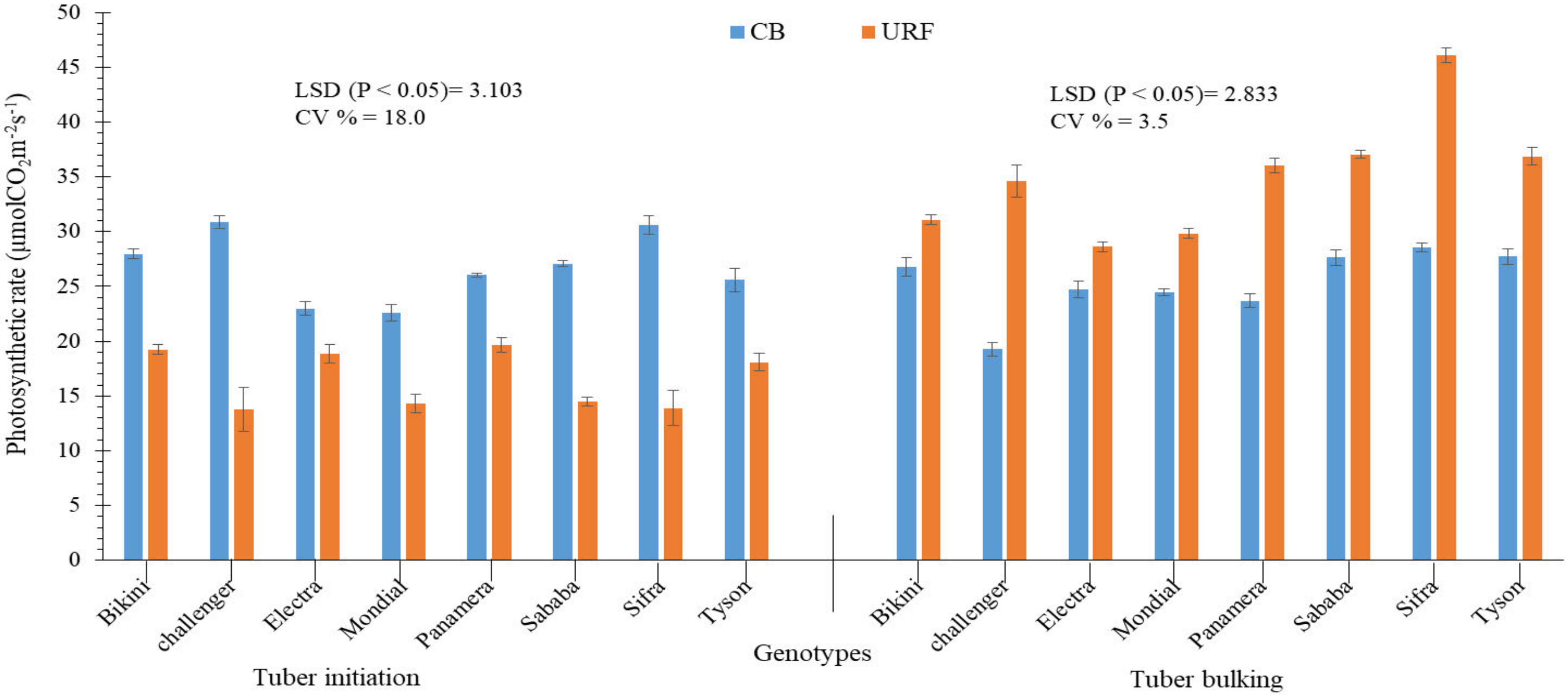

Figure 5.4: The rate of photosynthesis during tuber initiation and tuber bulking stage of potato genotypes grown at different production sites.

