# ROLE OF COMPONENT TRAITS IN YIELD PERFORMANCE OF CORN AND SORGHUM GENOTYPES UNDER DIFFERENT IRRIGATION REGIMES

A Thesis

by

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# ABSTRACT

Grain yield is a trait of economic importance to farmers and agricultural industries. There has been much research at molecular and genetic levels to improve grain yield, but environmental factors can be equally or more important. Drought is a common problem in Texas and other arid and semi-arid regions around the globe, affecting crop production adversely. There is always a need of genotypes that can not only grow and develop but produce high yields in water stress conditions. Corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) are two major cereal crops of Texas. To identify physiological characteristics of high yielding and drought tolerant corn and sorghum genotypes, 15 entries of each crop were planted in Uvalde, Texas in 2016 and 2017. Three commercial and 12 experimental hybrids of corn as well as eight hybrids and seven inbred lines of sorghum were tested. Performance was evaluated in full and deficit irrigation regimes through plant height, agronomic canopy and leaf traits, grain composition, and grain yield measurement. A sub-sample of genotypes was also tested for soil-water use and transpiration rates; sorghum was found to absorb water to 100-120 cm of soil depth, while corn was limited to 60-80 cm of soil depth. Corn hybrids REV28HR20 (REV26V21), BH8732VTTP, NP2643GT/Tx777 and GP7169GT/Tx777 and sorghum genotypes ATx631/RTx437, ATx642/RTx437, B.Tx642, and B.Tx623 performed good confirming water efficient behavior. Few other genotypes showed water efficient behavior but contributed more towards vegetative development, thus lowering grain yield. Number of green leaves in corn was negatively correlated with grain yield, while in sorghum positive effect on grain yield was observed. Corn hybrids in 2016 and 2017 and sorghum hybrids in 2017 did not show any significant correlation between grain starch content and grain yield. Corn hybrids showed higher water-use efficiency compared to sorghum in terms of grain yield and aboveground biomass. Linear discriminant analysis showed that leaf thickness, leaf dry matter content, osmotic potential, plant height, and NDVI are the most important predictive traits to focus on in the future for similar research to save resources.

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# CHAPTER I

# INTRODUCTION

Numerous studies have shown the relation of plant morphology and physiology to yield (Johnson et al., 1955; Fischer and Wood, 1979; Fischer et al., 1998; Tuberosa et al., 2002; Choudhary and Kholová, 2017; Shekoofa and Choudhary, 2017). Plant traits undergo certain changes based on the amount of water available in the soil to meet their demand. To survive and thrive in limited soil-water availability or drought conditions, plants need to reduce water use. But reducing water use tends to reduce biomass accumulation and grain yield (de Wit, 1958; Passioura, 1977; Tanner and Sinclair, 1983; Blum, 2011). In addition, different genotypes of a crop might respond differently to drought conditions and have different physiological characteristics that can alter their ability to capture water, such as deeper roots. Genotypes that show better yield and biomass accumulation at the cost of less water transpired are considered water efficient. However, under field conditions it is difficult and expensive to measure transpiration of many genotypes that have been selected for study. Because of this, soil-water availability and sap-flow rate measurements usually are restricted to only selected genotypes. At the same time, some morpho-physiological traits such as plant height, number of leaves, leaf area index, leaf angle, chlorophyll content, leaf thickness, osmotic potential, specific leaf area, NDVI, harvest index, etc. are less expensive to measure, but may still be useful to indicate variations in grain yield and aboveground dry biomass among different genotypes of a crop in different irrigation regimes.

Presence of incomplete-imperfect flowers in corn but incomplete-perfect flowers in sorghum leads to two different types of pollination. Generally, cross-pollination is seen in corn and selfpollination in sorghum based on positioning of male and female reproductive structures. Difference in positioning of male and female reproductive structures in corn leads to pollen viability due to desiccation and shortening of silking duration due to drought (Assefa et al., 2014a) and yield loss due to decrease in number of ovules forming kernels and increasing kernel abortion at high temperature during flowering and grain-filling stages (Shim et al., 2017). In sorghum, water stress at early stage leads to decrease in number of seeds per head, whereas, in late stage it affects grain filling, thus reducing grain size (Trostle and Fromme, 2010). In addition, there exists a good positive correlation between green leaf area at physiological maturity with green leaf retention and with green leaf number in water-deficit sorghum (Wanous et al., 1991). However, it is not the case with water-deficit corn (Bolaños and Edmeades, 1996). Hence, sorghum maintains its greenness for longer duration (in general sense, even after physiological maturity) as compared to corn in water-deficit condition. Greenness in sorghum for longer duration might result in active photosynthesis for a longer time. Corn dries at faster rate in water-deficit condition and faces early mortality in high temperature. Incomplete flowering followed by loss in grain yield has also been seen in sorghum during severe drought at the boot stage (Gerik et al., 2003). $C_4$ plants such as corn and sorghum are able to maintain leaf photosynthesis with reduced stomatal conductance, a way to thrive in drought (Lopes et al., 2011). Compared to corn, sorghum is considered to have better adaptability in water stress or drought conditions (Ludlow and Muchow, 1990; Sanchez et al., 2002; Lopes et al., 2011).

Grain yield reduction in drought or water-deficit conditions raises a need for water efficient and drought tolerant genotypes. Drought tolerance is the ability of plants to withstand water-limited conditions up to a certain extent. Drought tolerance is a quantitative trait controlled by many genes (Gurian, 2012; Merewitz et al., 2012, 2014; Jespersen et al., 2016) that are challenging for molecular and genetic approaches to manipulate one at a time (Gurian, 2012). In addition, different genotypes might be tolerant to drought at different stages of crop growth. Furthermore, a drought tolerant genotype/cultivar may or may not be water efficient (Blum, 2009; Long and Ort, 2010). However, there is a widely accepted concept that the higher the water use, the higher grain yield formation and biomass accumulation will be in plants. To survive in water deficit or drought conditions, some genotypes/cultivars tend to conserve water by reducing their stomatal size or stomatal closure, leaf rolling, etc. By conserving water, such genotypes/cultivars often thrive through mild to moderate drought or short duration drought, hence proving their drought tolerance behavior, but less water use during this period might result in reduction in biomass accumulation and grain yield. Many farmers would not prefer drought tolerant genotypes for planting if it meant losing yield. There is always the need for genotypes that are drought tolerant and water efficient. Again, drought tolerance behavior of genotypes also depends on severity and duration of drought. Studying the performance of several crop-traits under the same environmental/management conditions can help to identify crop genotypes that are both drought tolerant and water efficient.

Soil structure and texture play an important role in determining soil-water availability to crops. Water stress or drought condition arises when there is limited available soil-water to meet crop evapotranspiration demand (Jaleel et al., 2009; Chai et al., 2014). Clay soil (fine textured) has higher number of small pores with low rate of infiltration but high water holding capacity (WHC), whereas, sandy soil (coarse textured) has large pore sizes with high rate of infiltration but low WHC (O’Geen, 2012). Despite higher WHC, the presence of very small sized pores in clay soil lowers the water uptake rate by plants in deficit irrigation, especially when soil-water content (θ) is close to permanent wilting point. Field capacity and permanent wilting point mark the upper and lower limit, respectively, of soil water content from which plants can absorb water. Plants with shallow roots might show low water uptake during water stress, whereas, plants with deeper roots can continue absorbing water from the deeper soil even during top soil water stress. Although, deeper roots can capture water from a deeper soil depth this might not work in case of prolonged drought conditions. However, to thrive in water stress or drought conditions, some genotypes might use less water to produce higher yields, thus confirming their water efficient behaviors.

Plant height and leaf number have direct relations with yield. Increased plant height with large number of leaves results in higher grain yield (Scarsbrook and Doss, 1973; Law et al., 1978). Corn and sorghum genotypes with higher plant height received maximum incident solar radiation compared to short height genotypes in plots because short height genotypes often get shaded with widespread leaves of genotypes with higher plant height. This incident solar radiation increases photosynthetic activity in taller genotypes. In addition, the larger the number of leaves, the higher is the photosynthetic activity. Higher water use generally results in higher grain yield and biomass accumulation. Corn and sorghum have dense canopies that prevent incident solar radiation to reach the ground, thus reducing soil evaporation and increasing plant transpiration. In the United States corn have larger number of leaves compared to sorghum (Assefa et al., 2014b), thus having higher grain yield. Leaf structure and orientation are two other factors that determine grain yield. Plants with higher leaf area index (LAI) tend to receive more solar radiation, thus increasing photosynthetic activity contributing to higher grain yield. Apart from LAI, photosynthetic activity also depends on leaf angle (mean tilt angle). For maximum photosynthetic activity, leaves should make an angle of 45° to 90° to incident solar radiation.

However, in water stress or drought, genotypes with higher plant height and large number of leaves showing low LAI or leaf angle but higher grain yield are considered as water efficient.

Chlorophyll and normalized difference vegetation index (NDVI) also contribute to grain yield. Chlorophyll is responsible for absorbing and converting light energy for use in photosynthesis, whereas NDVI is a measure of canopy greenness derived from amount of light absorbed and reflected in near-infrared and visible red ranges (Govaerts and Verhulst, 2010a). NDVI correlates with leaf chlorophyll content and provides a clear picture about how healthy/green the leaves are. Genotypes with higher chlorophyll content and NDVI have potential to be high yielding. At the same time, genotypes with higher NDVI and chlorophyll content may also use more water for biomass accumulation and grain yield and planting several genotypes/cultivars in same environment/management condition will help us to identify those producing higher grain yield at normal or low water use compared to others. NDVI measured during early stages of crop growth do not show good correlation with yield (Teal et al., 2006), but when measured after flowering stage, they show good correlation (Spitkó et al., 2016). Genotypes maintaining their greenness even in water stress condition are considered more drought tolerant. Based on grain yield they may also be categorized as water efficient.

Osmotic potential, specific leaf area, leaf dry matter content, leaf tissue density, and leaf thickness (LT) are some additional leaf traits determining water use. Leaf thickness is influenced by light intensity. Compared to shade leaves, sun leaves have thicker lamina (Popma and Bongers, 1988; Cornelissen, 1992; Dong, 1993; Hodgson et al., 2011). In addition, leaf thickness also varies from tip to ligule. Leaves are thickest at point halfway between ligule and tip. Thus, for measurement to be comparable, a common criterion should measure leaf thickness. Leaf tissue density (LD) is a ratio of leaf dry mass per unit area and LT (Bartlett et al., 2012a) and any change in LT will more likely change the leaf tissue density. However, leaf dry matter content (LDMC) is the ratio of dry leaf mass and saturated leaf mass (Hodgson et al., 2011; Bartlett et al., 2012a) and does not depend on thickness. LDMC also shows good positive relation with LD (Shipley and Vu, 2002), so LD can be replaced with LDMC. Specific leaf area (SLA) can be defined as leaf area per unit leaf biomass or dry matter content accumulated. LDMC and LT are inverse function of SLA. LDMC is also a measure for leaf water content (Garnier et al., 2001). Cell wall composition contributes most to dry matter in leaves. Higher dry matter content in leaves generally relates to higher drought tolerance. Higher solute concentration in vacuoles is related to lower osmotic potential. The lower (more negative) the osmotic potential, the higher the capacity of plants to absorb water from the soil. Genotypes that continue to absorb water from drying soil tend to avoid drought or water stress, hence confirming their drought tolerance behavior.

Quantification of grain starch and protein using NIRS also helps in determining drought tolerance behavior of genotypes. Carbohydrates are stored in grains mainly in the form of starch. Limited soil-water availability affects starch content of grains, reducing the grain size (Thitisaksakul et al., 2012) and decreasing grain yield but increases oligosaccharides and sucrose content (Lahuta et al., 2000). However, studies by Slafer et al. (1990) and Uauy et al. (2006) suggest a higher grain yield with high grain protein content in some crops.

It is well known that leaf and canopy traits contribute to grain yield formation. Manual measurement of leaf traits at different growth stages of a crop is time-consuming and labor-intensive, especially when there are many genotypes planted in many replications. In such case, it becomes important to know which traits among all the measured attributes contributes more to grain yield. If such traits are known, it will save time for breeders, as they will focus more on measuring a few selected traits that show maximum contribution to grain yield. In contrast, a question arises that why should not we go for high-throughput phenotyping and why manual measurement? No doubt, high-throughput phenotyping can collect large number of data in a short interval of time. It has efficiency to measure many different traits attributing to grain yield. However, interpretation of these larger datasets can become difficult. In addition, studying plant performance by linking data collected by high-throughput phenotyping is sometime not clear. On the other hand, traits measured by manual phenotyping are definite, although with some uncertainties. Although manual phenotyping is time-consuming and labor-intensive, utilizing some statistical measures we have tried to identify traits that show maximum contribution to grain yield in all genotypes of corn and sorghum. As discussed above, if such traits are being identified, it will assist in data interpretation in high-throughput phenotyping in the future. In addition, it is interesting to see to what extent a diverse array of crop genotypes confirm to, or deviate from, the widely observed trend that higher grain yield and higher biomass accumulation in plants are achieved by higher water consumption. An attempt has been made to verify if this paradigm holds true for different corn and sorghum genotypes. There might be some genotypes that produce higher grain yield with less water use and some others that use more water but produce low grain yield. Identification of such genotypes can provide a direction for future research in corn and sorghum improvement program. Studying multiple traits and their relationships with grain yield will provide a better understanding of the ecophysiological mechanisms leading to improved drought tolerance and water use efficiency in corn and sorghum. The objectives of this research are:

i) To identify corn and sorghum genotypes showing good performance with high yield in full and deficit irrigation regimes.

ii) To identify traits showing maximum contribution towards grain yield in both the irrigation regimes based on linear discriminant analysis and path coefficient analysis.

iii) Based on the variables measured, compare commercial to experimental hybrids in corn, inbreds to hybrids in sorghum, and the two crops.

# CHAPTER II

# CANOPY AND LEAF TRAITS STUDY, AND GRAIN NUTRIENTS QUANTIFICATION TO PREDICT WATER USE BY CORN AND SORGHUM GENOTYPES

## Introduction

Canopy and leaf traits play important roles in contribution to grain yield and biomass accumulation in corn (Zea mays L.) and sorghum (Sorghum bicolor L.). Some traits may have positive effect on grain yield, while others might show adverse effect. Effect of some traits also depends on their structure and orientation, for example, leaf area, leaf area index, leaf angle. Contribution of some traits to grain yield also depends on crop development stages. Some traits might contribute to grain yield and biomass accumulation in full irrigation, but in deficit irrigation or water-stress condition might not show good performance. All such traits can help predict water use of corn and sorghum genotypes and crop water use is directly related to grain yield (Hanks, 1974; French and Schultz, 1984; Condon et al., 2002; Richards et al., 2002; Zhang et al., 2008; Blum, 2009; Steduto et al., 2012).

### *Plant height and number of leaves*

As explained earlier, plant height and number of leaves are considered important physiological traits, variable among genotypes, but that contributed to grain yield. Taller plant height and greater number of leaves, results in higher photosynthesis and thus higher grain yield and biomass accumulation. Plant height shows positive correlations with grain yield, however breeders have developed some semi-dwarf varieties that still can produce higher grain yield (Joppa, 1973; Law et al., 1978). Higher photosynthesis means higher water use, but this is not possible in deficit irrigation or water-stress environments. Under deficit irrigation or water-stress conditions plants tend to close their stomatal to prevent water loss in the form of transpiration that lowers the rate of soil drying (Drake and Leadley, 1991; Samarakoon and Gifford, 1995), thus improving water-use efficiency and tissue water status, adding up to grain yield and plant growth (Drake et al., 1997; Jarvis et al., 1999). However, the question arises if terminal plant height and number of green leaves show strong positive correlations with grain yield for all corn and sorghum genotypes? Water use in some genotypes might contribute to vegetative growth, such as number of leaves and plant height, rather than reproductive development, thus lowering grain yield.

### ***Leaf structure and orientation***

Leaf structure and orientation of crops can help predict their water use. It is well known that a higher leaf area index (LAI) with leaf angle or mean tilt angle (MTA) almost horizontal to ground absorbs more solar radiation, thus maximizing photosynthetic efficiency of plants. Higher photosynthetic efficiency means higher $CO_2$-$H_20$ exchange rate and higher water use is directly related to higher grain yield (de Wit, 1958; Passioura, 1977; Tanner and Sinclair, 1983; Blum, 2011). Here a question arises, does higher LAI contributes to higher yield in all the crops/genotypes? If so, how are genotypes/crops in deficit irrigation or water-stress condition able to yield high? Several studies suggest that it is not true in every case that higher LAI means higher grain yield (Ainsworth and Long, 2005; Morgan et al., 2005; Long et al., 2006; Drewry et al., 2010a; b; Ainsworth et al., 2012; Srinivasan et al., 2017). Corn and sorghum are typically planted in high density; in these cases having higher LAI increases the number of shade leaves (Drewry et al., 2010a; b), thus reducing photosynthesis by crops or genotypes. In addition, higher LAI, leaf biomass, etc. shows higher investment of energy towards vegetative growth, rather than reproductive development that tends to reduce grain yield. In water-stress conditions, plants tend to produce fewer leaves, reduced leaf area, as well as minimizing stomatal aperture and these all reduce the number of shade leaves, prevent water loss; thus, some genotypes might show higher grain yield in deficit irrigation.

### ***Leaf thickness, Leaf tissue density, Leaf dry matter content, Specific leaf area, and osmotic potential***

Leaf physiological components can help predict water use of different corn and sorghum genotypes. Osmotic potential is the measure of solute present in cell at full hydration and plays an important role in determining drought tolerance ability of genotypes/crops (Bartlett et al., 2012a). Water tends to move from low solute concentration to high solute concentration in cells. The higher the cell solute accumulation the more negative (lower) is the osmotic potential resulting in continuous absorption of water from deep soil layer during water-stress condition and this helps plants to thrive in drought. Another question is if this type of water use contributes to higher grain yield or not. Leaf dry matter content (LDMC) is the ratio of dry leaf mass and saturated leaf mass (Hodgson et al., 2011). LDMC is the cell wall material present in leaves and plays an important role during permanent wilting point. Higher LDMC present in leaves results in higher is the relative water content of leaf cells (Bartlett et al., 2012a; b), thus conserving water during the permanent wilting point and helps plants to better withstand drought conditions. Leaf tissue density (LD) is the ratio of leaf dry mass per unit area (LMA) and leaf thickness (LT) (Bartlett et al., 2012a). It is the density of cells present in leaves. If a genotype having similar leaf area compared to others show higher LD, it means size of cells is small for particular genotype resulting in increase in efficiency of osmotic adjustment (Bartlett et al., 2012a), thus adding up to drought tolerance (Cutler et al., 1977). LDMC shows strong positive correlation with LD (Shipley and Vu, 2002; Bartlett et al., 2012a). Specific leaf area (SLA) is inversely related to LMA (Garnier et al., 2001), so any change in leaf thickness due to amount of solar radiation received also affects SLA, LMA, and LD. Leaf thickness is related to photosynthetic efficiency of plants. More thicker is the leaf, higher will be its photosynthetic efficiency (Givnish, 1979).

### ***Chlorophyll content and NDVI***

Different corn and sorghum genotypes might vary in the level of chlorophyll content and NDVI. Higher chlorophyll content defines higher photosynthetic efficiency of a crop or a genotype. As, explained earlier, higher photosynthetic efficiency results in higher water use by plants that might finally result in high grain yield. When exposed to deficit irrigation or water-stress conditions during the pre-flowering stage, plants tend to have shorter staygreen periods. They lose greenness and dry fast. Sometimes photosynthesis or chlorophyll content may not show a good or positive correlation with grain yield. Reasons for this might include that in corn and sorghum plots it is hard to measure chlorophyll content of all plants in a plot or all leaves of a plant when there are many such plots (and plants within plots) to measure. Generally, representative plants per plot are selected to measure chlorophyll content of canopy leaves involved in photosynthesis. Sometimes, leaves selected to measure chlorophyll content might be from shaded portion in high density planting. To get rid of this, NDVI is another variable than explains greenness of crop canopy. NDVI is based on light absorption and reflection principles in near infrared and visible red regions (Govaerts and Verhulst, 2010b; Spitkó et al., 2016) and show positive correlation with grain yield when measured at late vegetative to early reproductive stage. NDVI also shows good correlation with leaf N content (Raun et al., 2001) and can be a good predictor of drought tolerant genotypes. A study by Spitkó et al. (2016) suggest that NDVI measured post-flowering shows the best correlation with grain yield because assimilates production at this stage are closely related to grain filling.

### *Grain nutrients*

The composition of grain can tell a lot about the success of each plot in reaching its yield potential of crops/genotypes. Grain composition is related to grain yield, harvest index, and plant biomass (Donald and Hamblin, 1976; Hay, 1995; Triboi and Triboi-Blondel, 2002). Grain yield is the result of assimilation of photosynthates formed due to the  capture of solar radiation by canopy leaves and absorbed $CO_2$ (Triboi and Triboi-Blondel, 2002) during grain filling stage. Plants get nitrogen from soil and other nitrogenous sources and carbon from absorbed atmospheric $CO_2$. During the grain filling stage, N is assimilated in grains as protein and C as starch and oil (Triboi and Triboi-Blondel, 2002). Carbon in protein also comes from $CO_2$ absorbed. During photosynthesis, plants absorb solar radiation and CO2; assimilation of photosynthates forms grain composition, so C occupies major portion of grains, hence increase in starch (Duvick and Cassman, 1999) and oil (Wilcox and Cavins, 1995) is considered to show positive correlation with yield (Triboi and Triboi-Blondel, 2002). Any increase in C of grains results in decrease of grain N, followed by increase in yield potential of crops/genotypes. Several studies in wheat (Canevara et al., 1994; Duvick and Cassman, 1999), soybean and rapeseed (Specht et al., 1999; Cober and Voldeng, 2000), and corn (Duvick and Cassman, 1999) support this. Studies of starch and protein content in corn and sorghum genotypes in two different irrigation regimes might provide a broad explanation of their yield potential.

The objectives of this study were:

i) To predict water-use and grain yield of corn and sorghum genotypes under full and deficit irrigation regimes based on their plant height and agronomic canopy and leaf traits measurement.

ii) To study the contribution of measured traits of corn and sorghum genotypes towards grain composition, grain yield, and aboveground dry biomass.

## Materials and Methods

The project was conducted at Texas A&M AgriLife Research and Extension Center, Uvalde, Texas (29° 12' 52" N, 99° 47' 23" W) in 2016 and 2017. Fifteen genotypes each of corn and sorghum were sown in two different irrigation regimes – full irrigation and deficit irrigation. In 2016 and 2017, corn genotypes consisted of 10 temperate-tropical derived, three temperate derived (commercial), one mostly temperate derived, and one tropical derived hybrids (Table 2.1). Sorghum genotypes consisted of seven inbred lines and eight hybrids in both the years (Table 2.1). In 2016, the planting date was March 16 for both crops and in 2017, the planting date was April 8. The planting was done in split plot design with three replications each of full and deficit irrigation under field conditions. Each plot consisted of four rows with row spacing 2.5 ft. and plot length 20 ft. Several plant traits were measured in both years. Additional traits measurement was thought to provide a clearer picture. There was no plan to exclude any measurement in 2017, but due to weed infestation it was done. In addition, weather data for both years were collected from the weather station at the Uvalde Research Center.

**Table 2.1. Corn and sorghum genotypes planted at Uvalde in 2016 and 2017.**

| **Corn (2016 and 2017)** | **Corn tropical/temperate derived** | **Sorghum (2016)** | **Sorghum (2017)** | **Sorghum hybrid/inbred** |
|---|---|---|---|---|
| Tx775/Tx777 | 25% Temperate, 75% Tropical | ATx378/RTx7000 | ATx378/RTx7000 | Hybrid |
| Tx781/Tx777 | 25% Temperate, 75% Tropical | ATx623/RTx430 | ATx642/RTx437 | Hybrid |
| GP7169GT/Tx777 | 50% Temperate, 50% Tropical | ATx3197/RTx7000 | ATx642/RTx436 | Hybrid |
| SGI890/Tx777 | 50% Temperate, 50% Tropical | ATx645/RTx437 | ATx645/RTx437 | Hybrid |
| TR8145/Tx777 | 50% Temperate, 50% Tropical | ATx645/RTx436 | ATx645/RTx436 | Hybrid |
| Tx149/LH195 | 50% Temperate, 50% Tropical | ATx631/RTx436 | ATx631/RTx436 | Hybrid |
| LH195/Tx777 | 50% Temperate, 50% Tropical | ATx631/RTx437 | ATx631/RTx437 | Hybrid |
| Tx773/LH195 | 50% Temperate, 50% Tropical | ATx2752/RTx430 | ATx2752/RTx430 | Hybrid |
| NP2643GT/Tx777 | 50% Temperate, 50% Tropical | R.Tx7000 | R.Tx7000 | Inbred |
| Tx775/GP474GT | 75% Temperate, 25% Tropical | B.TX378 | B.Tx378 | Inbred |
| Tx772WRS/LH195 | Mostly Temperate | B.Tx623 | B.Tx642 | Inbred |
| DKB64-69 | Temperate (commercial) | R.Tx436 | R.Tx436 | Inbred |
| REV28HR20 (2016)<br>REV26V21 (2017) | Temperate (commercial) | B.TX3197 | R.Tx437 | Inbred |
| BH8732VTTP | Temperate (commercial) | B.Tx645 | B.Tx645 | Inbred |
| Tx150/Tx777 | Tropical | R.Tx437 | B.Tx631 | Inbred |

### ***Canopy and leaf traits measurement***

Several canopy and leaf traits such as plant height, number of leaves, leaf area index, mean tilt angle, leaf thickness, leaf tissue density, leaf dry matter content, specific leaf area, osmotic potential, chlorophyll content, and NDVI were measured for different corn and sorghum genotypes in 2016 and 2017.