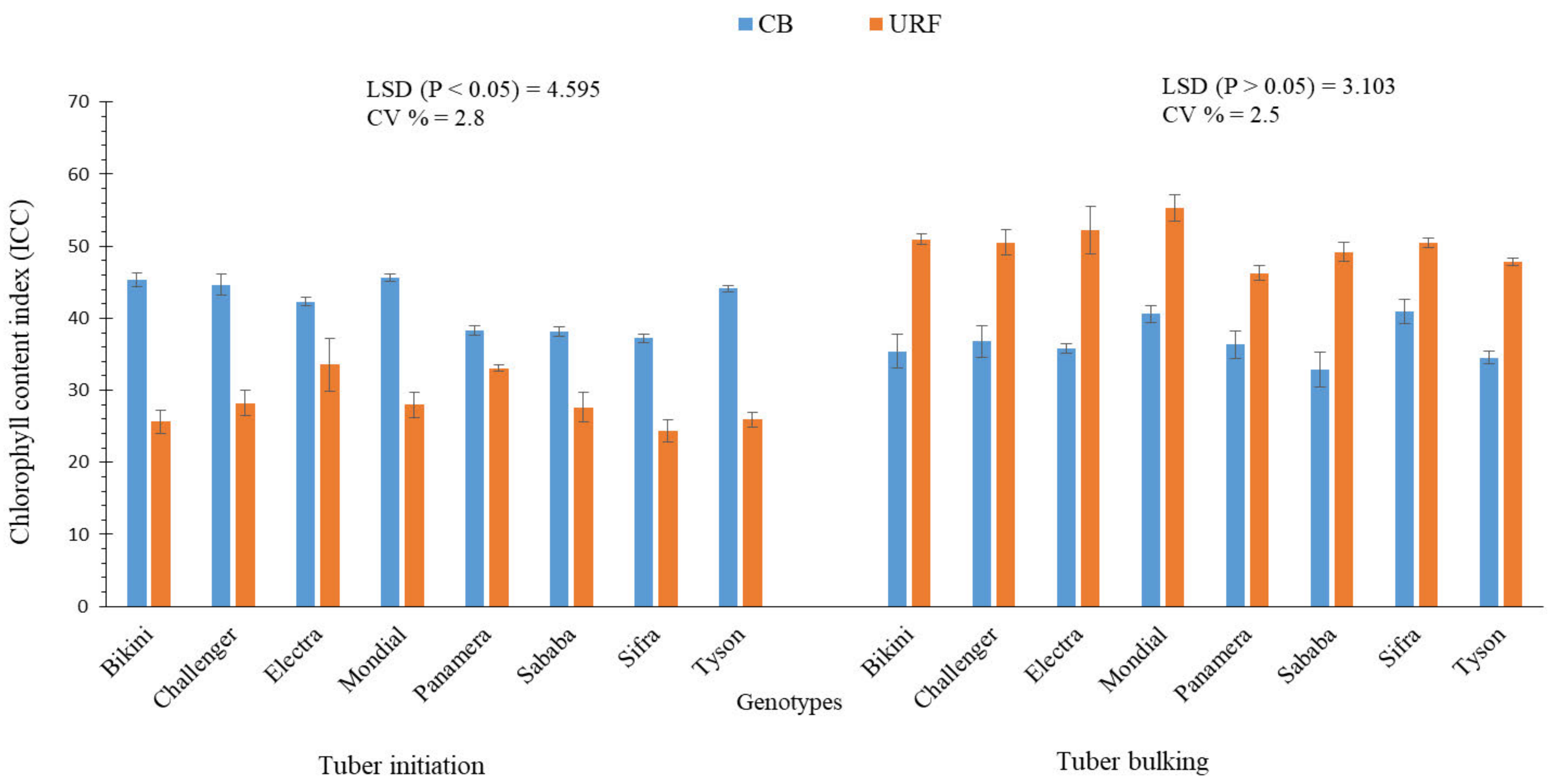

Figure 5.5: The influence of production sites on chlorophyll content index (CCI) during tuber initiation and tuber bulking stage of potato genotypes grown under rainfed conditions (CB and URF).

5.4.5 Potato yield

Significant differences were observed among the genotypes with regards to yield at two production sites (Figure 5.6). Interactions between production sites and genotypes were also highly significant ($p < 0.011$). Genotypes had highly significantly ranged from 1.170 to 2.478 t/ha from both site production. The yield at URF 1.218 to 2.492 t/ha whereas at CB yield ranged from 1.170 to 1.478 t/ha. The genotypes Challenger (2.492 t/ha), Electra (2.302 t/ha) and Tyson (2.099 t/ha) showed the best performance than Bikini (1.218 t/ha), Mondial (1.273 t/ha) and Panamera (1.411 t/ha) at URF. At CB, Electra (1.478 t/ha), Tyson (1.336 t/ha) and Sababa (1.301 t/ha) produced higher yield than Panamera (1.170 t/ha), Challenger (1.177 t/ha) and Sifra (1.188 t/ha). Electra, Tyson and Sababa best performed in both sites whereas Panamera, Sifra and Mondial affected in both production sites.