#### *Plant height and number of leaves*

Three representative plants per plot were selected for plant height measurement using a ruler. Plant heights of different genotypes were measured once every 2 weeks (at every growth stage) in 2016. In 2017, weed infestation occurred in corn and sorghum plots that disturbed scheduled plant height measurements and measurements were taken just 4-5 times. Plant growth curves were plotted to study variations among genotypes. During every plant height measurement, the number of leaves per plant was counted. Mean value of three representative plants for plant height and number of leaves was considered as plant height and number of leaves for plot.

#### *Leaf structure and orientation*

A LI-COR 2200 Canopy Analyzer was used to measure leaf area index and leaf angle (mean tilt angle) in 2016. The measurement was taken just once during flowering stage in corn and sorghum. Evening time, after 7:00 pm and before darkness, was selected for measuring leaf area index and leaf angle distribution for all genotypes to avoid the influence of beam radiation on measurement quality. In 2017, this measurement was replaced by leaf osmotic potential.

#### *LT, LD, LDMC, SLA, and osmotic potential*

Approach used by Bartlett et al. (2012a) was followed for measurements in this section. One representative plant per plot was selected for measurement in corn and sorghum. The 3rd leaf in sorghum and 5th/6th leaf in corn were selected from different genotypes. Leaves were selected based on that they should not be too exposed to solar radiation and not too shaded. Leaves were cut in the field and the cut ends were submerged in water in a bucket overnight under high humidity condition by enclosing the bucket with a polyethene bag. This was repeated in two batches – during flowering stage and during dough stage. Leaves were taken out one by one from the bucket, blotted with paper towel to remove surface water, and punched in midway from both extremes to collect one leaf disc per leaf (8 mm in size). Each leaf disc was inserted separately in a pre-labeled eppendorf tube and was immediately frozen in liquid nitrogen. The eppendorf tubes with leaf discs from different genotypes were then stored in refrigerator at -80 °C until they were measured using an osmometer. Leaf thickness (in mm) was measured using Mitutoyo 500-196$^{CE}$ absolute digital caliper 0-6’’ in range. The caliper was placed on leaf at the point where leaf disc was punched, and leaf thickness was measured. Leaf area (in cm) was measured using LI-COR 3100 area meter. Saturated leaf weight and dry leaf weight of punched leaves were measured separately for different genotypes. Dry leaf weight was measured after drying leaves separately in oven at 70 °C for 2 days. Leaf dry matter content (mg/g) was calculated as leaf dry weight/leaf saturated weight (Hodgson et al., 2011). Leaf density (mg/g) was calculated as LMA/LT (Bartlett et al., 2012a). Leaf dry mass/area (LMA) can be calculated as leaf dry mass/leaf area (Bartlett et al., 2012a) and the inverse of LMA is specific leaf area (SLA) (Shipley and Vu, 2002). SLA ($mm^2$ $mg^{-1}$) is also calculated as 1/(LDMC x LT) (Garnier et al., 2001; Shipley and Vu, 2002; Hodgson et al., 2011) or 1/(LD x LT) (Shipley and Vu, 2002; Hodgson et al., 2011). Since LT is influenced by light intensity, LMA was used to calculate SLA ($mm^2$ $mg^{-1}$). To calculate osmolality, leaf discs stored in refrigerator were taken out in batches in a container quarter-filled with dry ice. Specifically, leaf discs in eppendorf tubes were taken out one by one from dry ice container, punched 4-5 times with a pair of pointed tweezers to allow equilibration vapor pressure to be reached sooner while thawing in the measurement chamber of the Wescor 5520 Vapro osmometer. The osmolality readings were noted after vapor pressure equilibration was reached in 6-10 minutes. Osmometer shows a decrease in readings followed by an increasing pattern. The minimum osmolality reading (mmol/Kg) after which value shows ascending pattern is considered as equilibrium point. Osmolality was then converted into osmotic potential (MPa) following an equation:

$$\Psi_s = -CiRT \qquad \textbf{…2.1}$$

where $C$ is the osmolality value in mmol/Kg, $i$ is the ionizing constant assumed equal to unity, $R$ is the ideal gas constant (0.0083143 Kg MPa $\mathrm{mol^{-1}\ K^{-1}}$), and $T$ is the absolute temperature (K = °C+273) assuming room temperature 25 °C. Prior to loading leaf disc on sample holder, the osmometer was calibrated using 290 mmol/Kg, 1000 mmol/Kg, and 100 mmol/Kg of standard solutions in that order. A blank reading was taken after every 10 samples measurement. Clean test was run after every 50 samples measurement and if the value was found above five, thermocouple was cleaned and recalibrated for further measurements.

*Chlorophyll content and NDVI*

Chlorophyll content in sorghum was measured thrice, twice during vegetative stage and once during maturity in 2016 and in 2017 it was measured twice during dough stage. For corn, chlorophyll content was measured twice during the vegetative stage in 2016 and in 2017 it was measured twice during dough-dent stage. Three representative plants were selected in each plot and chlorophyll content was measured using a SPAD meter at tip, mid-way and near the ligule of 3rd and 5th corn leaves and 2nd and 3rd sorghum leaves. Values were then averaged to get an estimate of chlorophyll content for every genotype. NDVI was measured in 2017 using an ACS-430 Crop Circle sensor mounted on a backpack-sensing frame, a modified version of push-wheel sensing cart designed at Uvalde Center to get canopy measurements for plant height > 1m (Figure 2.1).

**Figure 2.1.** Backpack-sensing frame with ACS-430 crop circle sensor mounted on top to collect NDVI data.

*Statistical analysis*

MS Excel was used to calculate mean values of replicated genotypes in two different irrigation regimes and standard error was calculated as standard deviation/*n*, where *n* is count. In 2016, no significant difference was observed between deficit and full irrigation, so averaged values for replicated genotypes were not separated based on irrigation regimes. Statistical software JMP 13.0 was used to get ANOVA results, student's t-test for trait values of different genotypes from standard least squares analysis, and to perform PCA. Principal component analysis (PCA) was used to investigate the leading correlations between traits; finally, a path coefficient value was considered to study the relationships between traits because path coefficient includes correlation as well as regression. Linear discriminant analysis (LDA) was used to identify which trait and/or traits combination shows highest percentage of categorization of genotypes in full and deficit irrigation regimes.  Using CRAN-R-3.4.4 function combn (S, r) all possible combination of 'r' unique samples from a vector having 'S' number were enumerated. S is a collection of all interested variables. The combinations were run for LDA values in Minitab 18.1.0.0 software. Prior to running the code for LDA, traits were checked for normality. Data for several traits were transformed close to normality. In corn 2017, LDMC and LD were found to be normal. Even after transformation, LT and LN failed to attain normality, so original data were used. SLA was transformed as log (SLA), osmotic potential as -1/osmotic potential, NDVI as $(\text{NDVI})^{10}$, and plant height as $(\text{height})^2$. In sorghum 2017, LDMC, LD, SLA, and osmotic potential were found to be normal. LN and LT could not attain normality even after transformation, so original data were used. NDVI was transformed as $(\text{NDVI})^3$ and plant height as $(\text{height})^3$. ANOVA was used to determine significant differences for grain yield and attributing leaf and canopy traits. Path analysis in the form of path coefficient values explaining direct and indirect effects of different traits on grain yield were obtained from R-studio package 'agricolae'. Out of several traits measured in 2016 and 2017, few traits were selected based on LDA and path coefficient values showing maximum contribution towards grain yield.

### *Grain yield and biomass measurement and grain starch and protein quantification*

Harvesting of corn genotypes started at 135 DAS and sorghum genotypes at 150 DAS in 2016. In 2017, harvesting of corn genotypes started at 121 DAS and sorghum genotypes were harvested on 125 DAS. Two middle rows of corn and sorghum plots were harvested to get grain weight per plot. Moisture level of grains per plot was measured using a moisture meter and total grain weight was brought at standard moisture level of 15.5% in corn and 14% in sorghum using equation 2.2:

$$Grain\ yield\ = \frac{grain\ weight \times (100 - actual\ grain\ moisture\ \%)}{(100 - standard\ moisture\ \%)} \qquad \textbf{...2.2}$$

The grain yield calculated is at standard moisture level in g plot$^{-1}$, which is further converted into Kg/ha. 1000 count kernel weight in corn and test weight of grains in sorghum were also measured. A week before harvesting one representative plant per plot were cut and were separated into stem, leaves, cobs/panicles, tassel (in corn). These plant parts per genotype were placed separately in different envelopes and dried in oven for 4 days at 75 °C to get dry biomass. Then, harvest index for each genotype was calculated as dry grain weight/total dry biomass.

Near infrared spectroscopy (NIRS) was used to quantify grain starch, oil and protein content. In NIRS, samples are scanned by emitting and NIR light and quantifying the samples absorbance. In 2016 and 2017, 200 g corn and sorghum whole grain sample per genotype were pulled from total grain yield. These samples were put in different envelopes and plot number were marked on each envelope. In 2016 and 2017, corn grains were scanned using Antaris II FT-NIR analyzer. Approx. 200 g whole grain samples were loaded on moving disc and program was run. Three different sets of data were obtained for each scan. Sorghum grain samples were scanned using FOSS XDS NIR spectrometer (FOSS North America, Eden Prairie, MN, USA). Each whole grain sample was loaded in two different rectangular shaped cups with dimensions 15.24 cm X 3.81 cm X 5.08 cm (Dykes et al., 2014). Each cup was scanned separately for every grain sample. Pivot tables in MS Excel was used to calculate mean values of replicated genotypes in two different irrigation regimes and standard error was calculated as standard deviation/*n*, where *n* is count. Standard least squares analysis in JMP Pro 13.0.0 was used to study fixed and random effects of different sources on measured traits in 2016 and 2017. Student's t-test at 95% confidence level and p-value < 0.05 was used to find significant differences among different genotypes under full and deficit irrigation regimes.

### *Issues during research*

i) In 2016, experimental plots received 11 inches of rainfall from planting to harvesting time.
ii) Bird damage in sorghum plots was seen in 2016 and 2017.
iii) Fall armyworm infestation was seen in corn plots during vegetative stage in 2017.
iv) Infestation by pigweed (*Amaranthus spp.*) in corn plots was observed in 2017, whereas, sorghum plots were infested by pigweed and johnson grass (*Sorghum halepense* (L.) Pers.). No effect of Peak and Huskie herbicides were seen on weeds. Later, prior to flowering stage in sorghum weeds were cleaned manually using weed eater.

## Results

Various canopy and leaf traits were studied in corn and sorghum to predict grain yield.

### ***Corn***

Performance of all 15 hybrids have been studied based on plant height, number of leaves, leaf structure and orientation, LT, LD, LDMC, SLA, osmotic potential (OP), chlorophyll content, NDVI, biomass accumulation, grain yield, harvest index, and grain composition.

#### *Plant height and number of leaves*

It is known that plants that are taller at the end of the season (terminal plant height) yield better, especially in Texas (Farfan et al., 2013). Plant height growth curves for all 15 genotypes in two different irrigation regimes were plotted for 2016 and 2017. Main effect of irrigation and its interaction with genotypes on terminal plant height were not significant in both the years (Table 2.2 and Table 2.3). Effect of genetic make-up on terminal plant height was significant in both the years. Temperate derived commercial hybrid, REV28HR20 (REV26V21) and BH8732VTTP were significantly taller than DKB64-69 in both the years (Table 2.2 and Table 2.3). REV28HR20 was significantly taller than all other hybrids in 2016 (Table 2.2 and Figure 2.2), whereas, in 2017 commercial hybrids were significantly shorter than some experimental hybrids (Figure 2.3 and Table 2.3). Experimental hybrids TR8145/Tx777, SGI890/Tx777, and Tx149/LH195 were significantly taller in height and Tx775/GP474GT, Tx781/Tx777, and Tx775/Tx777 were significantly shorter in 2016 and 2017 (Table 2.2 and Table 2.3). Plant height of Tx775/Tx777 was significantly different from Tx775/GP474GT and Tx781/Tx777 in 2016 and 2017. Random effect showed that some unknown factors also contributed to variations in plant height of different corn hybrids in both the years. Weed infestation was the reason behind no height measurement between 55 DAS to 93 DAS.

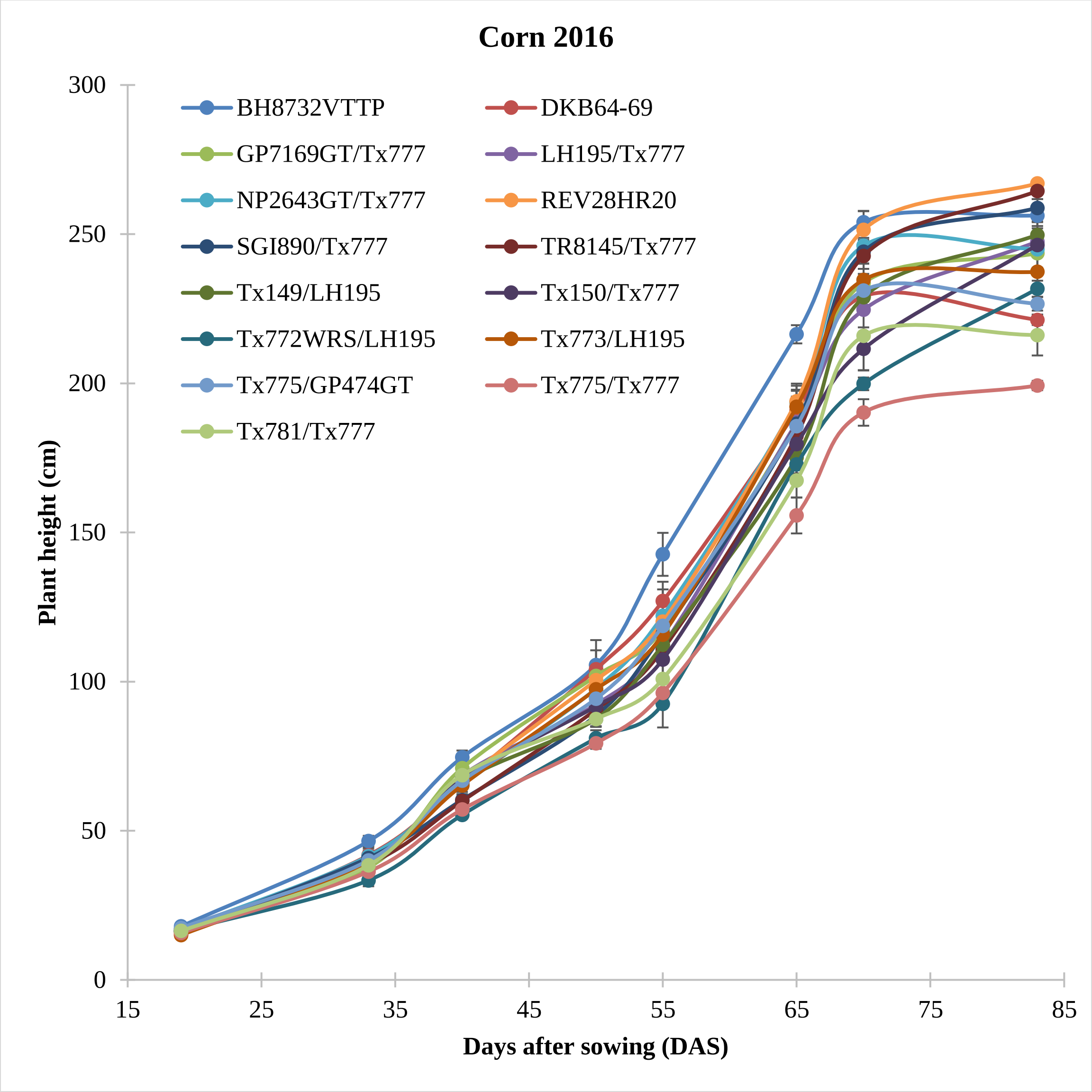


**Figure 2.2.** Plant growth curve for corn hybrids in 2016. Standard error bars represent standard error of the mean.

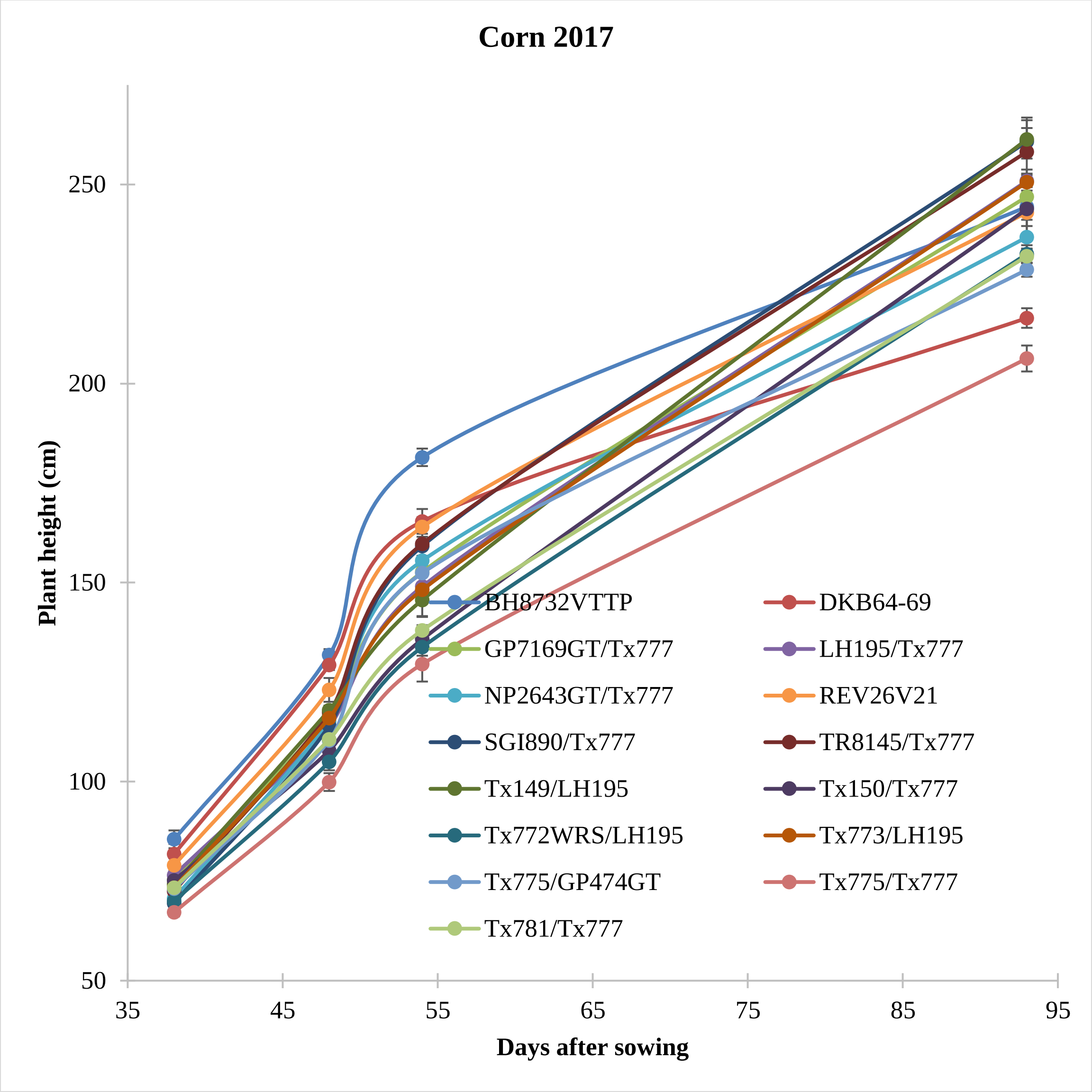


**Figure 2.3.** Plant growth curve for corn hybrids in 2017. Standard error bar represents standard error of the mean.

**Table 2.2. Fixed and random effects of various sources on terminal plant height (cm) resulting in significant differences among different corn hybrids in 2016. Result has been obtained from standard least square analysis in JMP 13.0 (α = 0.05). Genotypes connected by different letters were significantly different. Values with asterisk (*) shows significant main effect. Irrigation regimes showed no significant main effect on terminal plant height. Var represents variance.**

| Genotypes | | Least Sq Mean |
|---|---|---|
| REV28HR20 | A | 269.1 |
| TR8145/Tx777 | A B | 261.06 |
| BH8732VTTP | B C | 259.08 |
| SGI890/Tx777 | B C | 257.81 |
| Tx149/LH195 | B C D | 253.15 |
| LH195/Tx777 | C D E | 250.9 |
| Tx150/Tx777 | D E F | 247.65 |
| NP2643GT/Tx777 | E F | 242.43 |
| GP7169GT/Tx777 | F | 241.02 |
| Tx773/LH195 | F | 240.74 |
| Tx772WRS/LH195 | G | 228.32 |
| DKB64-69 | G | 227.33 |
| Tx775/GP474GT | G H | 226.77 |
| Tx781/Tx777 | H | 218.72 |
| Tx775/Tx777 | I | 201.08 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 1.46 | 0.23 |
| Genotypes | 37.12 | <.0001* |
| Irrigation Regimes*Genotypes | 0.93 | 0.53 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.08 | 4.51 | 6.34 | 7.64 |
| Residual | | 54.57 | 10.13 | 92.36 |

**Table 2.3. Fixed and random effects of various sources on terminal plant height (cm) resulting in significant differences among different corn hybrids in 2017. Result has been obtained from standard least square analysis in JMP 13.0 (α = 0.05). Irrigation regimes showed no significant main effect on terminal plant height. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | | | | | | Least Sq Mean |
|---|---|---|---|---|---|---|---|
| TR8145/Tx777 | A | | | | | | 258.8 |
| SGI890/Tx777 | A | | | | | | 258.09 |
| Tx149/LH195 | A | | | | | | 255.69 |
| Tx773/LH195 | | B | | | | | 248.08 |
| LH195/Tx777 | | B | | | | | 247.79 |
| REV26V21 | | B | | | | | 247.65 |
| BH8732VTTP | | B | | | | | 247.51 |
| Tx150/Tx777 | | B | | | | | 244.4 |
| GP7169GT/Tx777 | | B | | | | | 243.84 |
| NP2643GT/Tx777 | | | C | | | | 234.95 |
| Tx772WRS/LH195 | | | C | D | | | 231.99 |
| Tx781/Tx777 | | | C | D | | | 229.31 |
| Tx775/GP474GT | | | | D | | | 225.5 |
| DKB64-69 | | | | | E | | 215.05 |
| Tx775/Tx777 | | | | | | F | 205.88 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 1.12 | 0.35 |
| Genotypes | 34.3 | <.0001* |
| Irrigation Regimes*Genotypes | 0.98 | 0.48 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.12 | 5.07 | 5.61 | 10.66 |
| Residual | | 42.49 | 8.03 | 89.34 |

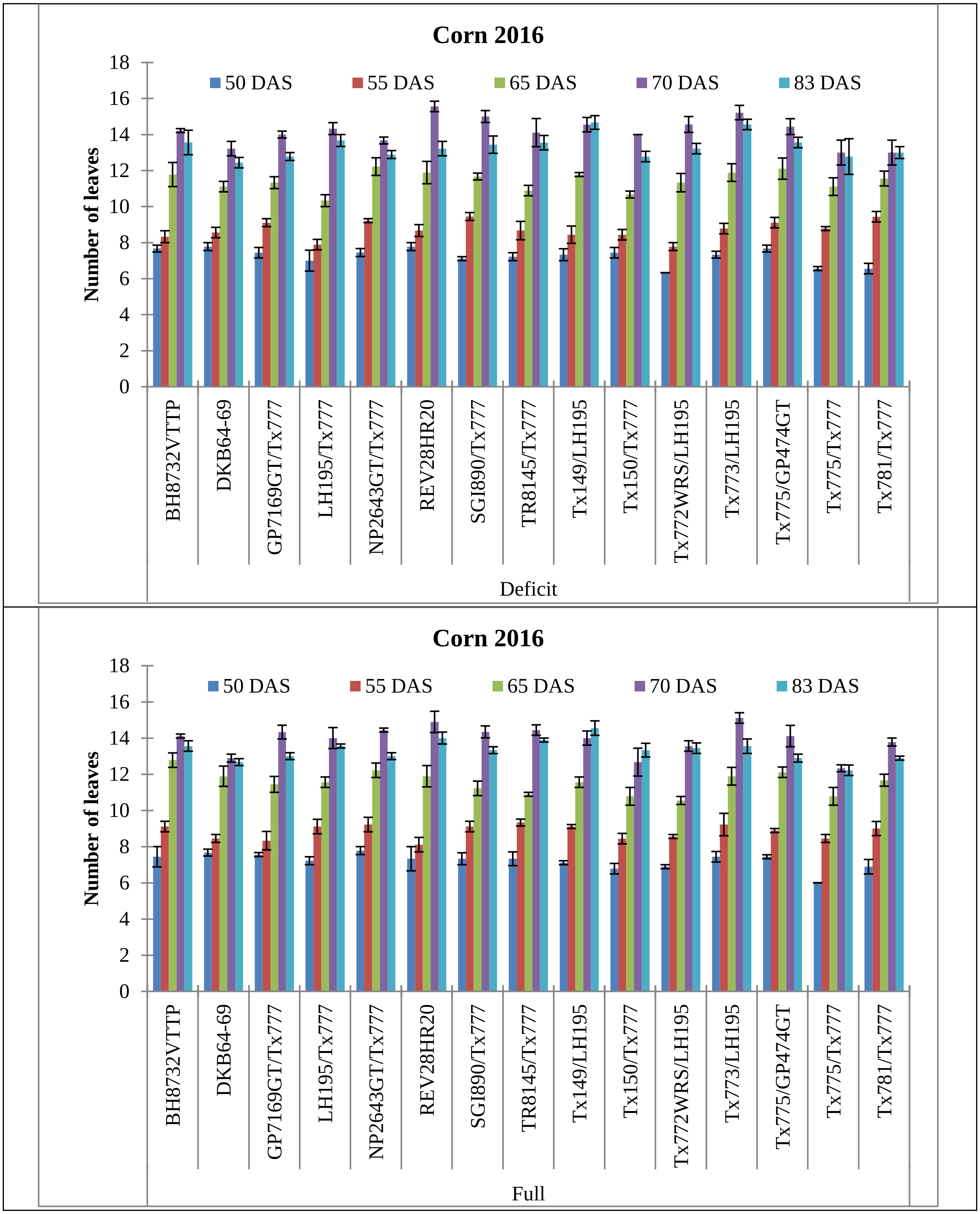


**Figure 2.4.** Number of green leaves/plant present in corn hybrids at different growth stages in deficit and full irrigation regimes in 2016. Standard error bar represents standard error of the mean.

**Table 2.4. Significant differences among different corn hybrids based on number of green leaves/plant present at 83 DAS in 2016. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| Tx149/LH195 | A | 14.61 |
| Tx773/LH195 | A B | 14.06 |
| TR8145/Tx777 | B C | 13.72 |
| REV28HR20 | B C D | 13.61 |
| LH195/Tx777 | B C D | 13.61 |
| BH8732VTTP | B C D E | 13.56 |
| SGI890/Tx777 | C D E F | 13.39 |
| Tx772WRS/LH195 | C D E F | 13.33 |
| Tx775/GP474GT | C D E F | 13.22 |
| Tx150/Tx777 | D E F G | 13.06 |
| Tx781/Tx777 | E F G | 12.95 |
| NP2643GT/Tx777 | E F G | 12.95 |
| GP7169GT/Tx777 | F G | 12.89 |
| DKB64-69 | G | 12.56 |
| Tx775/Tx777 | G | 12.5 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.02 | 0.9 |
| Genotypes | 5.87 | <.0001* |
| Irrigation Regimes*Genotypes | 1 | 0.47 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.23 | 0.08 | 0.09 | 19.01 |
| Residual | | 0.32 | 0.06 | 80.99 |

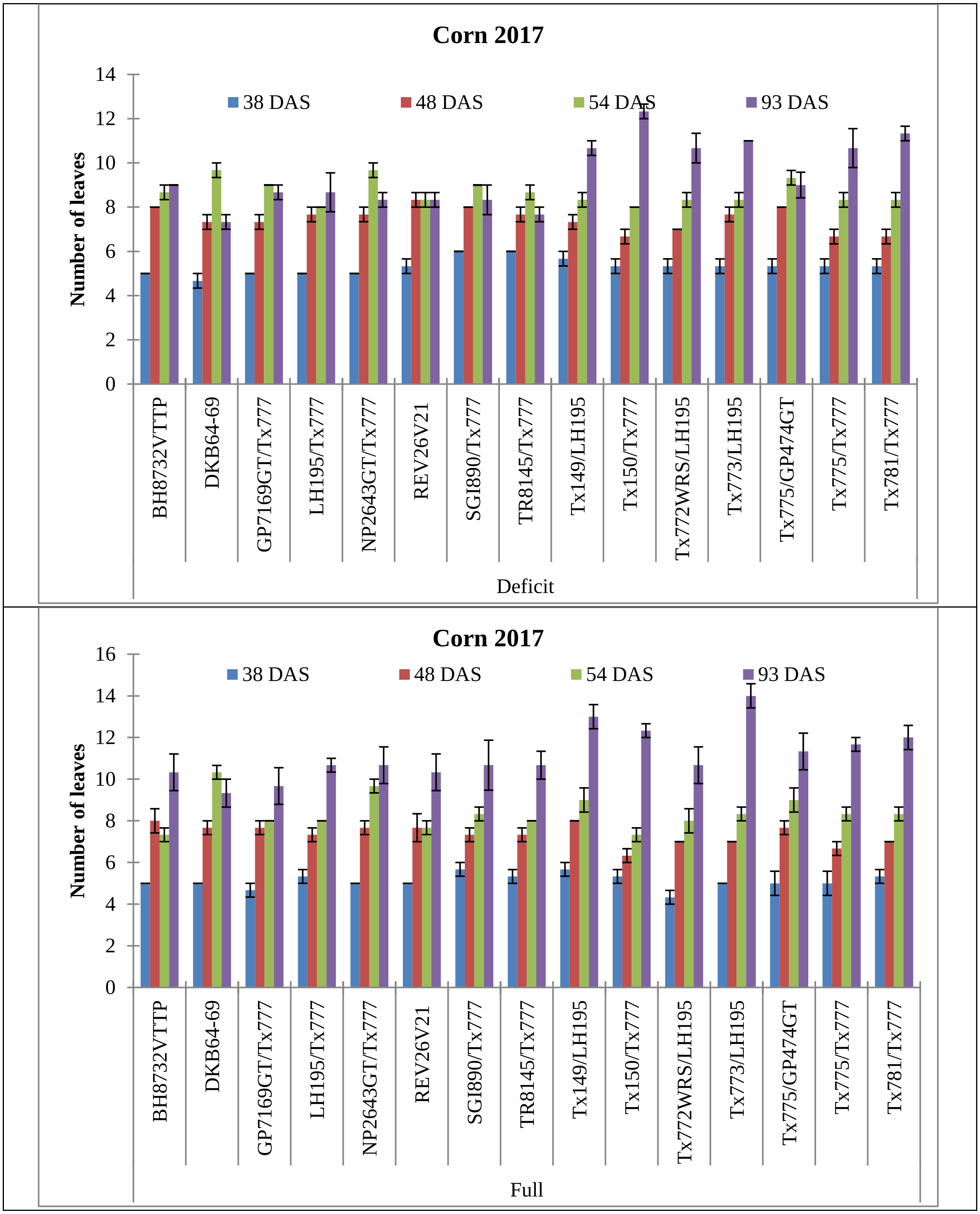


**Figure 2.5.** Number of green leaves/plant present in corn hybrids at different growth stages in deficit and full irrigation regimes in 2017. Standard error bar represents standard error of the mean.

**Table 2.5. Significant differences among different corn hybrids based on number of green leaves/plant present at 93 DAS in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| **Level** | | **Least Sq Mean** |
|---|---|---|
| Tx773/LH195 | A | 12.5 |
| Tx150/Tx777 | A B | 12.33 |
| Tx149/LH195 | A B C | 11.83 |
| Tx781/Tx777 | A B C | 11.67 |
| Tx775/Tx777 | B C D | 11.17 |
| Tx772WRS/LH195 | C D E | 10.67 |
| Tx775/GP474GT | D E F | 10.17 |
| BH8732VTTP | E F | 9.67 |
| LH195/Tx777 | E F | 9.67 |
| NP2643GT/Tx777 | E F G | 9.5 |
| SGI890/Tx777 | E F G | 9.5 |
| REV26V21 | F G | 9.33 |
| GP7169GT/Tx777 | F G | 9.17 |
| TR8145/Tx777 | F G | 9.17 |
| DKB64-69 | G | 8.33 |

| **Irrigation** | | **Least Sq Mean** |
|---|---|---|
| Full | A | 11.16 |
| Deficit | B | 9.47 |

| **Fixed Effect** | **F Ratio** | **Prob > F** |
|---|---|---|
| Irrigation Regimes | 17.61 | 0.0137* |
| Genotypes | 9.84 | <.0001* |
| Irrigation Regimes*Genotypes | 1.38 | 0.19 |

| **Random Effect** | **Var Ratio** | **Var Component** | **Std Error** | **% Variance** |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.17 | 0.17 | 0.17 | 14.55 |
| Residual | | 1.03 | 0.19 | 85.45 |

Commercial temperate corn hybrid DKB64-69 showed significantly fewer green leaves in full and deficit irrigation regimes compared to other commercial hybrids at 83 DAS in 2016 (Table 2.4) and 93 DAS in 2017 (Table 2.5). Compared to other experimental hybrids, Tx149/LH195, Tx773/LH195, TR8145/Tx777, and LH195/Tx777 showed significantly greater number of green leaves compared to NP2643GT/Tx777, GP7169GT/Tx777, and Tx775/Tx777 at 83 DAS in 2016 (Table 2.4 and Figure 2.4). In 2017, greater number of green leaves were observed in experimental hybrids Tx773/LH195, Tx150/Tx777, Tx149/LH195, and Tx781/Tx777 and the values were significantly different from SGI890/Tx777, GP7169GT/Tx777, and TR8145/Tx777 showing fewer green leaves at 93 DAS in 2017 under both the irrigation regimes (Table 2.5 and Figure 2.5). Main effect of irrigation and interaction of irrigation x genotypes were not significant, but significant effect of genetic make-up was observed in 2016. In 2017, irrigation regimes also showed significant main effect and number of green leaves under full irrigation regime was significantly higher than that under deficit irrigation.

### *Leaf structure and orientation*

Leaf structure and orientation plays an important role in predicting water use of a plant/genotype. Leaf area index (LAI) and mean tilt angle (MTA) were measured in 2016 during the flowering period in corn. No significant effects of irrigation or irrigation x genotypes interaction on LAI were observed. Genetic make-up and unknown residual were major sources causing variations in LAI of different hybrids. Experimental hybrids, Tx773/LH195, Tx150/Tx777, LH195/Tx777, Tx149/LH195, and Tx772WRS/LH195 showed significantly higher LAI compared to all other hybrids under both the irrigation regimes (Table 2.6). Significantly lower LAI were observed in TR8145/Tx777, Tx775/GP474GT, GP7169GT/Tx777, NP2643GT/Tx777, and BH8732VTTP (commercial). No significant main effect of irrigation, genotypes, and their interaction were observed on MTA of corn hybrids (Table 2.7). Unknown residual caused maximum variations in MTA of hybrids.

**Table 2.6. Significant differences among different corn hybrids based on leaf area index (LAI) in 2016. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---:|
| Tx773/LH195 | A | 5.02 |
| Tx150/Tx777 | A B | 5 |
| LH195/Tx777 | A B C | 4.99 |
| Tx149/LH195 | A B C D | 4.73 |
| Tx772WRS/LH195 | A B C D E | 4.64 |
| DKB64-69 | B C D E | 4.56 |
| SGI890/Tx777 | C D E | 4.55 |
| Tx775/Tx777 | D E | 4.54 |
| Tx781/Tx777 | D E F | 4.32 |
| REV28HR20 | D E F | 4.3 |
| TR8145/Tx777 | E F | 4.24 |
| Tx775/GP474GT | E F | 4.23 |
| GP7169GT/Tx777 | E F | 4.23 |
| NP2643GT/Tx777 | F | 3.91 |
| BH8732VTTP | F | 3.9 |

| Fixed Effect | F Ratio | Prob > F |
|---|---:|---:|
| Irrigation Regimes | 0.75 | 0.39 |
| Genotypes | 5.31 | <.0001* |
| Irrigation Regimes*Genotypes | 1.34 | 0.22 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---:|---:|---:|---:|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.24 | 0.04 | 0.04 | 19.49 |
| Residual | | 0.15 | 0.03 | 80.51 |

**Table 2.7. Fixed and random effect of different sources of variation on mean tilt angle (MTA) of corn hybrids in full and deficit irrigation regimes in 2016. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Fixed Effect | F Ratio | Prob > F |
|---|---:|---:|
| Irrigation Regimes | 0.24 | 0.63 |
| Genotypes | 1.47 | 0.15 |
| Irrigation Regimes*Genotypes | 1.13 | 0.35 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---:|---:|---:|---:|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 46.21 | 8.44 | 100 |

### *Leaf thickness (LT), leaf tissue density (LD), leaf dry matter content (LDMC), specific leaf area (SLA), and osmotic potential*

No significant increase in leaf thickness (LT) from flowering to dough stage was seen for corn hybrids (Figure 2.6). Main effect of genetic make-up (genotypes) was significant at flowering stage but no significant main effect of any sources were seen at dough stage. As explained on page 12, LT is positively related with photosynthetic efficiency. Thicker leaves tend to absorb more $CO_2$. Commercial hybrids REV26V21, DKB64-69, and BH8732VTTP showed no significant differences based on their leaf thickness. However, significantly low LT was observed in DKB64-69 and BH8732VTTP (Table 2.8). Experimental hybrids Tx775/Tx777, TR8145/Tx777, and Tx150/Tx777 showed significantly higher LT and NP2643GT/Tx777, Tx772WRS/LH195, and GP7169GT/Tx777 showed significantly lower LT (Table 2.8).

Leaf dry matter content (LDMC) is important during dough stage. Higher LDMC relates to higher relative water content of cells in any crop/genotype that prevent plants from wilting early. However, main effect of irrigation, genotypes, and their interaction were not significant at dough stage. At flowering stage, genetic make-up showed significant main effect (Table 2.9). LDMC for corn hybrids increased from flowering to dough stage in both the irrigation regimes that shows resistance of plants to permanent wilting point (Figure 2.7). Commercial hybrid REV26V21 showed significantly lower LDMC compared to most of the hybrids. LDMC was significantly higher in experimental hybrids Tx775/Tx777 and LH195/Tx777 compared to all three commercial hybrids (Table 2.9).

As mentioned on page 11, positive correlation exists between leaf tissue density (LD) and LDMC. Corn hybrids showed an increase in LD from flowering to dough stage (Figure 2.8). Main effect of genetic make-up and its interaction with irrigation were significant at flowering stage, but only genetic effect was significant at dough stage (Table 2.10). Unknown residuals was also responsible for variations among genotypes under deficit and full irrigation regimes at flowering stage. Corn hybrids DKB64-69 and GP7169GT/Tx777 under deficit irrigation and Tx775/GP474GT and LH195/Tx777 under full irrigation showed significantly higher LD compared to TR8145/Tx777 and Tx149/LH195 under deficit irrigation and Tx149/LH195 and GP7169GT/Tx777 under full irrigation that showed significantly low LD (Table 2.10).

Specific leaf area (SLA) is an inverse function of LT and LDMC or LT and LD, so corn hybrids with higher LT and LDMC should have low SLA. SLA decreased from flowering to dough stage (Figure 2.9). Main effect of genetic make-up was significant at flowering stage and dough stage (Table 2.11). Irrigation and irrigation x genotypes did not show significant main effect. NP2643GT/Tx777 and GP7169GT/Tx777 with significantly low LT and Tx149/LH195 with significantly low LD showed significantly higher SLA. Tx775/Tx777, LH195/Tx777, Tx781/Tx777, and Tx150/Tx777 with high LT, LDMC, or LD showed significantly low SLA (Table 2.11) compared to abovementioned experimental hybrids showing higher SLA.

Overlapping standard error bars for most of the hybrids confirm that osmotic potential did not changed much from flowering to dough stage (Figure 2.10). However, full irrigation hybrids showed significantly higher osmotic potential compared to deficit irrigation hybrids at dough stage. During flowering stage, the genetic main effect was significant. Experimental hybrids Tx772WRS/LH195, Tx149/LH195, and Tx775/Tx777 showed significantly higher osmotic potential compared to LH195/Tx777 and Tx150/Tx777 (Table 2.12). Significantly lower osmotic potential confirms the higher soil-water use even at later growth stage. This might add to higher grain yield.

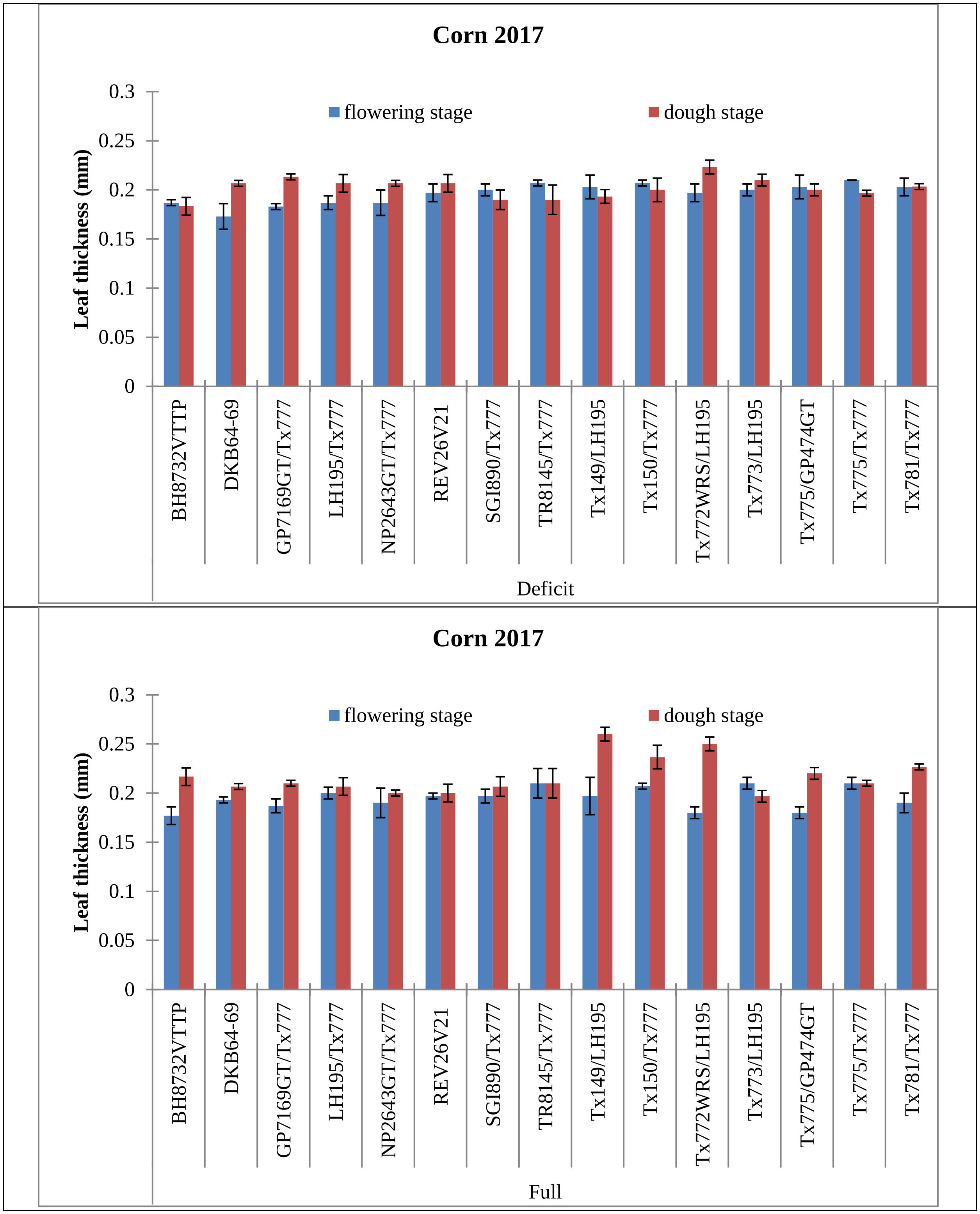


**Figure 2.6.** Leaf thickness (mm) for corn genotypes in full and deficit irrigation regimes in 2017. Blue bar is leaf thickness during flowering stage and red bar is leaf thickness during dough stage. Standard error bar represents standard error of the mean.

**Table 2.8. Significant differences among corn hybrids based on leaf thickness (mm) at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. No significant main effect of irrigation, genotypes, and their interaction were observed during dough stage. Values with asterisk (*) shows significant main effect.**

| **Level** | | **Least Sq Mean** |
|---|---|---|
| Tx775/Tx777 | A | 0.21 |
| TR8145/Tx777 | A B | 0.21 |
| Tx150/Tx777 | A B C | 0.21 |
| Tx773/LH195 | A B C | 0.21 |
| Tx149/LH195 | A B C D | 0.2 |
| SGI890/Tx777 | A B C D E | 0.2 |
| REV26V21 | A B C D E F | 0.2 |
| Tx781/Tx777 | A B C D E F | 0.2 |
| LH195/Tx777 | B C D E F | 0.19 |
| Tx775/GP474GT | C D E F | 0.19 |
| NP2643GT/Tx777 | D E F | 0.19 |
| Tx772WRS/LH195 | D E F | 0.19 |
| GP7169GT/Tx777 | D E F | 0.19 |
| DKB64-69 | E F | 0.18 |
| BH8732VTTP | F | 0.18 |

| **Fixed Effect** | **F Ratio** | **Prob > F** |
|---|---|---|
| Irrigation Regimes | 0.1 | 0.79 |
| Genotypes | 2.56 | 0.0066* |
| Irrigation Regimes*Genotypes | 0.99 | 0.48 |

| **Random Effect** | **% Variance** |
|---|---|
| Rep | 7.37 |
| Irrigation Regimes*Rep | 6.16 |
| Residual | 86.47 |

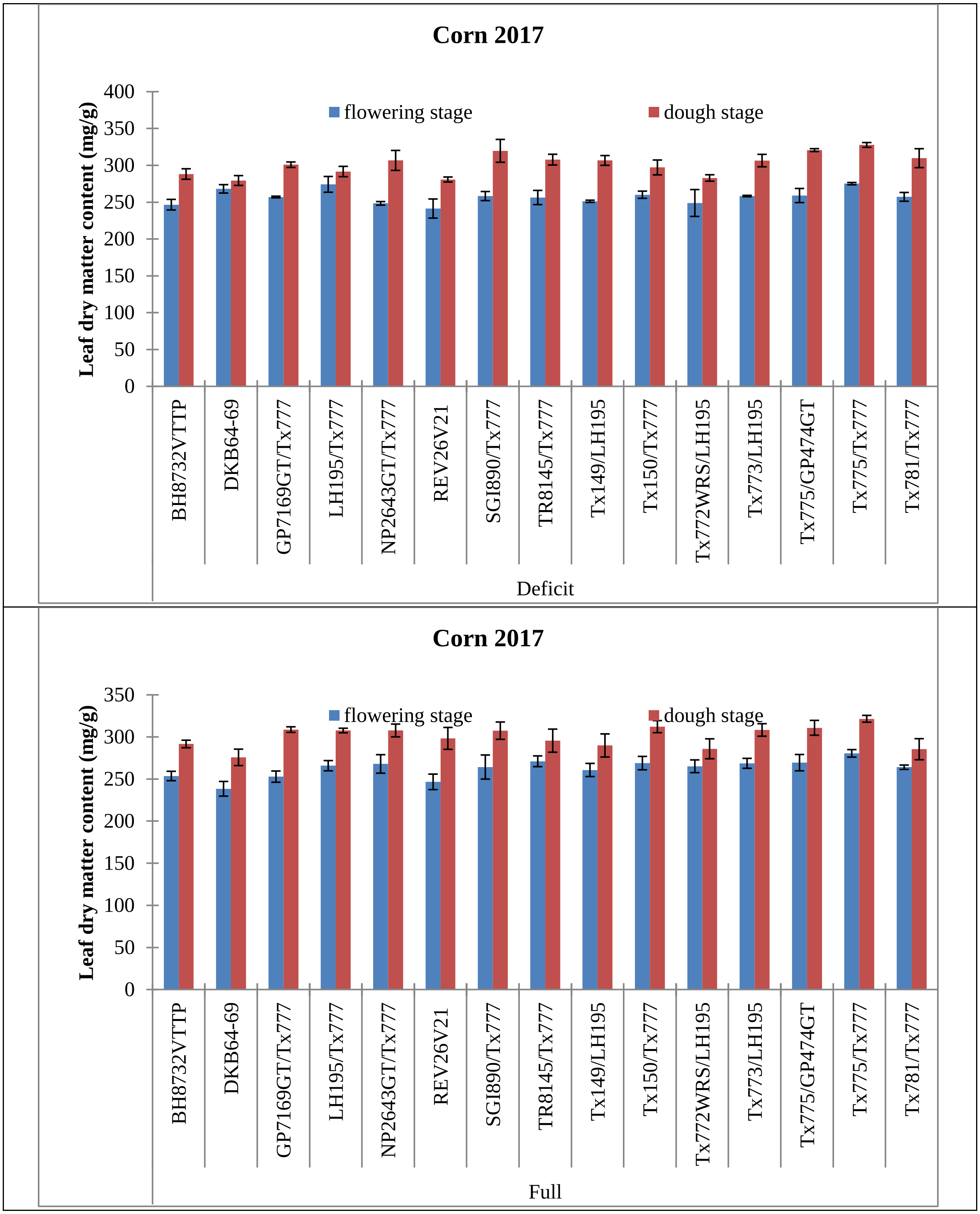


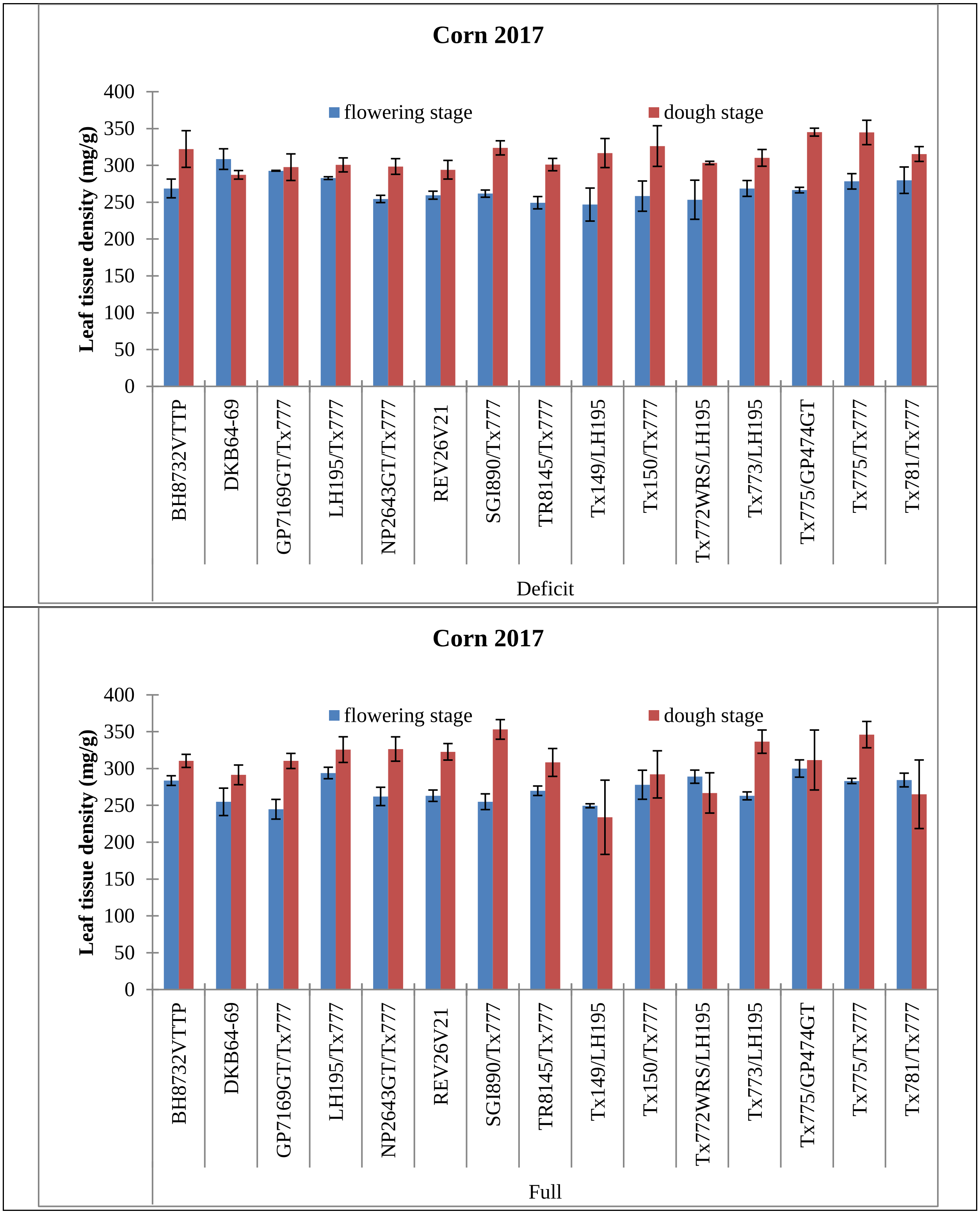
**Figure 2.7.** Leaf dry matter content (LDMC) (mg/g) for corn genotypes in full and deficit irrigation regimes in 2017. Blue bar is LDMC during flowering stage and red bar is LDMC during dough stage. Standard error bar represents standard error of the mean.