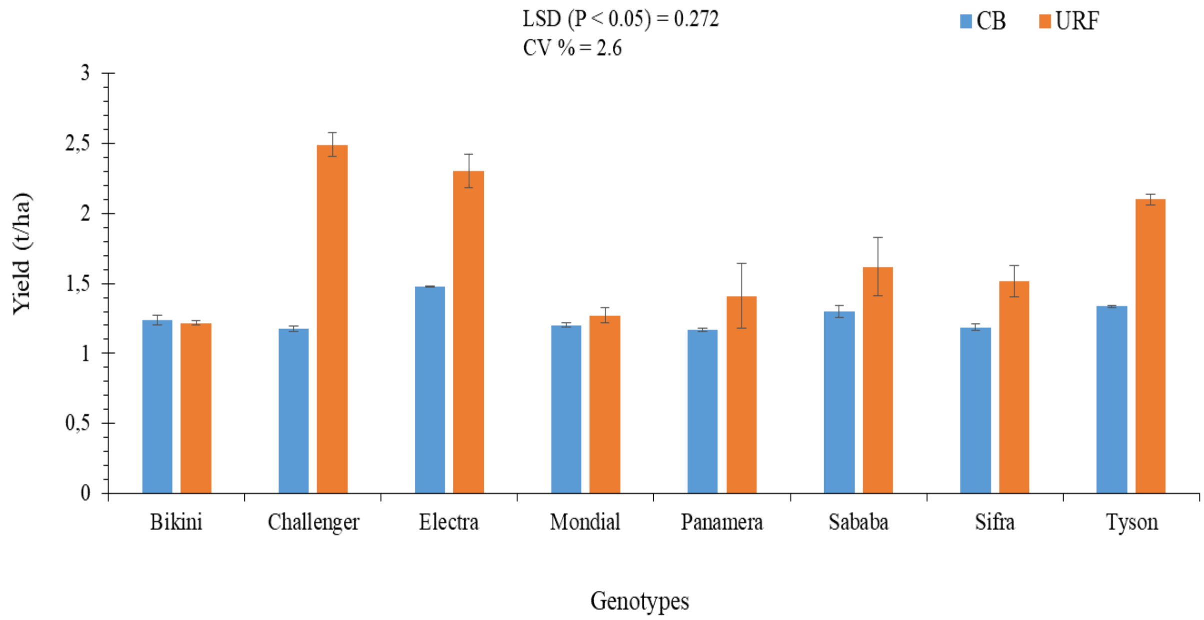

Figure 5.6: Effect of a different production site on the total yield of potato genotypes obtained from CB and URF.

5.4.6 Number of tubers

The number of tubers (NT) varied significantly ($p < 0.05$) across production sites and among genotypes (Figures 5.7). Interactions between production sites and genotypes had a highly significant ($p < 0.001$) effect on the NT. The highest NT were produced per plant at URF, with a range of 5.00 to 8.00, while at CB ranged from 2.00 to 5.00. In both production sites, genotype Mondial had significantly ($p < 0.001$) higher NT than Panamera at CB and Sifra at URF (Figures 5.7). Challenger and Tyson had a higher NT compared to other genotypes. It was noted that Mondial and Electra best recorded the highest NT in both sites while Sababa was affected in both sites by producing the lowest NT.