**Table 2.9. Significant differences among corn hybrids based on leaf dry matter content (mg/g) at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. Only genetic make-up of hybrids showed significant effect at dough stage.**

| Level | | Least Sq Mean |
|---|---|---:|
| Tx775/Tx777 | A | 277.84 |
| LH195/Tx777 | A B | 270.01 |
| Tx150/Tx777 | A B C | 264.52 |
| Tx775/GP474GT | A B C | 264.23 |
| TR8145/Tx777 | A B C | 263.74 |
| Tx773/LH195 | A B C | 263.5 |
| SGI890/Tx777 | B C | 261.28 |
| Tx781/Tx777 | B C | 260.64 |
| NP2643GT/Tx777 | B C D | 258.19 |
| Tx772WRS/LH195 | B C D | 257.02 |
| Tx149/LH195 | B C D | 255.98 |
| GP7169GT/Tx777 | B C D | 254.94 |
| DKB64-69 | C D | 253.26 |
| BH8732VTTP | C D | 250.13 |
| REV26V21 | D | 244.01 |

| Fixed Effect | F Ratio | Prob > F |
|---|---:|---:|
| Irrigation Regimes | 2.5 | 0.19 |
| Genotypes | 2.08 | 0.0277* |
| Irrigation Regimes*Genotypes | 1.11 | 0.37 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---:|---:|---:|---:|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.02 | 3.27 | 11.7 | 1.66 |
| Residual | | 193.66 | 36.6 | 98.34 |


Corn 2017

Corn 2017

**Figure 2.8.** Leaf tissue density (LD) (mg/g) for corn genotypes in full and deficit irrigation regimes in 2017. Blue bar is LD during flowering stage and red bar is LD during dough stage. Standard error bar represents standard error of the mean.

**Table 2.10. Significant differences among corn hybrids in full and deficit irrigation based on leaf tissue density (mg/g) at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. Only genetic make-up showed significant main effect at dough stage.**

| Level | | | | | | | | | | Least Sq Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| Deficit,DKB64-69 | A | | | | | | | | | 308.53 |
| Full,Tx775/GP474GT | A | B | | | | | | | | 300 |
| Full,LH195/Tx777 | A | B | C | | | | | | | 293.96 |
| Deficit,GP7169GT/Tx777 | A | B | C | D | | | | | | 292.71 |
| Full,Tx772WRS/LH195 | A | B | C | D | E | | | | | 288.94 |
| Full,Tx781/Tx777 | A | B | C | D | E | F | | | | 284.43 |
| Full,BH8732VTTP | A | B | C | D | E | F | G | | | 283.65 |
| Full,Tx775/Tx777 | A | B | C | D | E | F | G | | | 283.13 |
| Deficit,LH195/Tx777 | A | B | C | D | E | F | G | | | 282.7 |
| Deficit,Tx781/Tx777 | A | B | C | D | E | F | G | H | | 279.86 |
| Deficit,Tx775/Tx777 | A | B | C | D | E | F | G | H | I | 278.31 |
| Full,Tx150/Tx777 | A | B | C | D | E | F | G | H | I | 278.01 |
| Full,TR8145/Tx777 | | B | C | D | E | F | G | H | I | 269.83 |
| Deficit,Tx773/LH195 | | B | C | D | E | F | G | H | I | 268.69 |
| Deficit,BH8732VTTP | | B | C | D | E | F | G | H | I | 268.67 |
| Deficit,Tx775/GP474GT | | B | C | D | E | F | G | H | I | 266.46 |
| Full,REV26V21 | | | C | D | E | F | G | H | I | 263.11 |
| Full,Tx773/LH195 | | | C | D | E | F | G | H | I | 262.92 |
| Full,NP2643GT/Tx777 | | | C | D | E | F | G | H | I | 262.14 |
| Deficit,SGI890/Tx777 | | | C | D | E | F | G | H | I | 261.65 |
| Deficit,REV26V21 | | | C | D | E | F | G | H | I | 259.54 |
| Deficit,Tx150/Tx777 | | | | D | E | F | G | H | I | 258.26 |
| Full,SGI890/Tx777 | | | | | E | F | G | H | I | 254.95 |
| Full,DKB64-69 | | | | | E | F | G | H | I | 254.79 |
| Deficit,NP2643GT/Tx777 | | | | | E | F | G | H | I | 254.43 |
| Deficit,Tx772WRS/LH195 | | | | | | F | G | H | I | 253.36 |
| Full,Tx149/LH195 | | | | | | | G | H | I | 249.45 |
| Deficit,TR8145/Tx777 | | | | | | | G | H | I | 249.32 |
| Deficit,Tx149/LH195 | | | | | | | | H | I | 246.8 |
| Full,GP7169GT/Tx777 | | | | | | | | | I | 244.75 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.45 | 0.5 |
| Genotypes | 1.84 | 0.05* |
| Irrigation Regimes*Genotypes | 2.13 | 0.0225* |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 443.46 | 80.96 | 100 |

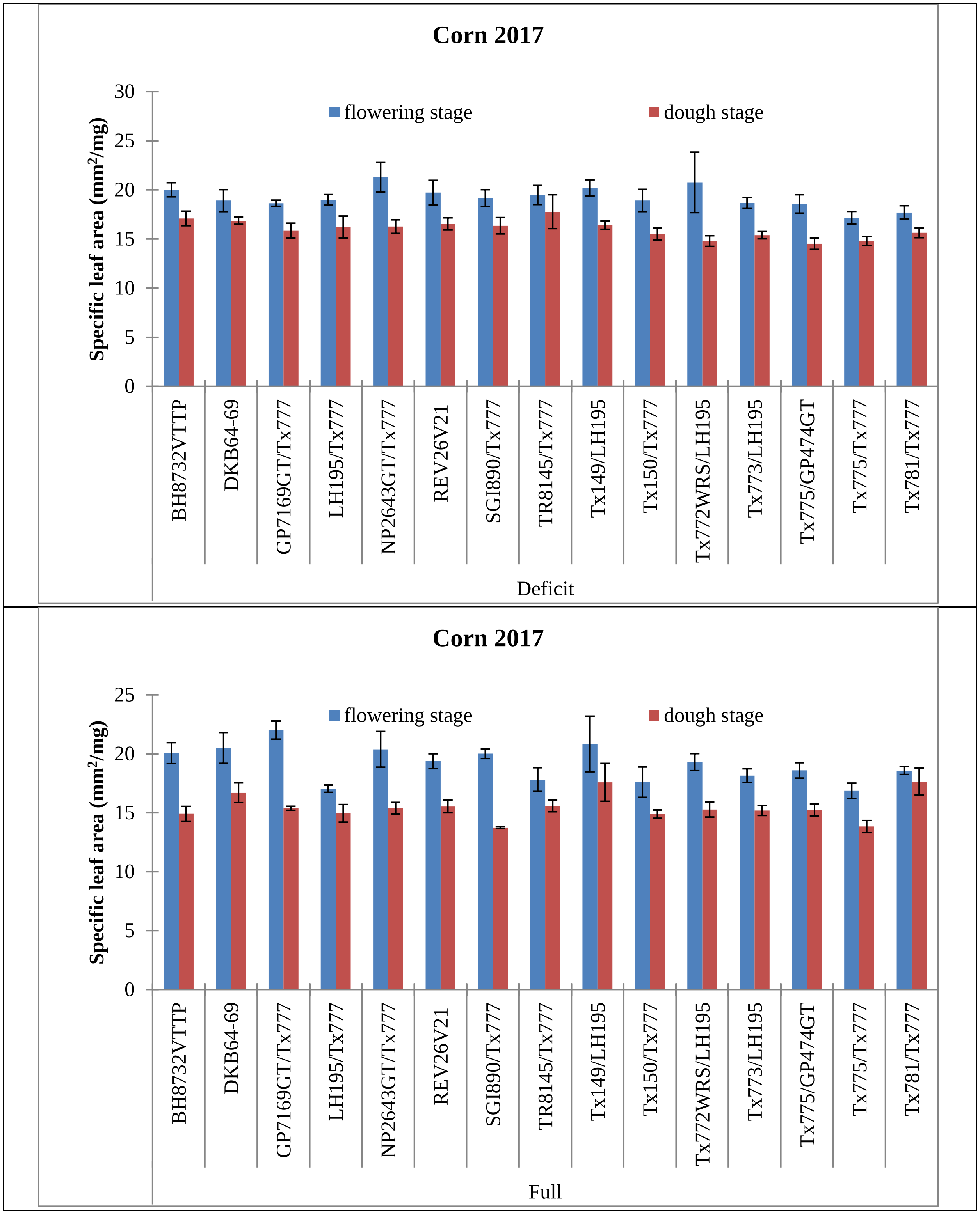


**Figure 2.9.** Specific leaf area (SLA) ($mm^2/mg$) for corn genotypes in full and deficit irrigation regimes in 2017. Blue bar is SLA during flowering stage and red bar is SLA during dough stage. Standard error bar represents standard error of the mean.

**Table 2.11. Significant differences among corn hybrids based on specific leaf area ($mm^2/mg$) at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. Main effect of genotypes was significant even at dough stage.**

| Level | | | | | | Least Sq Mean |
|---|---|---|---|---|---|---|
| NP2643GT/Tx777 | A | | | | | 20.83 |
| Tx149/LH195 | A | B | | | | 20.52 |
| GP7169GT/Tx777 | A | B | C | | | 20.33 |
| BH8732VTTP | A | B | C | D | | 20.04 |
| Tx772WRS/LH195 | A | B | C | D | | 20.03 |
| DKB64-69 | A | B | C | D | | 19.7 |
| SGI890/Tx777 | A | B | C | D | | 19.59 |
| REV26V21 | A | B | C | D | | 19.54 |
| TR8145/Tx777 | | B | C | D | E | 18.65 |
| Tx775/GP474GT | | B | C | D | E | 18.58 |
| Tx773/LH195 | | | C | D | E | 18.41 |
| Tx150/Tx777 | | | | D | E | 18.26 |
| Tx781/Tx777 | | | | D | E | 18.14 |
| LH195/Tx777 | | | | D | E | 18.02 |
| Tx775/Tx777 | | | | | E | 17.01 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.02 | 0.91 |
| Genotypes | 2.32 | 0.0135* |
| Irrigation Regimes*Genotypes | 0.93 | 0.53 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.08 | 0.27 | 0.58 | 7.15 |
| Irrigation Regimes*Rep | 0.1 | 0.3 | 0.51 | 8.11 |
| Residual | | 3.16 | 0.6 | 84.74 |

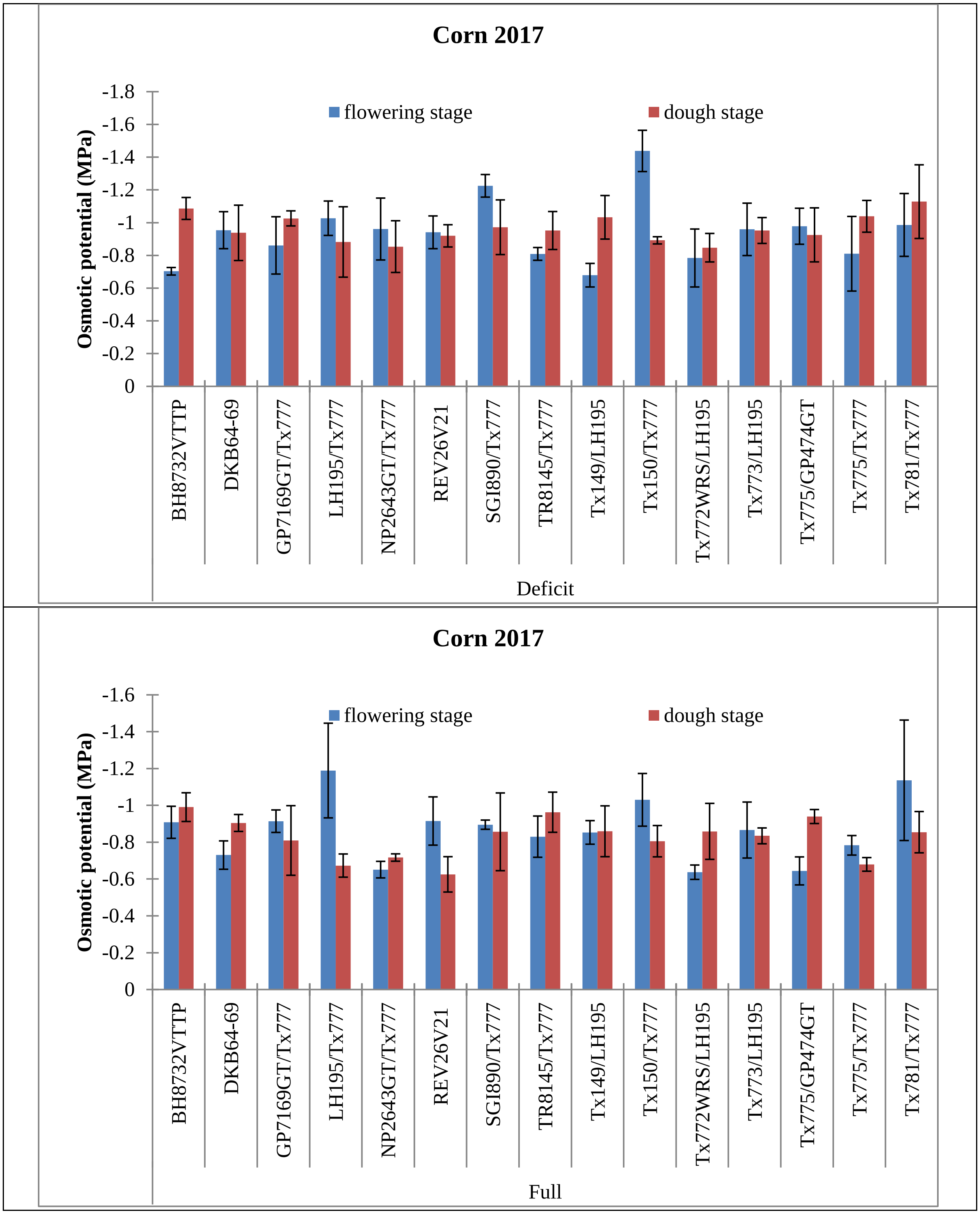


**Figure 2.10.** Osmotic potential (MPa) for corn genotypes in full and deficit irrigation regimes in 2017. Blue bar is osmotic potential during flowering stage and red bar is osmotic potential during dough stage. Standard error bar represents standard error of the mean.

**Table 2.12. Significant differences among corn hybrids based on osmotic potential (MPa) at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var. represents variance. Values with asterisk (*) shows significant main effect. At dough stage, only irrigation showed significant main effect and full irrigation hybrids had significantly higher osmotic potential than deficit irrigation hybrids.**

| Level | | | | | Least Sq Mean |
|---|---|---|---|---|---|
| Tx772WRS/LH195 | A | | | | -0.71 |
| Tx149/LH195 | A | | | | -0.77 |
| Tx775/Tx777 | A | B | | | -0.8 |
| BH8732VTTP | A | B | | | -0.81 |
| NP2643GT/Tx777 | A | B | | | -0.81 |
| Tx775/GP474GT | A | B | | | -0.81 |
| TR8145/Tx777 | A | B | | | -0.82 |
| DKB64-69 | A | B | C | | -0.84 |
| GP7169GT/Tx777 | A | B | C | | -0.89 |
| Tx773/LH195 | A | B | C | | -0.91 |
| REV26V21 | A | B | C | | -0.93 |
| SGI890/Tx777 | | B | C | D | -1.06 |
| Tx781/Tx777 | | B | C | D | -1.06 |
| LH195/Tx777 | | | C | D | -1.11 |
| Tx150/Tx777 | | | | D | -1.23 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 2.27 | 0.14 |
| Genotypes | 2.33 | 0.0125* |
| Irrigation Regimes*Genotypes | 1.14 | 0.34 |

| Random Effect | % Variance |
|---|---|
| Rep | 0.13 |
| Irrigation Regimes*Rep | 0 |
| Residual | 99.87 |

### *Chlorophyll content and NDVI*

No significant main effect of irrigation, genotypes, and their interaction were observed for chlorophyll content of corn hybrids at 34 days after sowing (DAS) and 40 days after sowing (DAS) in 2016 (Table 2.13 and Figure 2.11). In 2017, chlorophyll content for corn hybrids showed a significant main effect of irrigation and genetic make-up at 94 DAS (dough stage) and a significant main effect of irrigation on 101 DAS (maturity) (Figure 2.12 and Table 2.14). Chlorophyll content of hybrids under full irrigation at 94 DAS and 101 DAS was significantly higher than that under deficit irrigation. Hybrids with higher chlorophyll content even at dough stage confirms their prolonged staygreen period compared to others. This might be an advantage for their grain yield formation and biomass accumulation. Experimental hybrids Tx149/LH195, Tx775/Tx777, Tx150/Tx777, and Tx772WRS/LH195 showed significantly higher chlorophyll content compared to Tx773/LH195, Tx781/Tx777, NP2643GT/Tx777, LH195/Tx777, and TR8145/Tx777 (Table 2.14).

Normalized difference vegetation index (NDVI) of corn hybrids decreased sharply from milk stage to dough-dent stage, especially in deficit irrigation (Figure 2.13), confirming the short staygreen period of corn compared to sorghum. Decrease in NDVI from dough-dent stage to maturity was not as high as that from milk to dough-dent stage. Full irrigation NDVI was significantly higher that deficit irrigation NDVI at milk and dough-dent stage (Table 2.15 and Table 2.16), confirming the early drying of hybrids in water-stress condition. No significant main effect of irrigation or irrigation x genotypes on NDVI were observed at milk and dough-dent stage. Unknown residual was also responsible for some variations.

**Table 2.13. Fixed and random effect of different sources on chlorophyll content of corn hybrids under full and deficit irrigation regimes at 40 DAS in 2016. Results have been obtained from standard least square analysis using JMP 13.0 at $\alpha = 0.05$. Var represents variance. Values with asterisk (*) shows significant main effect. No significant main effect of irrigation, genetics or their interaction were observed even on 34 DAS.**

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.48 | 0.49 |
| Genotypes | 0.87 | 0.59 |
| Irrigation Regimes*Genotypes | 0.57 | 0.88 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.01 | 0.08 | 0.27 | 1.28 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual |  | 6.39 | 1.18 | 98.72 |

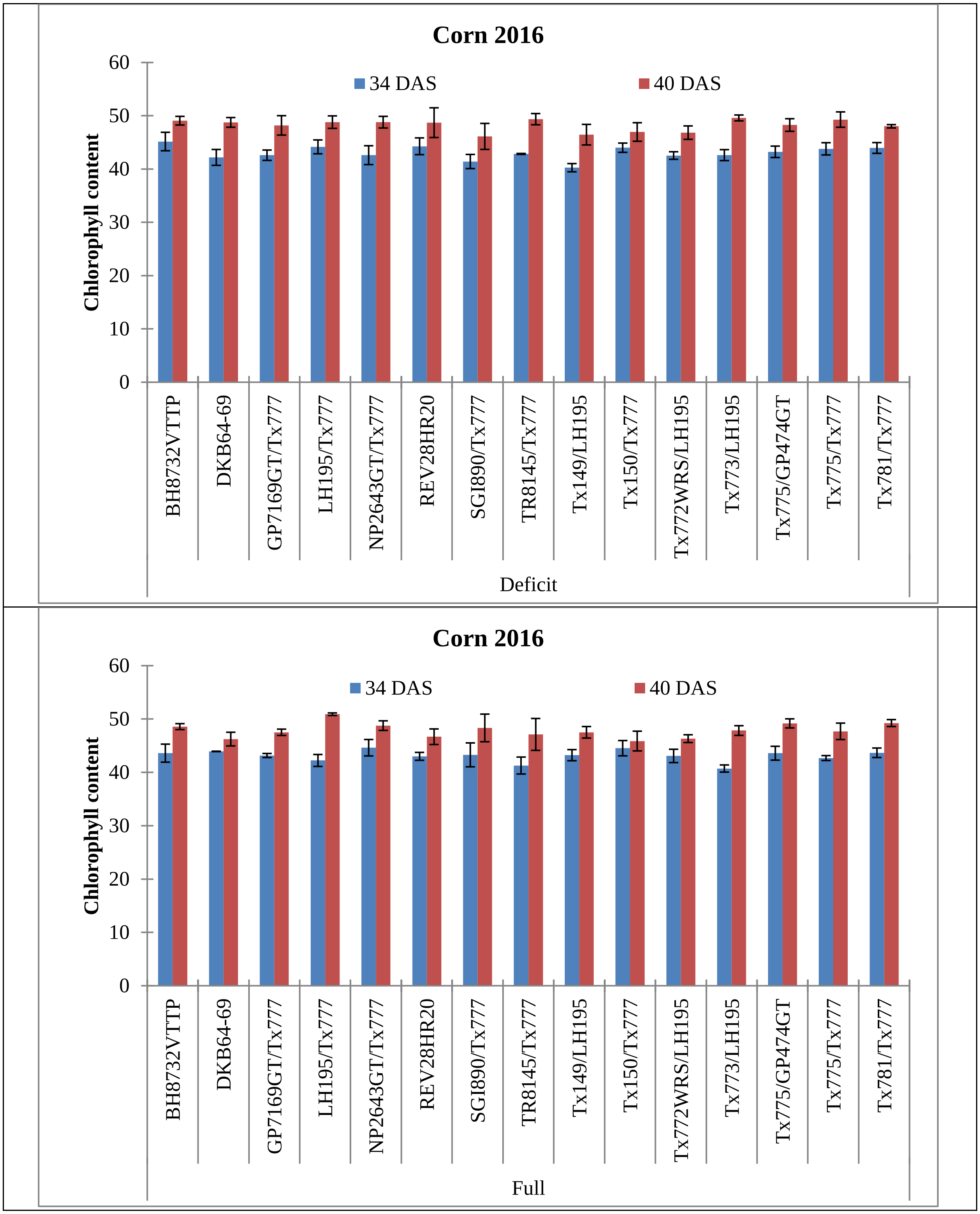


**Figure 2.11.** Chlorophyll content of corn genotypes measured at two different vegetative stages – 34 DAS (blue bar) and 40 DAS (red bar) for deficit and full irrigation regimes in 2016. Standard error bar represents standard error of the mean.

**Table 2.14. Significant differences among corn hybrids in full and deficit irrigation for chlorophyll content measured at 94 DAS in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at $\alpha = 0.05$. Genotypes and irrigation connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. Significant main effect of irrigation was also observed during maturity (101 DAS) and full irrigation chlorophyll content was significantly higher than that under deficit irrigation.**

| **Level** | | **Least Sq Mean** |
|---|---|---|
| Tx149/LH195 | A | 46.3 |
| Tx775/Tx777 | A B | 44.67 |
| Tx150/Tx777 | A B | 44.58 |
| Tx772WRS/LH195 | A B | 44.38 |
| Tx775/GP474GT | A B C | 42.35 |
| DKB64-69 | A B C D | 41.68 |
| BH8732VTTP | A B C D | 41.33 |
| REV26V21 | A B C D | 39.57 |
| GP7169GT/Tx777 | B C D | 38.37 |
| SGI890/Tx777 | B C D | 38.33 |
| Tx773/LH195 | C D | 36.85 |
| Tx781/Tx777 | C D | 36.55 |
| NP2643GT/Tx777 | C D | 36.52 |
| LH195/Tx777 | C D | 36.37 |
| TR8145/Tx777 | D | 35.03 |

| **Irrigation** | | **Least Sq Mean** |
|---|---|---|
| Full | A | 42.62 |
| Deficit | B | 37.76 |

| **Fixed Effect** | **F Ratio** | **Prob > F** |
|---|---|---|
| Irrigation Regimes | 15.03 | 0.0003* |
| Genotypes | 2.29 | 0.0143* |
| Irrigation Regimes*Genotypes | 0.61 | 0.84 |

| **Random Effect** | **Var Ratio** | **Var Component** | **Std Error** | **% Variance** |
|---|---|---|---|---|
| Rep | 0.46 | 16.09 | 17.27 | 31.27 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 35.37 | 6.57 | 68.73 |

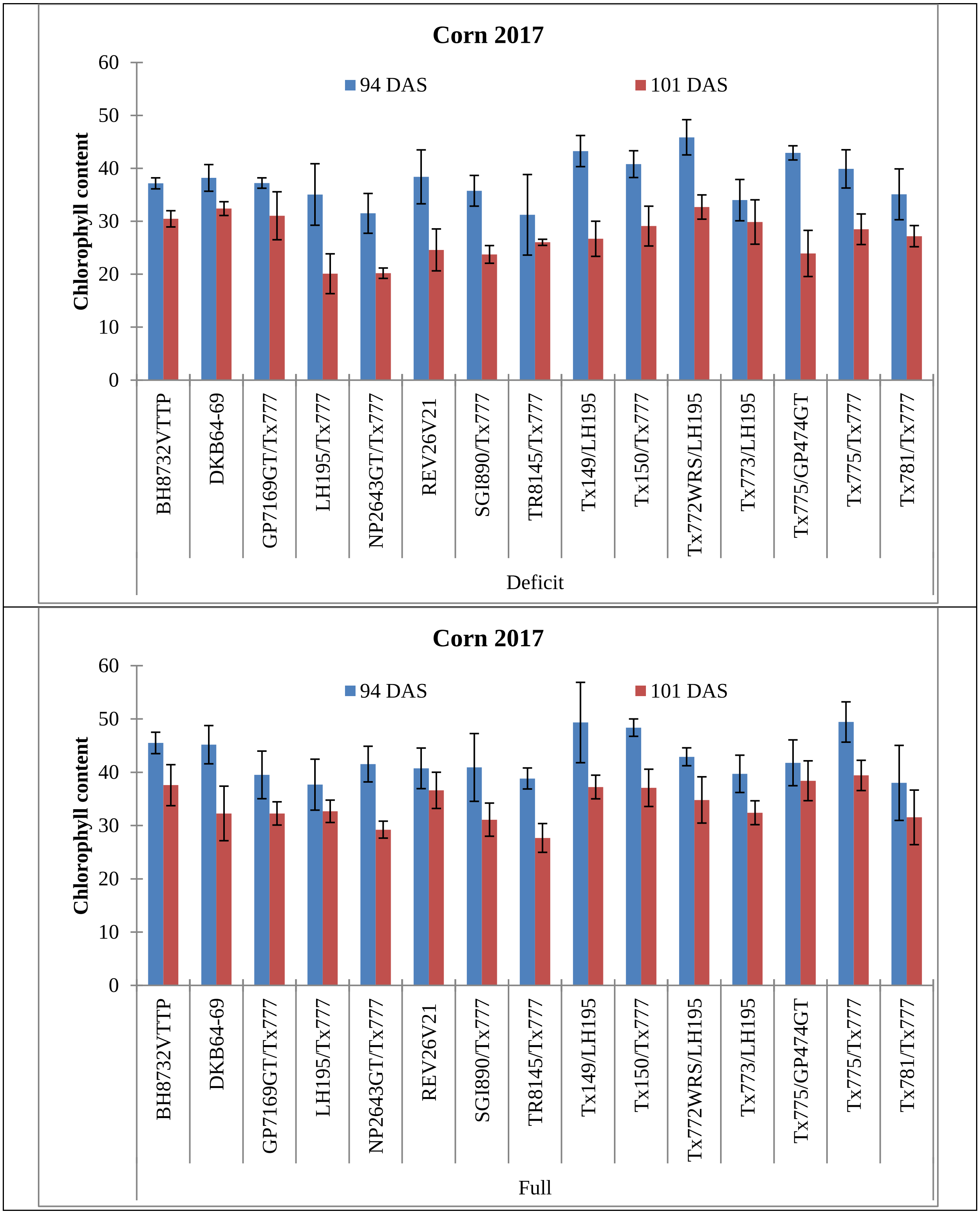


**Figure 2.12.** Chlorophyll content of corn genotypes measured during dough-dent stage (94 DAS) (blue bar) and maturity (101 DAS) (red bar) for deficit and full irrigation in 2017. Standard error bar represents standard error of the mean.

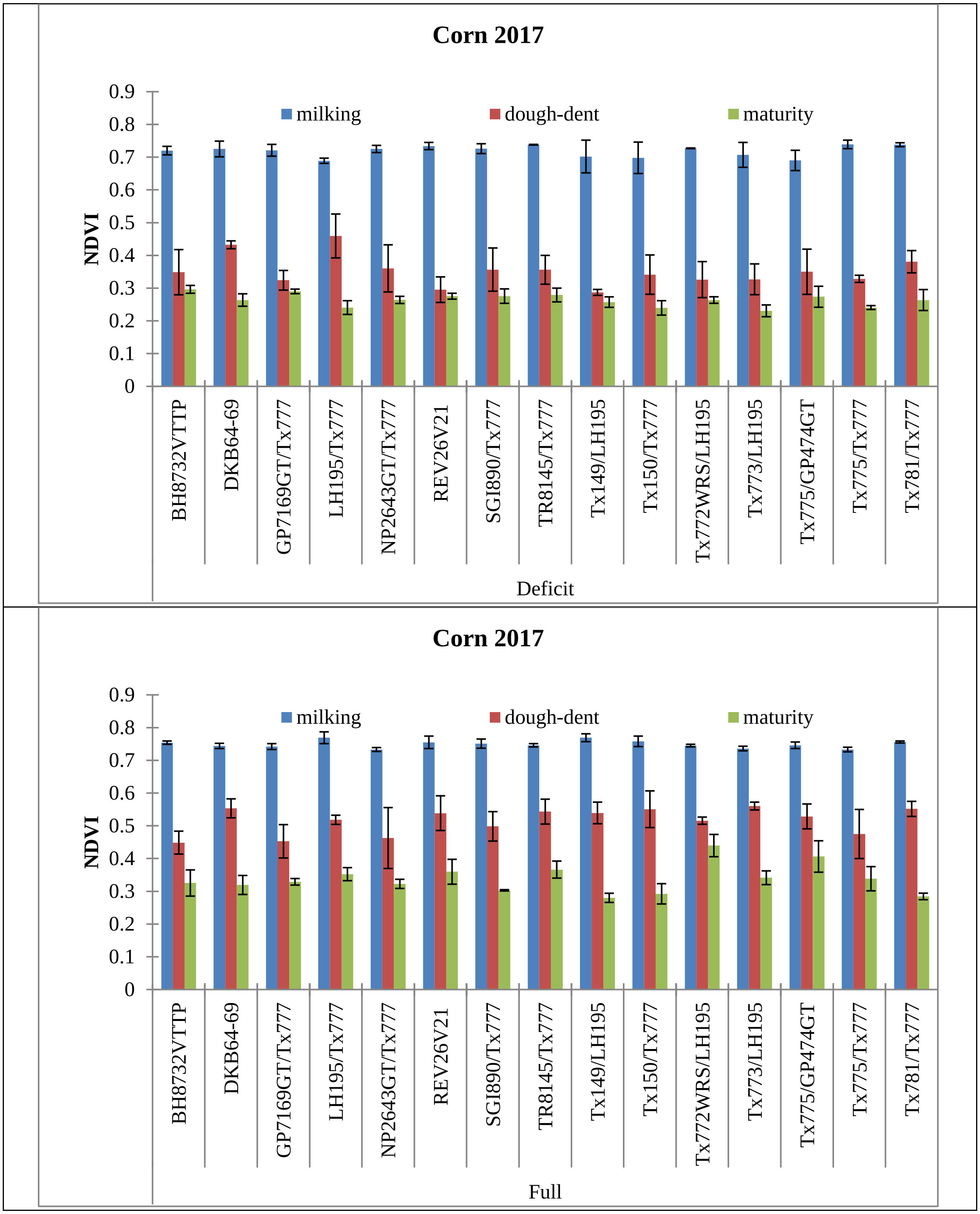


**Figure 2.13.** NDVI of corn genotypes measured during milking (blue bar), dough-dent (red bar) and maturity (green bar) stage for deficit and full irrigation in 2017. Standard error bar represents standard error of the mean.

**Table 2.15. Significant differences among full and deficit irrigation normalized difference vegetation index (NDVI) measured at milking stage (83 DAS) in 2017. Results have been obtained from standard least squares analysis in JMP 13.0 at α = 0.05. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Irrigation | | Least Sq Mean |
|---|---|---|
| Full | A | 0.75 |
| Deficit | B | 0.72 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 19.37 | <.0001* |
| Genotypes | 0.36 | 0.98 |
| Irrigation Regimes*Genotypes | 0.82 | 0.64 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 0 | 0 | 100 |

**Table 2.16. Significant differences among full and deficit irrigation normalized difference vegetation index (NDVI) measured at dent stage (95 DAS) in 2017. Results have been obtained from standard least squares analysis in JMP 13.0 at α = 0.05. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Irrigation | | Least Sq Mean |
|---|---|---|
| Full | A | 0.52 |
| Deficit | B | 0.35 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 90.56 | <.0001* |
| Genotypes | 0.88 | 0.58 |
| Irrigation Regimes*Genotypes | 0.72 | 0.74 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.05 | 0 | 0 | 4.65 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 0.01 | 0 | 95.35 |

### *Linear discriminant analysis and path coefficient analysis*

LDA and path coefficient values were performed in 2016 and 2017 to study the ability of a trait or combined ability of traits to categorize each genotype in their correct class and the effect of different traits on grain yield. In every table, LN represents number of green leaves. LDA was used to identify the trait or traits combinations that can correctly classify the genotypes into their respective classes. Ability of traits to make correct classification was tested for irrigation regimes in 2017 (Table 2.17). In 2017, the combinations of five traits (LT, LDMC, LD, NDVI, and LN) showed highest percentage of correct classification of genotypes in full and deficit irrigation regimes. There are three combinations with highest classification percentage in Table 2.17 but LDMC and LD shows positive correlation, either can be selected. In addition, the combination of four traits (LT, LDMC, NDVI, and LN) showed a correct classification percentage very close to five traits combinations classification percentage. NDVI selected in all the combinations confirmed its importance in drought tolerance related research.

**Table 2.17. Linear discriminant analysis (LDA) of canopy and leaf traits to categorize corn hybrids under full and deficit irrigation regimes in 2017. Values are in percentage.**

| Traits | Deficit | Full | Overall |
|---|---|---|---|
| LT, LDMC, LD, log(SLA), -1/OP, $(NDVI)^{10}$, $(Height)^2$, LN | 75.6 | 80 | 77.8 |
| LT, LDMC, LD, log(SLA), $(NDVI)^{10}$, $(Height)^2$, LN | 84.4 | 80 | 82.2 |
| LDMC, LD, log(SLA), $(NDVI)^{10}$, $(Height)^2$, LN | 84.4 | 80 | 82.2 |
| LT, LDMC, LD, $(NDVI)^{10}$, LN | 84.4 | 80 | 82.2 |
| LT, LDMC, log(SLA), $(NDVI)^{10}$, LN | 84.4 | 80 | 82.2 |
| LDMC, LD, log(SLA), $(NDVI)^{10}$, LN | 84.4 | 80 | 82.2 |
| LT, LDMC, $(NDVI)^{10}$, LN | 82.2 | 80 | 81.1 |
| $(NDVI)^{10}$, $(Height)^2$, LN | 75.6 | 80 | 77.8 |
| $(NDVI)^{10}$, LN | 75.6 | 80 | 77.8 |
| $(NDVI)^{10}$ | 73.3 | 66.7 | 70 |

Path coefficient analysis of different plant traits were performed in 2016 and 2017 (Table 2.18 to Table 2.19). Values in the last column of each table are the total effect of trait present in first column on grain yield. For example, LAI showed a strong negative total effect of -0.49 on grain yield of corn hybrids (Table 2.18). LAI alone showed a negative direct effect of -0.37 on grain yield, which was affected by indirect negative effect of plant height (-0.07) and number of green leaves (-0.14), and an indirect positive effect of mean tilt angle (MTA) (0.09).

**Table 2.18. Direct and indirect effects of canopy and leaf traits on grain yield of corn genotypes in 2016.**

| **Traits** | Height | LN | LAI | MTA | Total |
|---|---|---|---|---|---|
| Height | 0.89 | -0.34 | 0.03 | -0.22 | 0.37 |
| LN | 0.56 | -0.53 | -0.1 | -0.16 | -0.22 |
| LAI | -0.07 | -0.14 | -0.37 | 0.09 | -0.49 |
| MTA | 0.63 | -0.27 | 0.1 | -0.31 | 0.16 |

**Table 2.19. Direct and indirect effects of canopy and leaf traits measured at flowering stage on grain yield of corn genotypes in 2017.**

| **Traits** | Height | LN | Chl. | LT | LDMC | LD | SLA | OP | NDVI | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Height | -0.14 | 0 | 0.08 | 0.19 | 0.35 | -0.72 | 0.3 | 0 | -0.01 | 0.05 |
| LN | 0 | -0.3 | -0.08 | 0.73 | -0.44 | -0.11 | -0.38 | 0 | 0.02 | -0.56 |
| Chl. | 0.05 | -0.1 | -0.23 | 0.04 | -0.01 | -0.02 | 0.05 | 0 | 0.01 | -0.22 |
| LT | -0.02 | -0.17 | -0.01 | 1.28 | -0.68 | -0.31 | -0.61 | 0 | -0.01 | -0.53 |
| LDMC | 0.04 | -0.12 | 0 | 0.75 | -1.15 | 0.4 | -0.72 | 0 | 0.04 | -0.76 |
| LD | 0.09 | 0.03 | 0.01 | -0.35 | -0.4 | 1.14 | -0.53 | 0 | 0.02 | 0 |
| SLA | -0.04 | 0.12 | -0.01 | -0.83 | 0.88 | -0.64 | 0.95 | 0 | 0 | 0.41 |
| OP | 0.04 | 0.07 | -0.06 | -0.37 | 0.24 | -0.19 | 0.38 | 0 | 0 | 0.11 |
| NDVI | -0.02 | 0.06 | 0.03 | 0.09 | 0.38 | -0.2 | 0.08 | 0 | -0.1 | 0.31 |

### *Grain starch and crude protein quantification, aboveground biomass accumulation, and grain yield*

Availability of soil-water to plants is a factor leading to variation in different components of grain. With an increase in grain starch content, grain crude protein content decreased slightly (Figure 2.14 and Figure 2.15). Main effect of genetics on grain starch and protein content of corn hybrids was observed in 2016 and 2017 (Table 2.20 and Table 2.21). Irrigation or irrigation x genotypes did not show any significant effect. Variations was also contributed by some unknown factors (residual).

In 2016, Tx772WRS/LH195, REV28HR20, and GP7169GT/Tx777 showed significantly higher grain crude protein content and Tx150/Tx777 and Tx775/GP474GT showed significantly low grain crude protein (Table 2.20). Commercial hybrids DKB64-69 and BH8732VTTP showed significantly low grain crude protein compared to REV28HR20. Grain starch was higher in Tx149/LH195, TR8145/Tx777, LH195/Tx777, and SGI890/Tx777 and significantly lower in GP7169GT/Tx777, Tx775/Tx777, REV28HR20, Tx775/GP474GT, and BH8732VTTP (Table 2.20). Commercial hybrids showed no significant difference based on grain starch content in 2016.

In 2017, Tx772WRS/LH195, Tx781/Tx777, Tx150/Tx777, and SGI890/Tx777 showed significantly higher grain crude protein compared to Tx149/LH195, REV26V21, Tx775/Tx777, and Tx775/GP474GT (Table 2.21). Grain starch was higher in Tx149/LH195 and TR8145/Tx777 compared to all other experimental and commercial hybrids. Commercial hybrid BH8732VTTP showed significantly low grain starch content.

With increase in aboveground biomass, grain yield increased in both the years (Figure 2.16 and Figure 2.17). Commercial hybrids performed better than experimental hybrids in terms of grain yield and aboveground biomass. Genetic and its interaction with irrigation showed significant main effect on grain yield in 2016, however, effect of irrigation was also significant in 2017 (Table 2.22 and Table 2.23). Variations was also caused by residuals.

Among experimental hybrids, NP2643GT/Tx777 and Tx781/Tx777 under both the irrigation regimes, SGI890/Tx777 in deficit irrigation, and TR8145/Tx777 in full irrigation yielded high in 2016 (Table 2.22). No significant difference existed for grain yield of SGI890/Tx777 and TR8145/Tx777 under both the irrigation regimes. Grain yield of GP7169GT/Tx777 in both the irrigation regimes were not significantly different from other high yielding experimental hybrids. Significantly low yield was found in Tx772WRS/LH195 and Tx773/LH195 plots under both the irrigation regimes and Tx149/LH195 and Tx775/Tx777 in deficit irrigation (Table 2.22). Grain yield of Tx149/LH195 and Tx775/Tx777 showed no significant difference in full and deficit irrigation regimes. Full irrigation hybrids, Tx772WRS/LH195, Tx773/LH195, GP7169GT/Tx777, NP2643GT/Tx777, BH8732VTTP, and DKB64-69 and deficit irrigation hybrids, Tx781/Tx777, NP2643GT/Tx777, SGI890/Tx777, and REV28HR20 showed higher contribution to aboveground biomass (Figure 2.16).

In 2017, grain yield in full irrigation was significantly higher than that in deficit irrigation regimes (Table 2.23). Under deficit irrigation, experimental hybrids NP2643GT/Tx777 and GP7169GT/Tx777 showed higher grain yield compared to Tx775/Tx777, Tx772WRS/LH195, Tx149/LH195, and Tx150/Tx777. Higher aboveground biomass was found in REV26V21, BH8732VTTP, DKB64-69, and Tx150/Tx777 in deficit irrigation and DKB64-69, Tx149/LH195, TR8145/Tx777, and Tx773/LH195 in full irrigation (Figure 2.17).

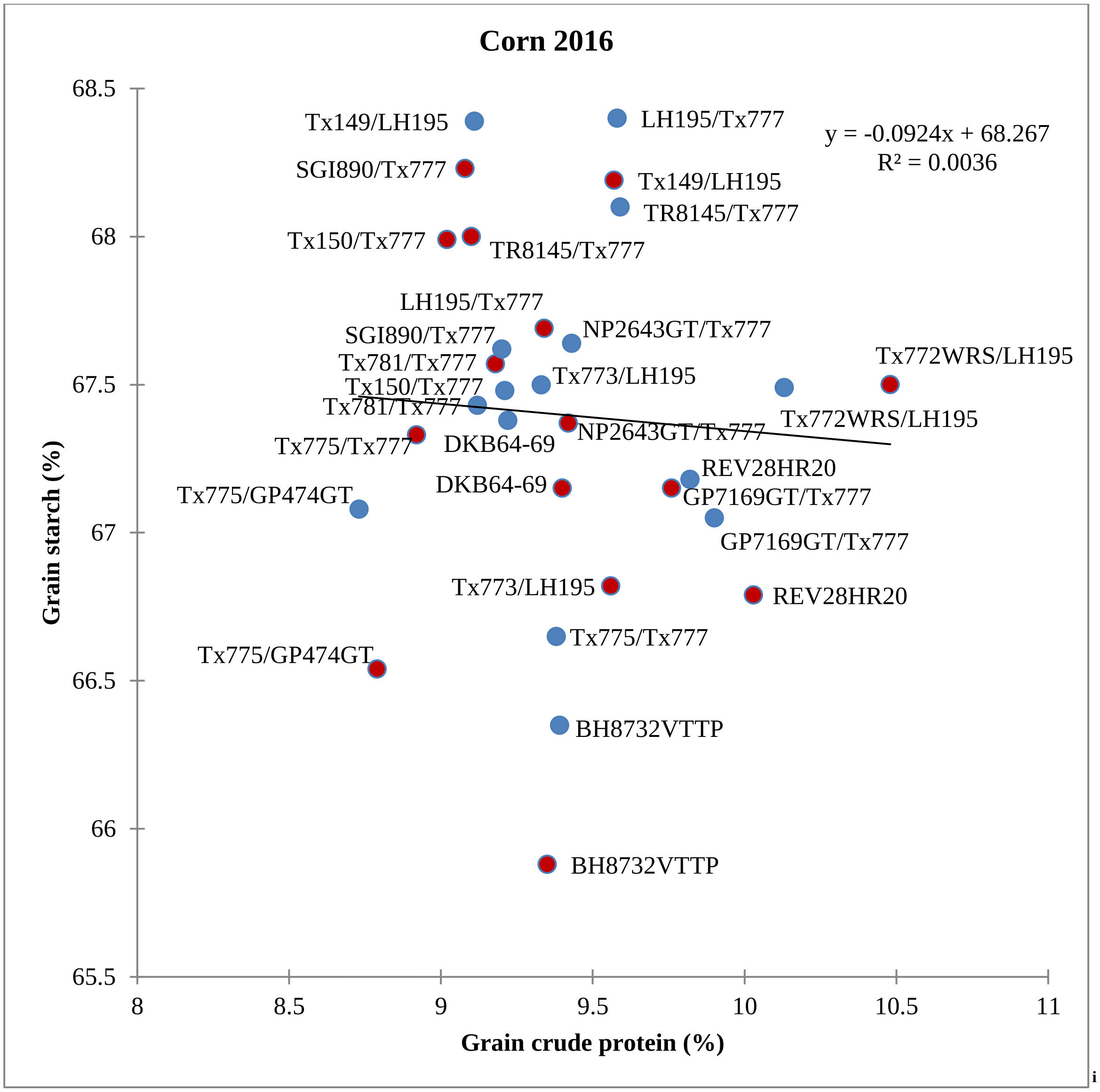


**Figure 2.14.** Scatterplot for grain starch and grain crude protein composition of different corn hybrids in 2016 in deficit (red dots) and full (blue dots) irrigation regimes. Values are in percentage.