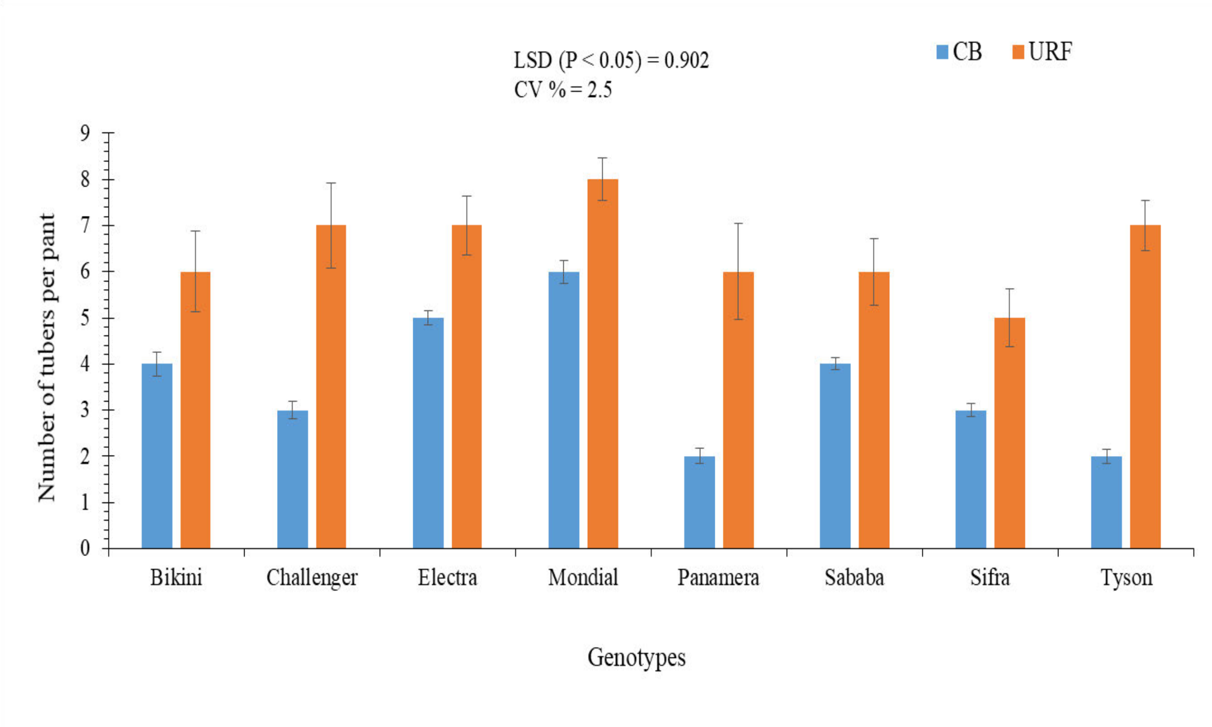

Figure 5.7: The effect of production sites on a number of tubers obtained from each genotype produced at URF and CB.

5.4.7 Dry matter content (%)

The interaction between genotypes and production sites showed a significant difference with Challenger and Panamera displaying a significantly higher DMC (20 and 19.18%) when compared to the other genotypes at URF (Figure 5.8). The dry matter percentage obtained at CB genotypes had a DMC percentage ranged from 13.71 to 17.47% with Sifra displaying a significantly lower DMC (13%) when compared to higher Bikini and Electra (17.47 and 16.00%).

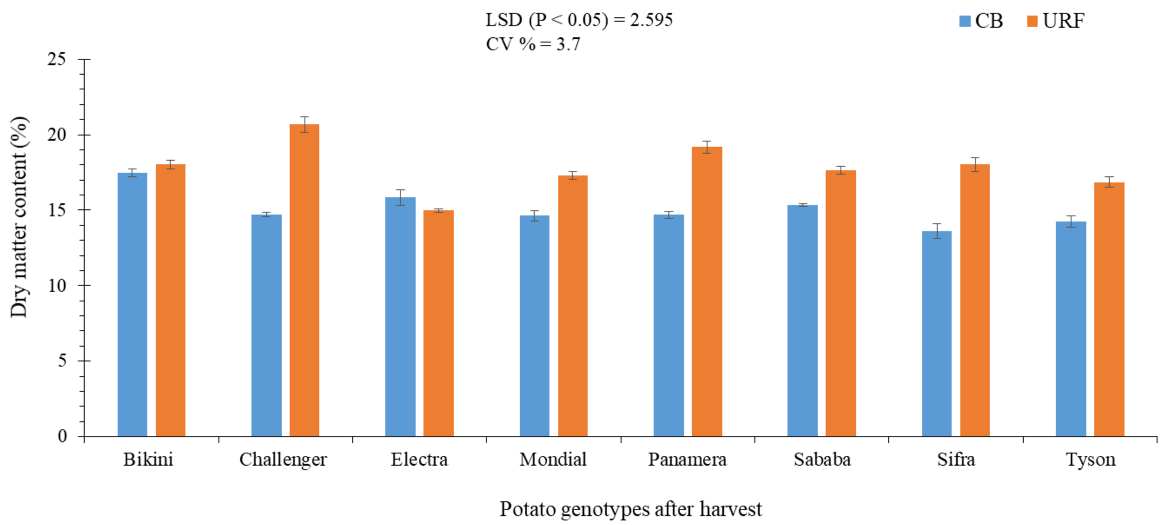

Figure 5.8: The influence of different production sites on tuber dry matter content of potato genotypes.

5.4.8 Specific gravity

Specific gravity varied significantly ($p < 0.05$) among genotypes. The interaction between production and genotypes was significant ($p < 0.05$) (Figure 5.9). The range of specific gravity (gml^{-1}) 1.0416 to 1.1043 gml^{-1} tubers harvested at URF and 1.0251 to 1.1348 gml^{-1} from tubers harvested at CB. Challenger and Sifra had higher SG in both production sites whereas Bikini, Sababa and Electra (1.0251 gml^{-1}, 1.0391 $gml^{-1}$and 1.048 gml^{-1}, respectively) recorded lowest SG at CB. The lowest SG at URF was observed for Bikini (1.0416 gml^{-1}) and Electra (1.0445 gml^{-1}).

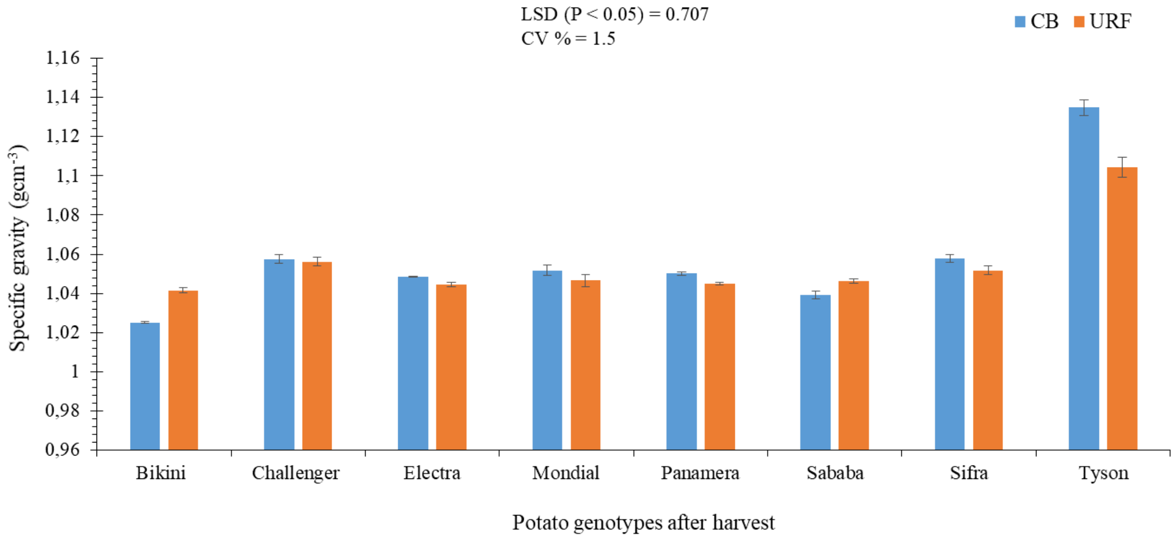

Figure 5.9: The effect of production sites on the specific gravity of potato genotypes produced at URF and CB.