**Table 2.20. Significant differences among corn hybrids based on grain starch (%) and crude protein content (%) in 2016. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Values with asterisk (*) shows significant main effect.**

**Grain crude protein content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| Tx772WRS/LH195 | A | 10.31 |
| REV28HR20 | B | 9.93 |
| GP7169GT/Tx777 | B | 9.83 |
| LH195/Tx777 | C | 9.46 |
| Tx773/LH195 | C | 9.45 |
| NP2643GT/Tx777 | C D | 9.43 |
| BH8732VTTP | C D | 9.37 |
| TR8145/Tx777 | C D | 9.35 |
| Tx149/LH195 | C D | 9.34 |
| DKB64-69 | C D | 9.31 |
| Tx775/Tx777 | C D | 9.15 |
| Tx781/Tx777 | C D | 9.15 |
| SGI890/Tx777 | C D | 9.14 |
| Tx150/Tx777 | D | 9.11 |
| Tx775/GP474GT | E | 8.76 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 0.03 | 0.87 |
| Genotypes | 10.84 | <.0001* |
| Irrigation*Genotypes | 1.44 | 0.16 |

| Random Effect | % Variance |
|---|---|
| Rep | 0 |
| Irrigation*Rep | 0 |
| Residual | 100 |

**Grain starch content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| Tx149/LH195 | A | 68.29 |
| TR8145/Tx777 | A B | 68.05 |
| LH195/Tx777 | A B | 68.05 |
| SGI890/Tx777 | A B C | 67.93 |
| Tx150/Tx777 | B C D | 67.74 |
| NP2643GT/Tx777 | C D E | 67.51 |
| Tx781/Tx777 | C D E | 67.5 |
| Tx772WRS/LH195 | C D E | 67.49 |
| DKB64-69 | D E F | 67.27 |
| Tx773/LH195 | E F | 67.16 |
| GP7169GT/Tx777 | E F | 67.1 |
| Tx775/Tx777 | E F | 66.99 |
| REV28HR20 | E F | 66.98 |
| Tx775/GP474GT | F | 66.81 |
| BH8732VTTP | G | 66.11 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 1.11 | 0.3 |
| Genotypes | 9.05 | <.0001* |
| Irrigation*Genotypes | 1.38 | 0.19 |

| Random Effect | % Variance |
|---|---|
| Rep | 0 |
| Irrigation*Rep | 12.02 |
| Residual | 87.98 |

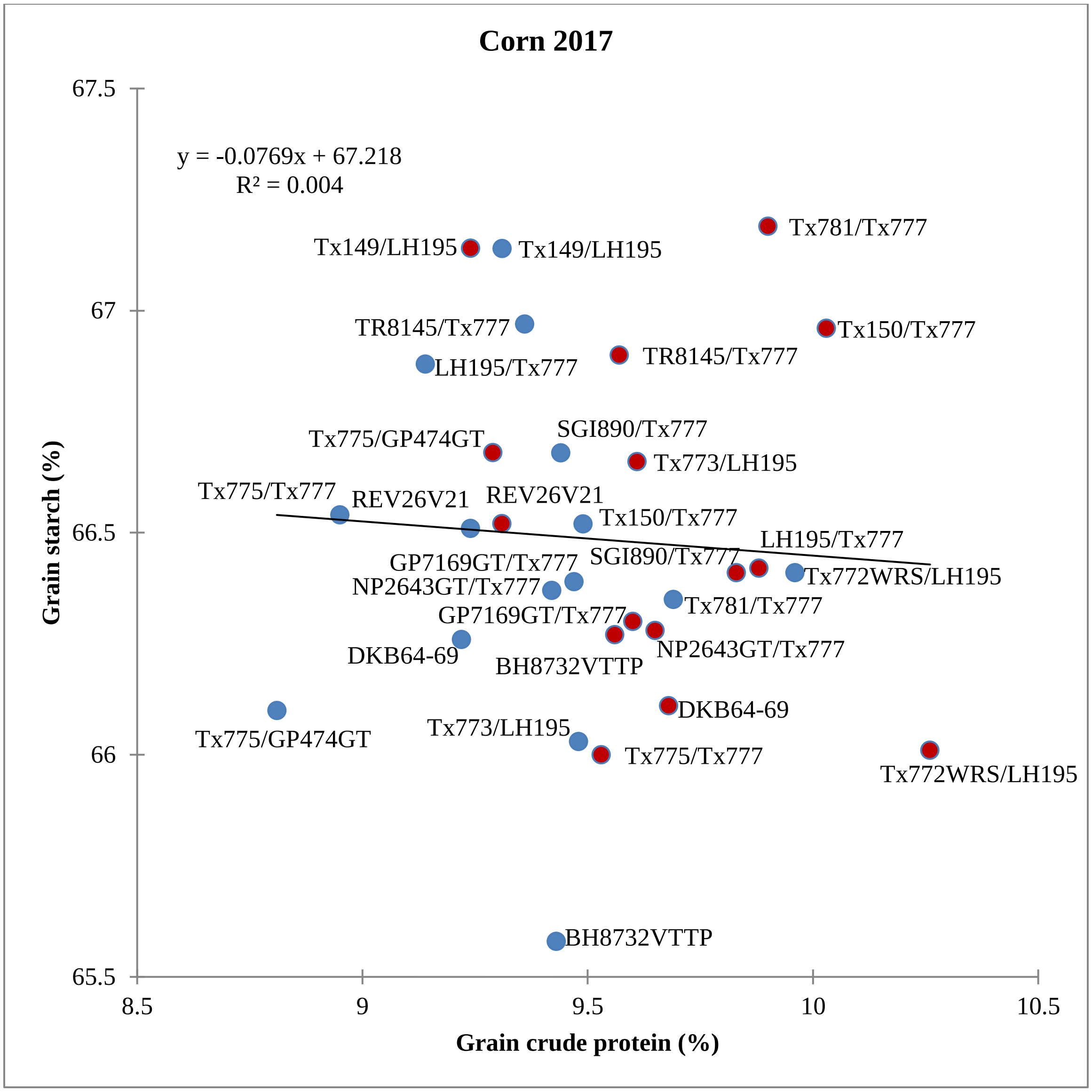


**Figure 2.15.** Scatterplot for grain starch and grain crude protein composition of different corn hybrids in 2017 in deficit (red dots) and full (blue dots) irrigation regimes. Values are in percentage.

**Table 2.21. Significant differences among corn hybrids based on grain starch (%) and crude protein content (%) in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Values with asterisk (*) shows significant main effect.**

**Grain crude protein content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| Tx772WRS/LH195 | A | 10.11 |
| Tx781/Tx777 | A B | 9.8 |
| Tx150/Tx777 | B C | 9.76 |
| SGI890/Tx777 | B C | 9.64 |
| Tx773/LH195 | B C D | 9.55 |
| GP7169GT/Tx777 | B C D | 9.54 |
| NP2643GT/Tx777 | B C D | 9.53 |
| LH195/Tx777 | B C D | 9.51 |
| BH8732VTTP | B C D | 9.5 |
| TR8145/Tx777 | C D | 9.47 |
| DKB64-69 | C D | 9.45 |
| Tx149/LH195 | D E | 9.28 |
| REV26V21 | D E | 9.27 |
| Tx775/Tx777 | D E | 9.24 |
| Tx775/GP474GT | E | 9.05 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 13.65 | 0.07 |
| Genotypes | 5.28 | <.0001* |
| Irrigation*Genotypes | 1 | 0.47 |

| Random Effect | % Variance |
|---|---|
| Rep | 8.83 |
| Irrigation*Rep | 5.64 |
| Residual | 85.53 |

**Grain starch content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| Tx149/LH195 | A | 67.14 |
| TR8145/Tx777 | A B | 66.93 |
| Tx781/Tx777 | A B C | 66.77 |
| Tx150/Tx777 | A B C D | 66.74 |
| LH195/Tx777 | A B C D | 66.65 |
| SGI890/Tx777 | B C D | 66.55 |
| REV26V21 | B C D | 66.52 |
| Tx775/GP474GT | B C D E | 66.39 |
| GP7169GT/Tx777 | C D E | 66.35 |
| Tx773/LH195 | C D E | 66.35 |
| NP2643GT/Tx777 | C D E | 66.33 |
| Tx775/Tx777 | C D E | 66.27 |
| Tx772WRS/LH195 | C D E | 66.21 |
| DKB64-69 | D E | 66.19 |
| BH8732VTTP | E | 65.93 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 0.14 | 0.72 |
| Genotypes | 2.49 | 0.0080* |
| Irrigation*Genotypes | 1.24 | 0.27 |

| Random Effect | % Variance |
|---|---|
| Rep | 0 |
| Irrigation*Rep | 15.6 |
| Residual | 84.4 |

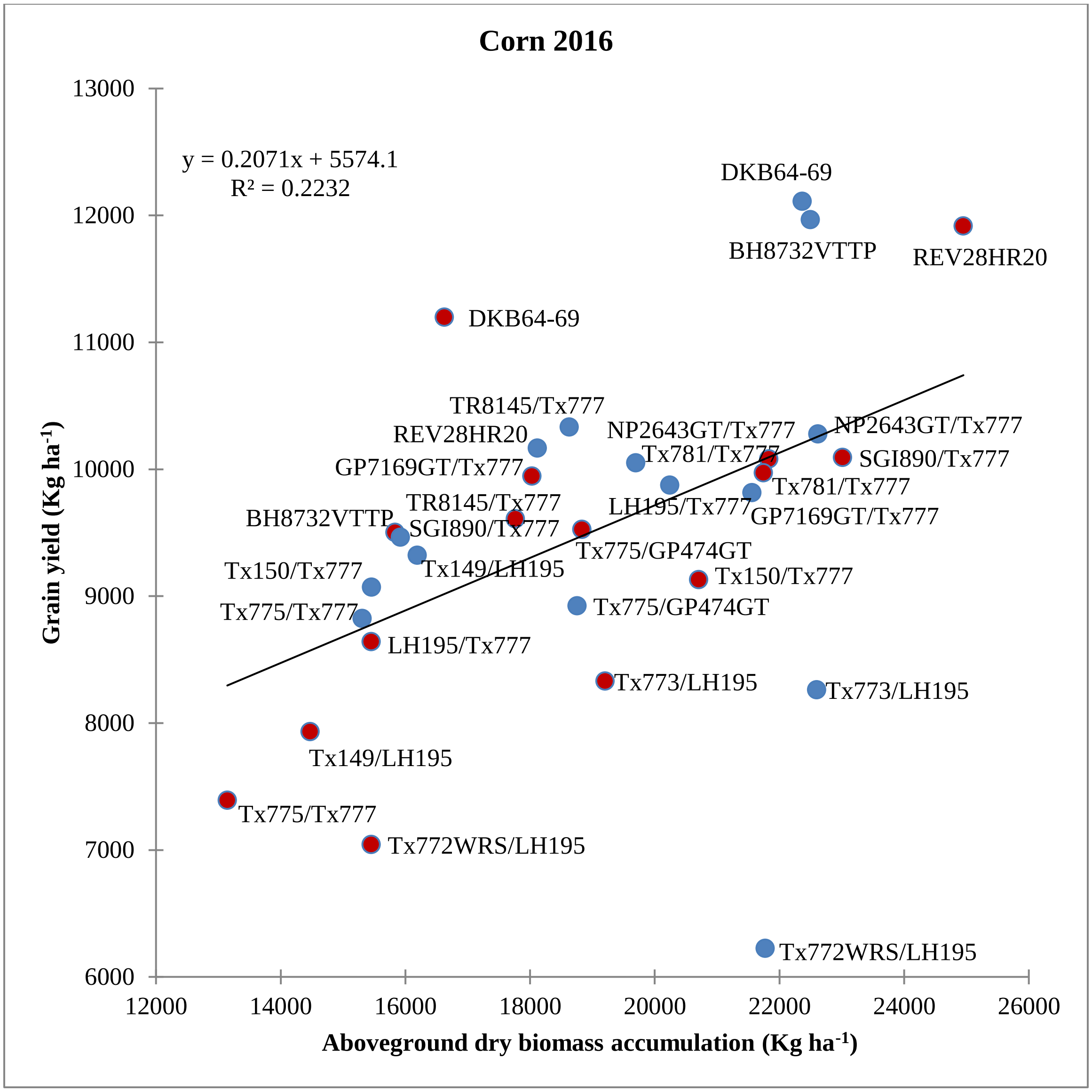


**Figure 2.16.** Scatterplot for grain yield vs. aboveground dry biomass in corn genotypes for 2016. Red dots represent deficit irrigation and blue dots represent full irrigation.

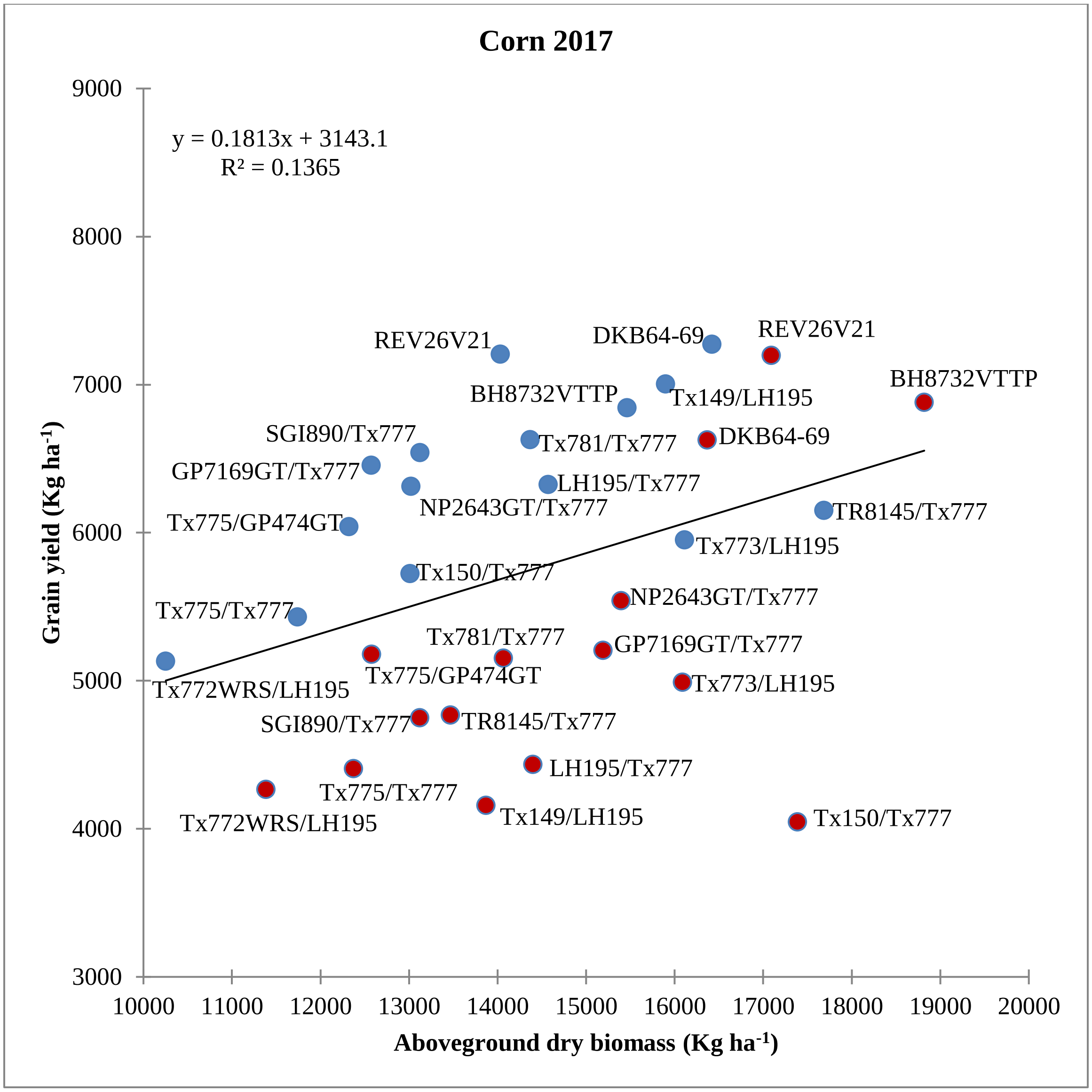


**Figure 2.17.** Scatterplot for grain yield vs. aboveground dry biomass in corn genotypes for 2017. Red dots represent deficit irrigation and blue dots represent full irrigation.

**Table 2.22. Significant differences among corn hybrids in full and deficit irrigation based on grain yield (Kg/ha) in 2016. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| Full,DKB64-69 | A | 12112.27 |
| Full,BH8732VTTP | A | 11968.14 |
| Deficit,REV28HR20 | A | 11916.33 |
| Deficit,DKB64-69 | A B | 11197.45 |
| Full,TR8145/Tx777 | B C | 10333.61 |
| Full,NP2643GT/Tx777 | B C D | 10278.15 |
| Full,REV28HR20 | B C D | 10166.53 |
| Deficit,SGI890/Tx777 | B C D E | 10092.6 |
| Deficit,NP2643GT/Tx777 | B C D E | 10080.54 |
| Full,Tx781/Tx777 | B C D E | 10051.01 |
| Deficit,Tx781/Tx777 | B C D E | 9972.85 |
| Deficit,GP7169GT/Tx777 | B C D E | 9946.08 |
| Full,LH195/Tx777 | B C D E | 9874.61 |
| Full,GP7169GT/Tx777 | B C D E F | 9816.92 |
| Deficit,TR8145/Tx777 | C D E F G | 9608.27 |
| Deficit,Tx775/GP474GT | C D E F G | 9526.08 |
| Deficit,BH8732VTTP | C D E F G | 9503.38 |
| Full,SGI890/Tx777 | C D E F G | 9465.3 |
| Full,Tx149/LH195 | C D E F G H | 9324.01 |
| Deficit,Tx150/Tx777 | C D E F G H | 9128.89 |
| Full,Tx150/Tx777 | C D E F G H | 9070.86 |
| Full,Tx775/GP474GT | C D E F G H | 8923.85 |
| Full,Tx775/Tx777 | D E F G H I | 8825.81 |
| Deficit,LH195/Tx777 | E F G H I | 8641.77 |
| Deficit,Tx773/LH195 | F G H I J | 8330.08 |
| Full,Tx773/LH195 | G H I J | 8263.07 |
| Deficit,Tx149/LH195 | H I J | 7931.04 |
| Deficit,Tx775/Tx777 | I J K | 7390.34 |
| Deficit,Tx772WRS/LH195 | J K | 7043.31 |
| Full,Tx772WRS/LH195 | K | 6224.65 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 2.38 | 0.13 |
| Genotypes | 11.84 | <.0001* |
| Irrigation Regimes*Genotypes | 2.15 | 0.0217* |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.02 | 12212.19 | 39518.23 | 1.49 |
| Residual | | 809610.14 | 150340.83 | 98.51 |

**Table 2.23. Significant differences among corn hybrids in full and deficit irrigation based on grain yield (Kg/ha) in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| Full,DKB64-69 | A | 7273.05 |
| Full,REV26V21 | A B | 7206.22 |
| Deficit,REV26V21 | A B | 7198.07 |
| Full,Tx149/LH195 | A B C | 7005.25 |
| Deficit,BH8732VTTP | A B C | 6879.82 |
| Full,BH8732VTTP | A B C | 6844.58 |
| Full,Tx781/Tx777 | A B C D | 6628.45 |
| Deficit,DKB64-69 | A B C D | 6626.33 |
| Full,SGI890/Tx777 | A B C D E | 6541.74 |
| Full,GP7169GT/Tx777 | A B C D E F | 6456.82 |
| Full,LH195/Tx777 | A B C D E F | 6326.25 |
| Full,NP2643GT/Tx777 | A B C D E F | 6313.9 |
| Full,TR8145/Tx777 | B C D E F G | 6151.06 |
| Full,Tx775/GP474GT | C D E F G H | 6041.76 |
| Full,Tx773/LH195 | C D E F G H | 5952.81 |
| Full,Tx150/Tx777 | D E F G H I | 5723.94 |
| Deficit,NP2643GT/Tx777 | E F G H I | 5541.14 |
| Full,Tx775/Tx777 | F G H I J | 5431.72 |
| Deficit,GP7169GT/Tx777 | G H I J K | 5205.06 |
| Deficit,Tx775/GP474GT | G H I J K | 5179.55 |
| Deficit,Tx781/Tx777 | G H I J K | 5152.46 |
| Full,Tx772WRS/LH195 | G H I J K | 5133.81 |
| Deficit,Tx773/LH195 | H I J K L | 4989.4 |
| Deficit,TR8145/Tx777 | I J K L | 4768.05 |
| Deficit,SGI890/Tx777 | I J K L | 4749.12 |
| Deficit,LH195/Tx777 | J K L | 4434.78 |
| Deficit,Tx775/Tx777 | J K L | 4405.94 |
| Deficit,Tx772WRS/LH195 | K L | 4266.67 |
| Deficit,Tx149/LH195 | K L | 4157.16 |
| Deficit,Tx150/Tx777 | L | 4047.19 |

| Irrigation | | Least Sq Mean |
|---|---|---|
| Full | A | 6335.42 |
| Deficit | B | 5173.38 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 71.67 | <.0001* |
| Genotypes | 7.83 | <.0001* |
| Irrigation Regimes*Genotypes | 1.92 | 0.0423* |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.04 | 15417.85 | 29664.36 | 3.51 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 423906.96 | 78717.55 | 96.49 |

**Table 2.24. Correlation of grain starch content (%), grain crude protein content (%), grain yield (Kg/ha), and aboveground biomass (Kg/ha) of corn hybrids in 2016 and 2017. Values with asterisk (*) are significant.**

| Year | Variables | Grain crude protein | Grain starch | Grain yield |
|---|---|---|---|---|
| **2016** | **Grain starch** | -0.19* | | |
| | **Grain yield** | -0.12 | -0.1 | |
| | **Biomass** | 0.11 | 0.06 | 0.27* |
| **2017** | **Grain starch** | -0.1 | | |
| | **Grain yield** | -0.4* | 0 | |
| | **Biomass** | -0.15 | 0.2 | 0.37* |

### *Sorghum*

Performance of eight hybrids and seven inbreds was studied based on plant height, number of leaves, leaf structure and orientation, LT, LD, LDMC, SLA, osmotic potential (OP), chlorophyll content, NDVI, biomass accumulation, grain yield, harvest index, and grain composition.

#### *Plant height and number of leaves*

No significant effect of irrigation and irrigation x genotypes were observed for terminal plant height of sorghum hybrids and inbreds in 2016 (Table 2.25 and Table 2.26) and 2017 (Table 2.27 and Table 2.28). Main effect of genetics was observed for sorghum hybrids and inbreds in both the years. Variations were also caused by residual. In 2016, hybrids such as ATx378/RTx7000, ATx631/RTx437, ATx631/RTx436 and ATx623/RTx430 were significantly taller compared to ATx645/RTx437, ATx645/RTx436, and ATx2752/RTx430 (Figure 2.18 and Table 2.25). Among inbreds, B.Tx623 and R.Tx7000 were significantly taller than B.Tx645 and R.Tx437

(Figure 2.19 and Table 2.26). Significant differences was also observed between the height of B.Tx623 and R.Tx7000 as well as B.Tx645 and R.Tx437.

In 2017, ATx631/RTx436, ATx631/RTx437, and ATx642/RTx436 were significantly taller than rest of the hybrids (Figure 2.20 and Table 2.27). Among inbreds, B.Tx378 and B.Tx631 were significantly taller than R.Tx437 and B.Tx642 (Figure 2.21 and Table 2.28). Significant differences was also observed between terminal height of R.Tx437 and B.Tx642. No significant differences was observed between terminal height of R.Tx437 and B.Tx645 as well as B.Tx631 and R.Tx7000.

Genetic effect was significant even for number of green leaves at 83 days after sowing (DAS) in 2016 for sorghum hybrids and inbreds and at 102 DAS in 2017 for sorghum hybrids. In 2016, number of green leaves in most of the sorghum hybrids and inbreds did not changed from 69 DAS (early flowering stage) to 83 DAS (early soft dough stage) (Figure 2.22). In 2017, greater number of green leaves were present at 102 DAS (hard dough-maturity stage) (Figure 2.23). Sorghum genotypes showed an increase in number of green leaves from 54 DAS to 102 DAS in 2017. This confirmed the higher photosynthetic efficiency of sorghum hybrids and inbreds.

In 2016, ATx378/RTx7000 and ATx3197/RTx7000 showed significantly fewer number of green leaves compared to rest of the hybrids at 83 DAS (Table 2.29). Among inbreds, significantly fewer number of green leaves were observed in B.Tx378, R.Tx7000, and B.Tx3197 at 83 DAS (Table 2.30).

In 2017, ATx631/RTx437 and ATx642/RTx437 showed significantly greater number of green leaves compared to ATx2752/RTx430 and ATx378/RTx7000 (Table 2.31). No significant genetic, irrigation, and their interaction effect were observed for sorghum inbreds in 2017 (Table 2.32).

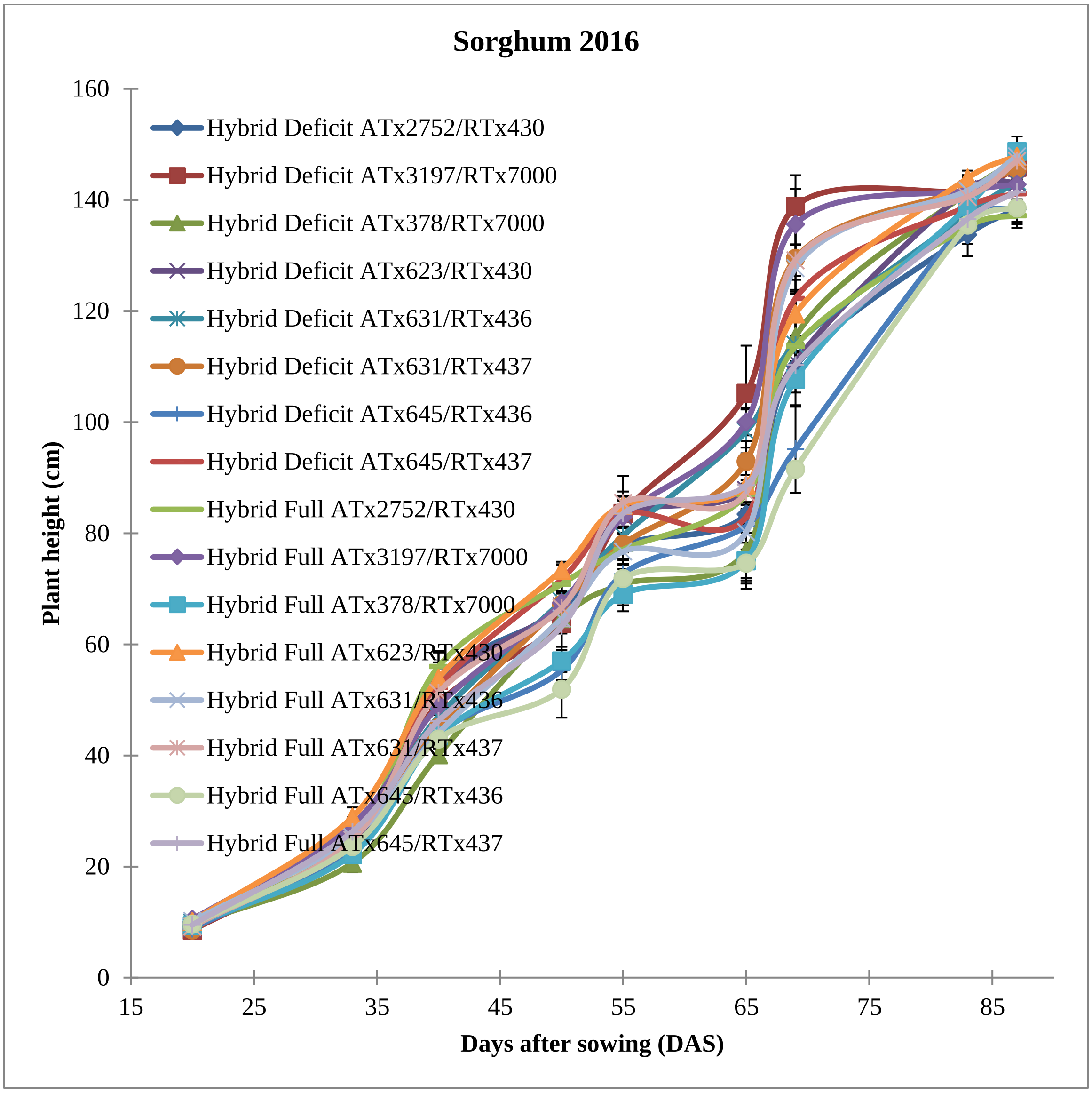


**Figure 2.18.** Plant growth curve for sorghum hybrids under full and deficit irrigation in 2016. Standard error bar represents standard error of the mean.