5.5 Discussion and conclusion

Change in climatic conditions (Table 5.2) at the URF and CB production sites had a significant effect on plant height, physiological traits, growth stages, yield and quality. High clay content at URF might have contributed to the root stress which reduces nutrients uptake, leading to delayed plant growth. On the other hand at CB sufficient soil moisture for growth attributed to better plant growth as an indication of nutrients availability. Khanal *et al*. (2014) and FAO, (2018) reported that temperatures below 15 °C (Table 5.2) and above 18 °C influence plant development while below 10 °C causes little growth. This could have been the main cause for the stunted plant growth at URF whereas at CB high photoperiod improved genotypes vegetative growth.

During tuber initiation, genotypes stomatal conductance were high in both production sites (Figure 5.2). It started to decrease at CB as the crop moved into the tuber bulking stage which automatically reduced the transpiration rate while at URF increased for most genotypes (Figure 5.3). At these stages coincided with increased demand for water by the crop, since many leaves were transpiring, therefore the crop had to regulate stomata by closing it. Stomatal closure is an indication of a water stress avoidance mechanism by a crop, however, it also decreases carbon dioxide (CO_2) intake from the atmosphere (Chaves *et al*., 2002). The unavailability of CO_2 affects the photosynthesis rate since it is the key substrate.

Environmental conditions such as sandy soils with low water holding capacity and high temperatures create a drought stress condition, as a result, crops lower stomatal conductance and CCI in response. This was evident at CB where grown genotypes recorded low values of stomatal conductance, CCI and photosynthesis during tuber bulking and this translated into low yield compared to URF (Figure 5.4 & 5.5). The difference in maturity period (Table 5.1) of genotypes contributed to the flux in photosynthesis also planting season.

Further observation that explained the low stomatal conductance, photosynthesis and CCI recorded at CB is a loss of water through the porous soil due to the poor holding water capacity of the sandy soil (Table 5.2). Even though the environment has sufficient annual temperature, but soil became problematic. Usually, crops grown in kind of soils can simply experience water deficit despite significant rainfall, much water is drained away from the root crop. Osakabe *et al*. (2014) reported that the decrease in stomatal conductance affirms the closely related to the availability of soil water content.

The genotypes grown at URF had higher stomatal conductance and CCI which suggests that photosynthesis was not limited. As a result, the leaves showed green pigment with no signs of chlorosis. This advocated that there was adequate soil water to meet crop demands for growth and evaporative even though plant height was slow compared to CB (Table 5.2). This observation stresses the important role played by temperatures during planting dates at the growth stage of potato crop (DAFF, 2015). The variations brought by climate change also emphases the importance for small-scale farmers to stay vigilant about their environmental conditions before the beginning of planting seasons to adjust their planting date based on the environmental conditions. For example, genotypes seemed to be adaptive at URF than URF based on the total yield obtained.

Potato genotypes with high dry matter content and specific gravity content (> 1.08 g ml^{-1}) are targeted for processing, particularly when frying (Figure 5.8 & 5.9). The processing involves limiting oil absorption, less water loss and guaranteeing textural stability in products (de Freitas *et al*., 2012). Therefore, Bikini, Challenger, Panamera and Tyson showed good potential for processing through frying and baking, due to a high dry matter content and specific gravity, which would result in good textural quality end-products. Potatoes with lower dry matter content and specific gravity (< 1.08 g ml^{-1}) could be used for canning and boiling as advised by Rady and Guyer (2015). The above findings are in agreement with those of Roy *et al*. (2017) who found that lower tuber weight and lower dry matter content of tuber result to the lower specific gravity. These results indicate that the internal quality of a potato is highly affected by the planting date, fertilizer type used and harvest day as stated by Solaiman *et al*. (2015). Furthermore, Abong *et al*. (2009) concluded that potato genotypes and stage of maturity are two important factors that significantly influenced dry matter content and specific gravity in potato tubers.

In conclusion, this study provided evidence that environmental conditions can stress the normal growth of potato genotypes through restricting crop growth patterns thus affecting optimum yield. Based on the study Challenger, Electra, Tyson and Sababa had higher yield in both sites. Notably, Mondial and Sifra performed best at URF and CB, respectively. The similarities on dry mass of these genotypes were also reported by van Niekerk *et al*. (2016), as they displayed characteristics of a waxy potato, evident from low dry matter content. These genotypes can be recommended for these production sites. However, the results of this study may need to be repeated since the climates always change as well as soil structure.

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Chapter 6: General discussion, conclusion and recommendations for future work

6.1 General discussion

Potato growers in South Africa are dependent on irrigation water (about 80 %) and rainfall for production of potato (PSA, 2017). Potato yields output are relatively low particularly under dry-land conditions, and this could be partly attributed to varied responses of the crop at different growth stages. An understanding of crop responses and sensitive of key growth stages to water stress is important under dryland conditions. To date, little is known on the studied potato genotypes water usage on different growth stages because it has received little research attention. Therefore, the overall aim of this study was to determine the responses of locally popular and newly introduced potato genotypes to water stress under controlled and field conditions.

A level of sensitivity to water deficit occurs at all growth stages of the crop but the sensitivity varies among growth stages and genotype and that has effects on the final yield of the crop. The yield formation stage is the most sensitive to water stress and this was confirmed in the controlled study (Chapter 3 and 4).

The first objective investigated the effect of water deficit imposed at different growth stages on morpho-physiological traits of different potato genotypes. Potato genotypes Bikini exhibited drought tolerance at the vegetative stage, Challenger at the tuber initiation stage, Electra at the tuber bulking and Mondial at maturity stage.

The study revealed that water deficit during tuberazation significantly affects tuber yield (fig 1a) and quality (Chapter 4), in agreement with reports by (Rodriguez *et al*., 2016; Saravia *et al*., 2016; Rodríguez-Perez *et al*., 2017). The present study revealed that potato genotypes Bikini, Challenger, Mondial and Sababa produced high tuber yields and high dry matter content (fig 2) therefore they are suitable for the processing industry and baking.

The significant genotype x environment effect on growth, physiological traits and tuber yield (chapter 5) suggested that the adaptation of different potato genotypes to different agronomical areas varies. Potato genotypes planted at Ukulinga research farm (humid environment) had higher yield compared to at eChibini. Challenger, Electra, and Tyson had high yield at Ukulinga whereas at eChibini yield Tyson, Electra and Sababa were the higher. Electra and Tyson were high-yielding in both sites but Ukulinga had higher number of tubers. This indicate wide adaptation. The outcome noted that most genotypes (such as Panamera and Sifra) struggled in areas highly dominated with sandy soil. Therefore, they should not be grown in sandy soil areas without performing proper agronomic practices (correct planting season, proper irrigation and ridging/earthing) that would ensures holding water capacity in the soil.

6.2 Conclusion

The study aimed to gain a deeper understanding of growth, physiology and yield that may determine the effect of production sites and water deficit occurring at different growth stages of potato growth and development; and how these affect yield performance and subsequent biomass production. The studied potato genotypes differed in relation to morpho-physiological and quality traits when subjected to water deficit at different growth stages. For this reason, we concluded that differences in physiological and morphological traits are associated with water stress of the studied potato genotypes at various growth stages. This allowed selection and recommendation of growth-stage specific drought tolerance potato genotypes for production and processing. Farmers situated in areas with warm, temperate and mild-climate with soils that vary from sandy loamy, light loamy to clay loamy can grow these genotypes (Challenger, Electra, Tyson and Mondial) however they should mindful of temperature and planting dates, since they tend to be sensitive to changes in environmental conditions, particularly extreme temperatures. The study was able to validate that potato growth, yield and quality are affected by various environmental conditions such as temperature, soil type and climate change not only water deficit.

6.3 Recommendations and future prospects

The differences among potato genotypes in response to production sites and water deficit imposed at different growth stages were successfully detected using physiological and morphological traits, the best performing genotypes in terms of yield were also identified. Vegetative stage and in between late tuber bulking to maturity stage were identified as drought tolerant stages compared to other growth stages, but potato genotypes response were dependent. However, the biochemical changes could not be analysed, therefore, further experiment on determination of sugar content using high standard apparatuses such as high-performance liquid chromatography (HPLC) and other secondary properties (phenolics and ascorbic acid (AA)) linked with water deficit, are recommended. It is also recommended to repeat the experiment using many potato genotypes and more regions so that adaptation can be in viewed in wide areas.

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