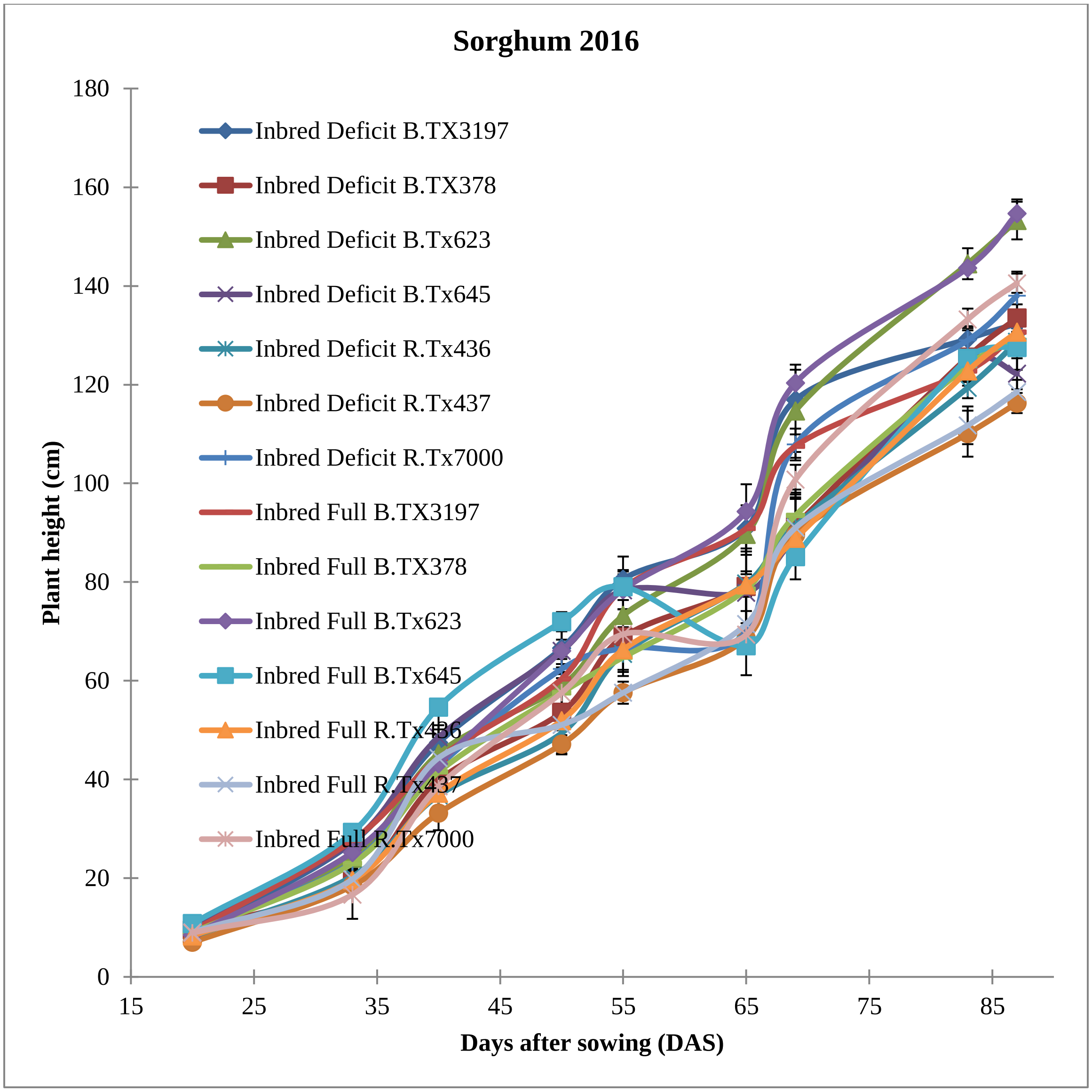


**Figure 2.19.** Plant growth curve for sorghum inbreds under full and deficit irrigation in 2016. Standard error bar represents standard error of the mean.

**Table 2.25. Fixed and random effects of various sources on terminal plant height (cm) resulting in significant differences among sorghum hybrids in 2016. Standard least square analysis in JMP 13.0 for α = 0.05 was performed. No significant main effect of irrigation or its interaction with genotypes were observed on terminal plant height. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| ATx378/RTx7000 | A | 147.89 |
| ATx631/RTx437 | A | 146.33 |
| ATx631/RTx436 | A | 145.63 |
| ATx623/RTx430 | A | 145.49 |
| ATx3197/RTx7000 | A B | 144.36 |
| ATx645/RTx437 | B C | 141.25 |
| ATx645/RTx436 | C | 138.43 |
| ATx2752/RTx430 | C | 137.72 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 1.17 | 0.29 |
| Genotypes | 7.04 | <.0001* |
| Irrigation Regimes*Genotypes | 0.87 | 0.54 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 12.24 | 3.06 | 100 |

**Table 2.26. . Fixed and random effects of various sources on terminal plant height (cm) resulting in significant differences among sorghum inbreds in 2016. Standard least square analysis in JMP 13.0 for α = 0.05 was performed. No significant main effect of irrigation or its interaction with genotypes were observed on terminal plant height. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| B.Tx623 | A | 153.95 |
| R.Tx7000 | B | 139.28 |
| B.TX3197 | C | 131.52 |
| B.TX378 | C | 131.23 |
| R.Tx436 | C D | 129.68 |
| B.Tx645 | D | 124.88 |
| R.Tx437 | E | 117.41 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.43 | 0.52 |
| Genotypes | 30.03 | <.0001* |
| Irrigation Regimes*Genotypes | 0.58 | 0.74 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 26.73 | 7.14 | 100 |

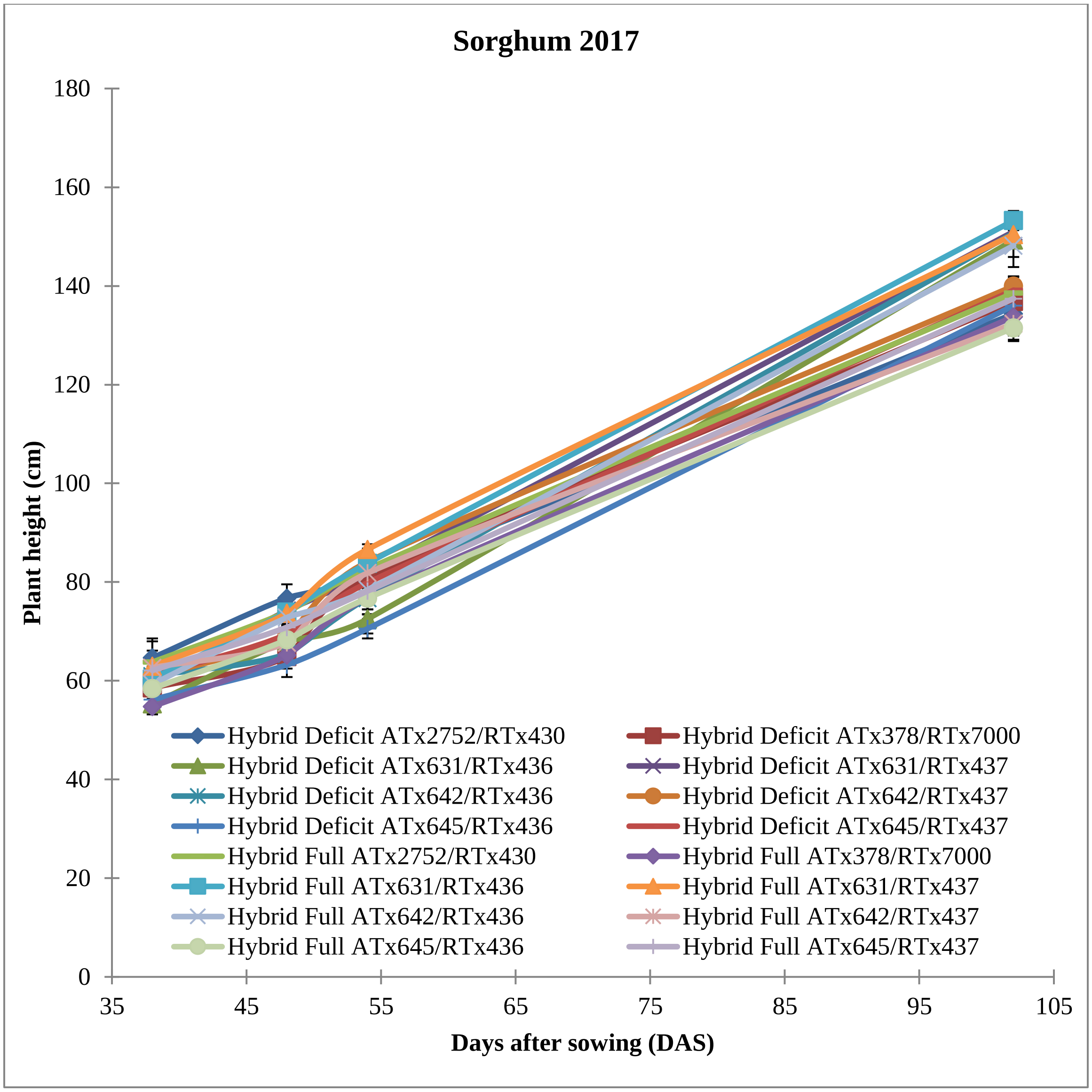


**Figure 2.20.** Plant growth curve for sorghum hybrids under full and deficit irrigation in 2017. Standard error bar represents standard error of the mean.

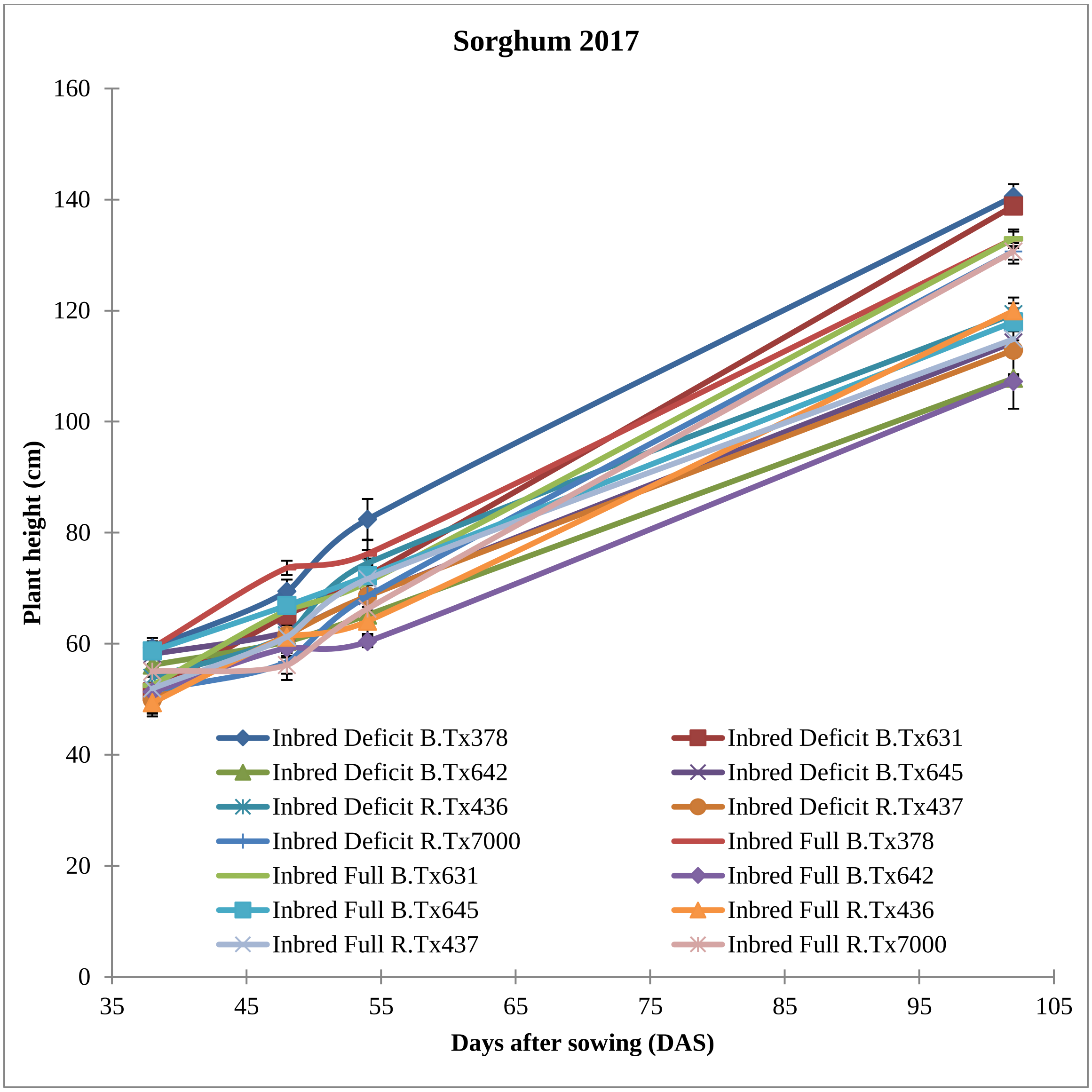


**Figure 2.21.** Plant growth curve for sorghum inbreds under full and deficit irrigation in 2017. Standard error bar represents standard error of the mean.

**Table 2.27. Fixed and random effects of various sources on terminal plant height (cm) resulting in significant differences among sorghum hybrids in 2017. Standard least square analysis in JMP 13.0 for α = 0.05 was performed. No significant main effect of irrigation or its interaction with genotypes were observed on terminal plant height. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| ATx631/RTx436 | A | 151.27 |
| ATx631/RTx437 | A | 150.71 |
| ATx642/RTx436 | A | 149.44 |
| ATx645/RTx437 | B | 138.29 |
| ATx2752/RTx430 | B | 136.45 |
| ATx642/RTx437 | B | 136.17 |
| ATx378/RTx7000 | B | 135.33 |
| ATx645/RTx436 | B | 133.77 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 1.48 | 0.23 |
| Genotypes | 19.44 | <.0001* |
| Irrigation Regimes*Genotypes | 1.36 | 0.26 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.02 | 0.28 | 1.42 | 1.52 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 17.86 | 4.61 | 98.48 |

**Table 2.28. Fixed and random effects of various sources on terminal plant height (cm) resulting in significant differences among sorghum inbreds in 2017. Standard least square analysis in JMP 13.0 for α = 0.05 was performed. No significant main effect of irrigation or its interaction with genotypes were observed on terminal plant height. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| B.Tx378 | A | 136.74 |
| B.Tx631 | A B | 135.89 |
| R.Tx7000 | B | 130.67 |
| R.Tx436 | C | 119.66 |
| B.Tx645 | C D | 116.13 |
| R.Tx437 | D | 113.88 |
| B.Tx642 | E | 107.53 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.6 | 0.48 |
| Genotypes | 37.41 | <.0001* |
| Irrigation Regimes*Genotypes | 1.2 | 0.34 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.01 | 0.15 | 2.42 | 0.7 |
| Residual | | 21.24 | 6.13 | 99.3 |

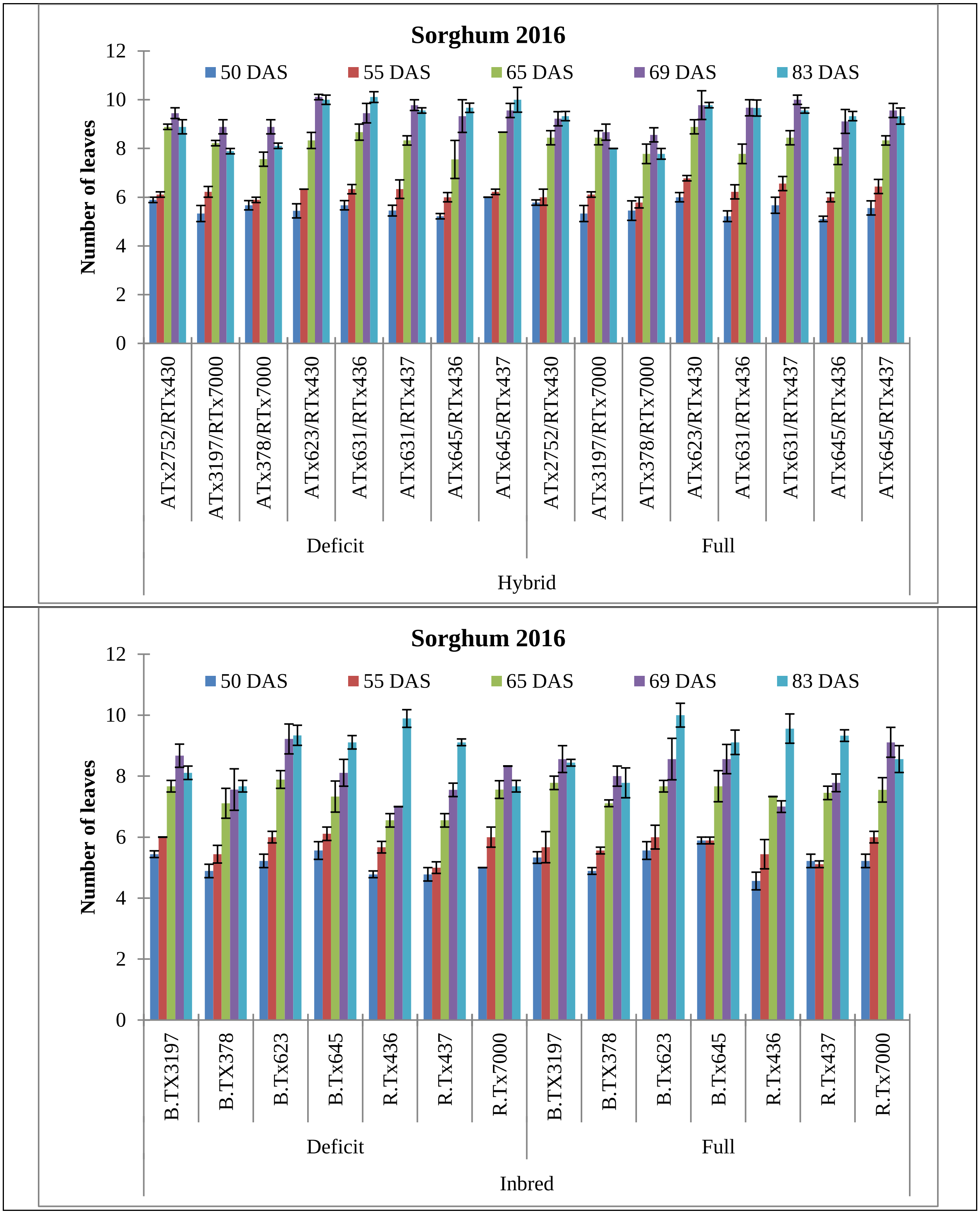


**Figure 2.22.** Number of green leaves present in sorghum hybrids and inbreds at different growth stages in deficit and full irrigation regimes in 2016. Standard error bar represents standard error of the mean.

**Table 2.29. Significant differences among different sorghum hybrids based on number of green leaves/plant present at 83 DAS in 2016. Results have been obtained from Student’s t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| ATx623/RTx430 | A | 9.89 |
| ATx631/RTx436 | A | 9.89 |
| ATx645/RTx437 | A | 9.67 |
| ATx631/RTx437 | A B | 9.56 |
| ATx645/RTx436 | A B | 9.5 |
| ATx2752/RTx430 | B | 9.11 |
| ATx3197/RTx7000 | C | 7.95 |
| ATx378/RTx7000 | C | 7.94 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 1.71 | 0.26 |
| Genotypes | 25.07 | <.0001* |
| Irrigation Regimes*Genotypes | 1.19 | 0.34 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.06 | 0.01 | 0.02 | 5.56 |
| Residual | | 0.16 | 0.04 | 94.45 |

**Table 2.30. Significant differences among different sorghum inbreds based on number of green leaves/plant present at 83 DAS in 2016. Results have been obtained from Student’s t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| R.Tx436 | A | 9.72 |
| B.Tx623 | A | 9.67 |
| R.Tx437 | A | 9.22 |
| B.Tx645 | A | 9.11 |
| B.TX3197 | B | 8.28 |
| R.Tx7000 | B | 8.11 |
| B.TX378 | B | 7.72 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 2.6 | 0.12 |
| Genotypes | 12.8 | <.0001* |
| Irrigation Regimes*Genotypes | 0.85 | 0.54 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.02 | 0.01 | 0.03 | 2.22 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 0.29 | 0.08 | 97.78 |

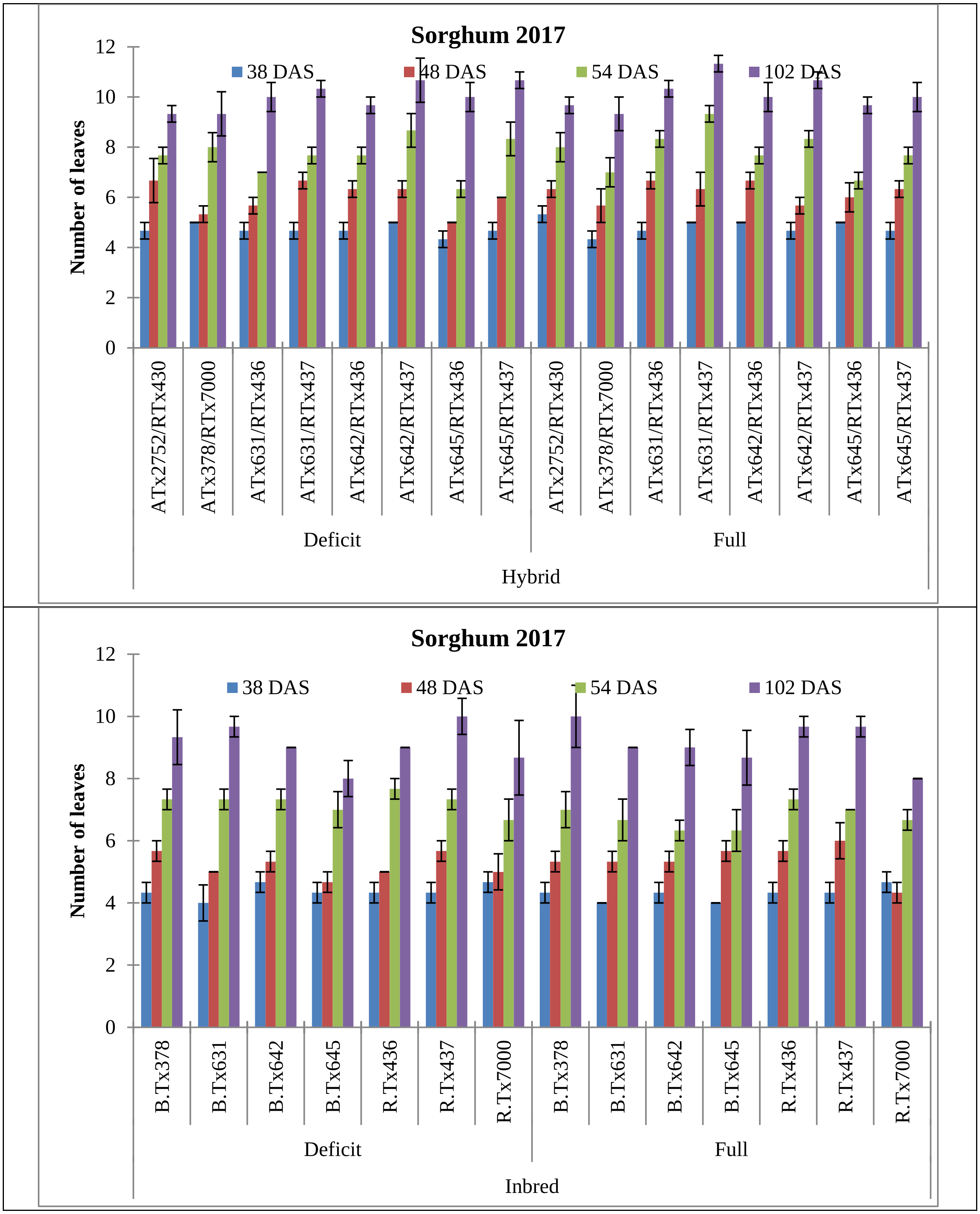


**Figure 2.23.** Number of green leaves present in sorghum hybrids and inbreds at different growth stages in deficit and full irrigation regimes in 2017. Standard error bar represents standard error of the mean.

**Table 2.31. Significant differences among different sorghum hybrids based on number of green leaves/plant present at 102 DAS in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | | | | Least Sq Mean |
|---|---|---|---|---|---|
| ATx631/RTx437 | A | | | | 10.83 |
| ATx642/RTx437 | A | B | | | 10.67 |
| ATx645/RTx437 | A | B | C | | 10.33 |
| ATx631/RTx436 | A | B | C | D | 10.17 |
| ATx642/RTx436 | | B | C | D | 9.83 |
| ATx645/RTx436 | | B | C | D | 9.83 |
| ATx2752/RTx430 | | | C | D | 9.5 |
| ATx378/RTx7000 | | | | D | 9.33 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.23 | 0.68 |
| Genotypes | 2.9 | 0.0205* |
| Irrigation Regimes*Genotypes | 0.64 | 0.72 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.33 | 0.2 | 0.25 | 24.04 |
| Irrigation Regimes*Rep | 0.05 | 0.03 | 0.1 | 3.43 |
| Residual | | 0.59 | 0.16 | 72.53 |

**Table 2.32. Fixed and random effects of different sources on number of green leaves/plant at 102 DAS in sorghum inbreds in full and deficit irrigation regimes in 2017. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance.**

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.01 | 0.91 |
| Genotypes | 2.08 | 0.09 |
| Irrigation Regimes*Genotypes | 0.56 | 0.76 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.11 | 0.11 | 0.19 | 9.72 |
| Residual | | 1.03 | 0.3 | 90.28 |

### *Leaf structure and orientation*

Main effect of irrigation, genotypes, and their interaction were not significant for leaf area index (LAI) and mean tilt angle (MTA) of sorghum hybrids (Table 2.33 and Table 2.34). Sorghum inbreds showed a significant genetic effect on LAI but no significant effect of irrigation, genetics, and their interaction were observed for MTA (Table 2.35 and Table 2.36). Interaction of irrigation x replication also caused some variations among sorghum hybrids. Variations in sorghum hybrids and inbreds were also caused by some unknown residual. R.Tx436 and B.Tx645 showed significantly higher LAI compared to B.Tx378 and B.Tx3197 (Table 2.35).

**Table 2.33. Fixed and random effect of different sources on leaf area index (LAI) of sorghum hybrids under full and deficit irrigation regimes in 2016. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance.**

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.55 | 0.5 |
| Genotypes | 1.24 | 0.31 |
| Irrigation Regimes*Genotypes | 1.53 | 0.2 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.13 | 0.02 | 0.03 | 11.6 |
| Residual | | 0.17 | 0.05 | 88.41 |

**Table 2.34. Fixed and random effect of different sources on mean tilt angle (MTA) of sorghum hybrids under full and deficit irrigation regimes in 2016. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance.**

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.22 | 0.66 |
| Genotypes | 1.21 | 0.33 |
| Irrigation Regimes*Genotypes | 0.37 | 0.91 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.11 | 2.12 | 3.33 | 9.61 |
| Residual | | 19.97 | 5.34 | 90.39 |

**Table 2.35. Significant differences among different sorghum inbreds in full and deficit irrigation regimes based on leaf area index (LAI) in 2016. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | | | Least Sq Mean |
|---|---|---|---|---|
| R.Tx436 | A | | | 3.78 |
| B.Tx645 | A | | | 3.76 |
| R.Tx7000 | A | B | | 3.42 |
| B.Tx623 | A | B | C | 3.18 |
| R.Tx437 | | B | C | 3.11 |
| B.TX378 | | B | C | 3.02 |
| B.TX3197 | | | C | 2.63 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.23 | 0.68 |
| Genotypes | 3.64 | 0.0104* |
| Irrigation Regimes*Genotypes | 1.41 | 0.25 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.01 | 0 | 0.04 | 1.33 |
| Irrigation Regimes*Rep | 0.02 | 0.01 | 0.05 | 2.31 |
| Residual | | 0.28 | 0.08 | 96.36 |

**Table 2.36. Fixed and random effect of different sources on mean tilt angle (MTA) of sorghum inbreds under full and deficit irrigation regimes in 2016. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance.**

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 4.16 | 0.11 |
| Genotypes | 1.72 | 0.16 |
| Irrigation Regimes*Genotypes | 0.63 | 0.7 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0.13 | 4.38 | 0.34 |
| Residual | | 39.32 | 11.35 | 99.66 |

### *Leaf thickness (LT), leaf tissue density (LD), leaf dry matter content (LDMC), specific leaf area (SLA), and osmotic potential*

A significant genetic effect for leaf thickness (LT) of sorghum hybrids and inbreds was observed at flowering stage in 2017 (Table 2.37 and Table 2.38). At flowering stage, main effect of irrigation x genotypes interaction was also significant for sorghum inbreds. For sorghum hybrids, no significant main effect of irrigation, genotypes, and their interaction were observed at dough stage, but main effect of genotypes was significant for sorghum inbreds. ATx631/RTx437 and ATx642/RTx436 had thicker leaves compared to other hybrids (Figure 2.24 and Table 2.37). B.Tx631 under deficit irrigation and B.Tx378 and R.Tx436 under full irrigation showed significantly thicker leaves compared to that of B.Tx645 and R.Tx436 under deficit irrigation and R.Tx7000 under full irrigation (Figure 2.24 and Table 2.38).

Sorghum hybrids and inbreds showed an increase in leaf dry matter content (LDMC) from flowering to dough stage (Figure 2.25). Higher LDMC increases the rigidity of cell wall, thus increasing relative water content and prevents wilting of plant. Main effects of irrigation, genotypes, and their interaction were not significant for sorghum hybrids at flowering and dough stage (Table 2.39). Sorghum inbreds showed a significant genetic effect on LDMC at flowering and dough stage. B.Tx645, B.Tx631, and B.Tx378 showed significantly higher LDMC compared to R.Tx7000 and B.Tx642 at flowering and dough stage (Table 2.40).

Leaf tissue density (LD) is positively related to drought tolerance nature of a crop/genotype. It also contributes towards LDMC. An increase in LD was observed from flowering to dough stage in sorghum hybrids and inbreds (Figure 2.26). Irrigation, genotypes, and their interaction did not show any significant main effect on LD of sorghum hybrids at flowering and dough stage (Table 2.41). In sorghum inbreds, genetic effect was significant at flowering stage, however, irrigation and irrigation x genotypes were not significant (Table 2.42). B.Tx645, R.Tx7000, B.Tx378, and R.Tx437 showed significantly higher LD compared to B.Tx631 and R.Tx436 at flowering stage. At dough stage, genotypes, irrigation, and their interaction did not show any significant effect in sorghum inbreds.

Specific leaf area (SLA) being an inverse function of LT and LDMC decreased from flowering to dough stage in sorghum hybrids and inbreds (Figure 2.27). At flowering stage, main effect of irrigation in sorghum hybrids and genetic effect in sorghum inbred was found significant (Table 2.43 and Table 2.44). At dough stage, no significant effect of irrigation, genotypes, and irrigation x genotypes was observed in sorghum hybrids, but a significant genetic effect was observed in sorghum inbreds. At flowering stage, SLA of hybrids under deficit irrigation was significantly higher compared to that under full irrigation (Table 2.43). R.Tx436 showed significantly higher flowering stage SLA compared to all other inbreds (Table 2.44).

Osmotic potential of some hybrids and inbreds of sorghum decreased from flowering to dough stage (Figure 2.28). Low osmotic potential at flowering and dough stage confirms the higher water use of a crop/genotype that might be an advantage in terms of grain yield. Main effects of irrigation, genotypes, and their interaction were not significant at flowering and dough stage for sorghum hybrids (Table 2.45). For inbreds, the main effects were not significant at flowering stage but at dough stage a significant genetic effect was observed (Table 2.46). B.TX378, B.Tx631, R.Tx437, R.Tx7000, and B.Tx642 showed significantly higher osmotic potential compared to B.Tx645.

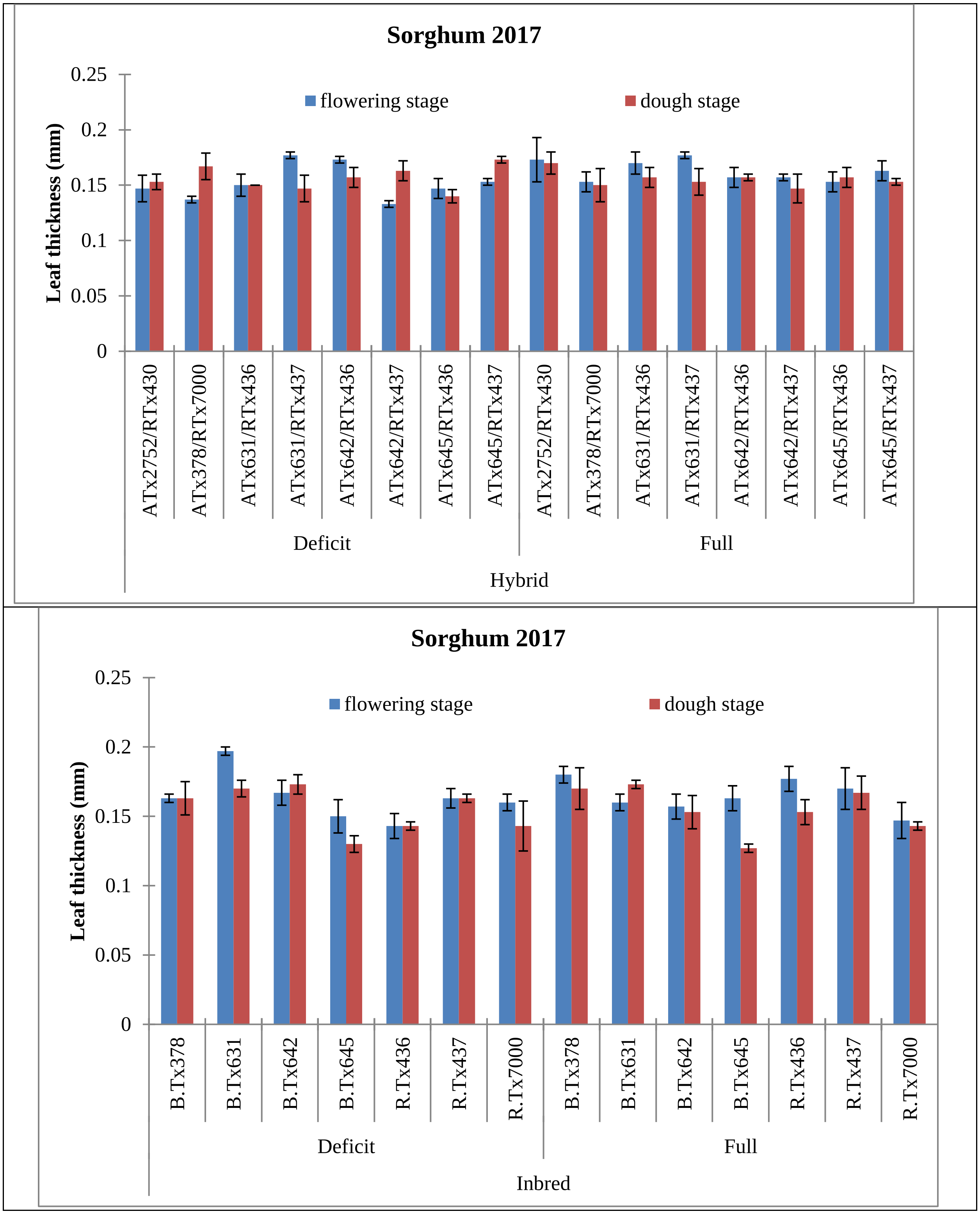


**Figure 2.24.** Leaf thickness (mm) for sorghum hybrids and inbreds in full and deficit irrigation regimes in 2017. Blue bar is leaf thickness during flowering stage and red bar is leaf thickness during dough stage. Standard error bar represents standard error of the mean.

**Table 2.37. Significant differences among sorghum hybrids based on leaf thickness (mm) at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. Main effects of irrigation, genotypes, and their interaction were not significant during dough stage.**

| Level | | | | Least Sq Mean |
|---|---|---|---|---|
| ATx631/RTx437 | A | | | 0.18 |
| ATx642/RTx436 | A | B | | 0.17 |
| ATx2752/RTx430 | A | B | C | 0.16 |
| ATx631/RTx436 | A | B | C | 0.16 |
| ATx645/RTx437 | | B | C | 0.16 |
| ATx645/RTx436 | | B | C | 0.15 |
| ATx378/RTx7000 | | | C | 0.15 |
| ATx642/RTx437 | | | C | 0.15 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 5.59 | 0.14 |
| Genotypes | 3.2 | 0.0128* |
| Irrigation Regimes*Genotypes | 1.41 | 0.24 |

| Random Effect | % Variance |
|---|---|
| Rep | 3.86 |
| Irrigation Regimes*Rep | 1.98 |
| Residual | 94.16 |

**Table 2.38. Significant differences among sorghum inbreds in full and deficit irrigation based on leaf thickness (mm) at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. At dough stage, only genetic make-up showed significant main effect on leaf thickness.**

| Level | | Least Sq Mean |
|---|---|---|
| Deficit,B.Tx631 | A | 0.2 |
| Full,B.Tx378 | A B | 0.18 |
| Full,R.Tx436 | A B C | 0.18 |
| Full,R.Tx437 | B C D | 0.17 |
| Deficit,B.Tx642 | B C D E | 0.17 |
| Deficit,R.Tx437 | B C D E F | 0.16 |
| Deficit,B.Tx378 | B C D E F | 0.16 |
| Full,B.Tx645 | B C D E F | 0.16 |
| Deficit,R.Tx7000 | B C D E F | 0.16 |
| Full,B.Tx631 | B C D E F | 0.16 |
| Full,B.Tx642 | C D E F | 0.16 |
| Deficit,B.Tx645 | D E F | 0.15 |
| Full,R.Tx7000 | E F | 0.15 |
| Deficit,R.Tx436 | F | 0.14 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.04 | 0.86 |
| Genotypes | 2.92 | 0.0277* |
| Irrigation Regimes*Genotypes | 5.11 | 0.0017* |

| Random Effect | % Variance |
|---|---|
| Rep | 9.81 |
| Irrigation Regimes*Rep | 23.35 |
| Residual | 66.84 |

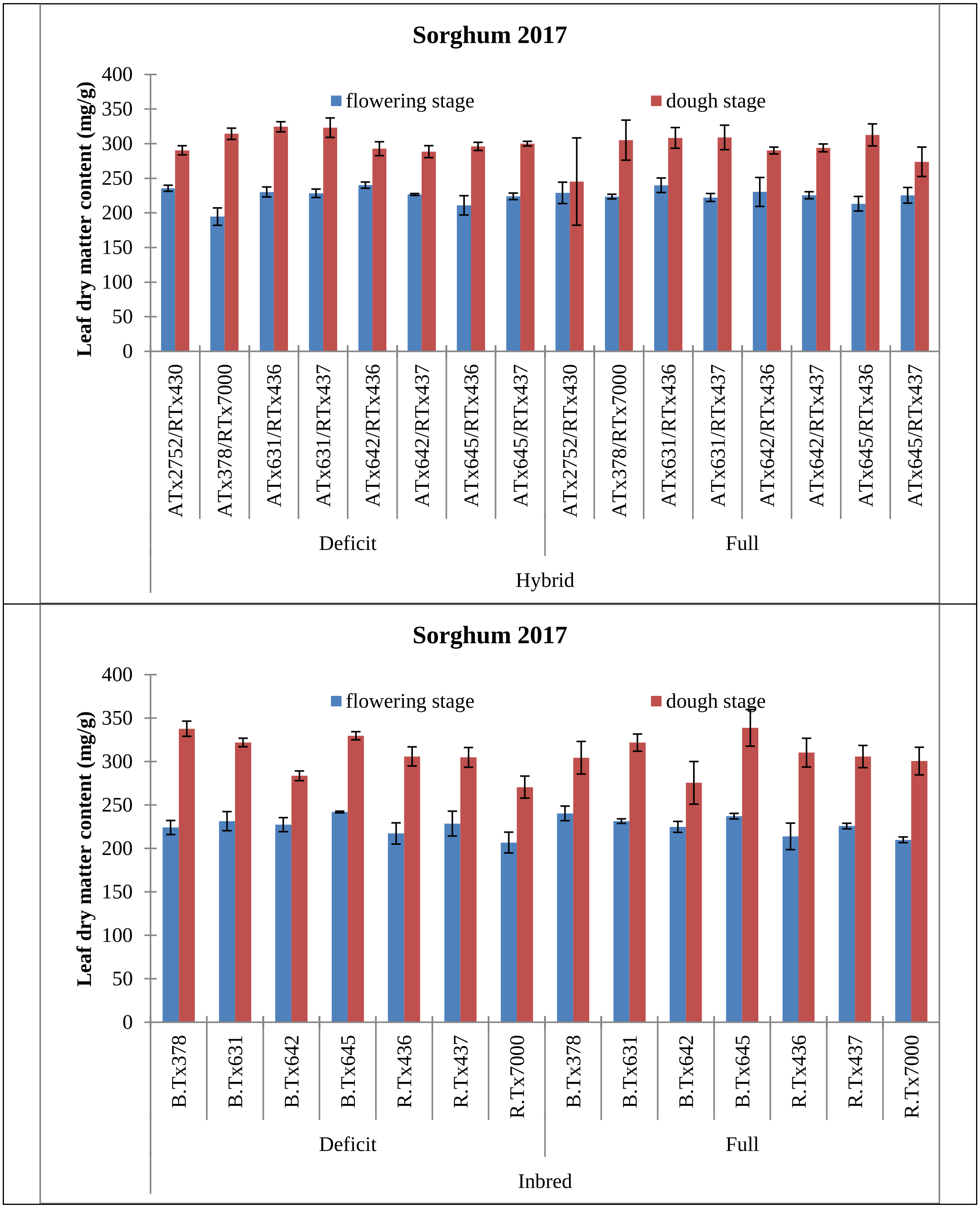


**Figure 2.25.** Leaf dry matter content (mg/g) for sorghum hybrids and inbreds in full and deficit irrigation regimes in 2017. Blue bar is LDMC during flowering stage and red bar is LDMC during dough stage. Standard error bar represents standard error of the mean.

**Table 2.39. Fixed and random effect of different sources on leaf dry matter content (mg/g) of sorghum hybrids under full and deficit irrigation regimes at dough stage in 2017. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Main effect of irrigation, genetic make-up, and their interaction were not significant even at flowering stage.**

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.88 | 0.45 |
| Genotypes | 1.54 | 0.19 |
| Irrigation Regimes*Genotypes | 0.5 | 0.83 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.07 | 77.39 | 218.76 | 6.17 |
| Irrigation Regimes*Rep | 0.08 | 85.64 | 225.13 | 6.82 |
| Residual | | 1092.09 | 291.87 | 87.01 |

**Table 2.40. Significant differences among sorghum inbreds based on leaf dry matter content (mg/g) at dough stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. Significant main effect of genotypes was also observed during flowering stage.**

| Level | | | | | Least Sq Mean |
|---|---|---|---|---|---|
| B.Tx645 | A | | | | 334.25 |
| B.Tx631 | A | B | | | 321.86 |
| B.Tx378 | A | B | | | 321.07 |
| R.Tx436 | | B | C | | 308.07 |
| R.Tx437 | | B | C | | 305.27 |
| R.Tx7000 | | | C | D | 285.56 |
| B.Tx642 | | | | D | 279.54 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0 | 0.98 |
| Genotypes | 5.9 | 0.0007* |
| Irrigation Regimes*Genotypes | 1.35 | 0.27 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.16 | 63.44 | 178.75 | 10.76 |
| Irrigation Regimes*Rep | 0.31 | 123.79 | 182.03 | 21 |
| Residual | | 402.39 | 116.16 | 68.25 |

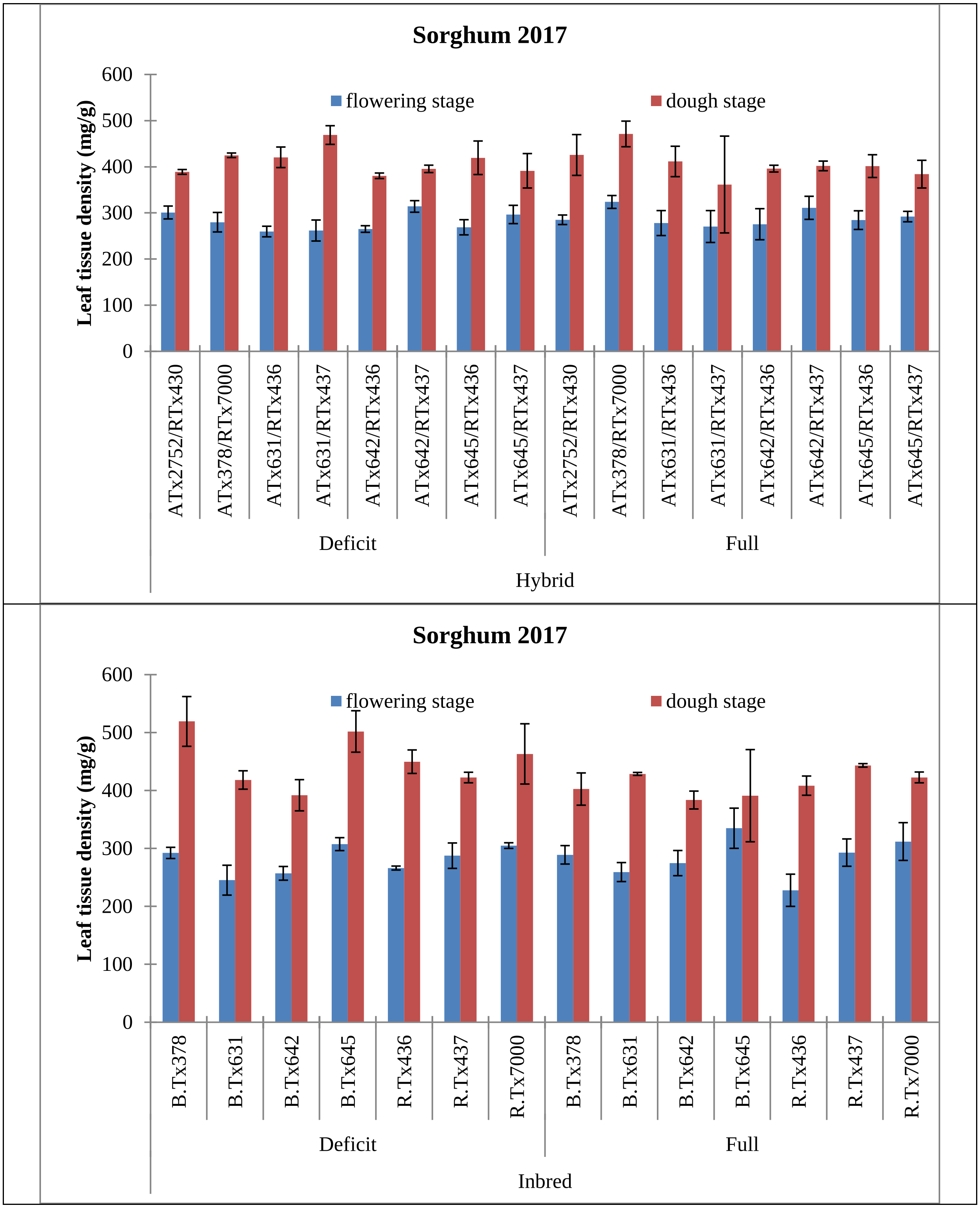


**Figure 2.26.** Leaf tissue density (LD) (mg/g) for sorghum hybrids and inbreds in full and deficit irrigation regimes in 2017. Blue bar is LD during flowering stage and red bar is LD during dough stage. Standard error bar represents standard error of the mean.

**Table 2.41. Fixed and random effect of different sources on leaf tissue density (mg/g) of sorghum hybrids under full and deficit irrigation regimes at flowering stage in 2017. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Main effects of irrigation, genetic make-up, and their interaction were not significant even at dough stage.**

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.81 | 0.38 |
| Genotypes | 1.43 | 0.23 |
| Irrigation Regimes*Genotypes | 0.39 | 0.9 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 1253.6 | 313.4 | 100 |

**Table 2.42. Significant differences among sorghum inbreds based on leaf tissue density (mg/g) at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. Main effects of irrigation, genetic make-up, and their interaction were not significant at dough stage.**

| Level | | | | Least Sq Mean |
|---|---|---|---|---|
| B.Tx645 | A | | | 321.15 |
| R.Tx7000 | A | | | 308.42 |
| B.Tx378 | A | B | | 290.62 |
| R.Tx437 | A | B | | 290.16 |
| B.Tx642 | | B | C | 265.86 |
| B.Tx631 | | | C | 252.2 |
| R.Tx436 | | | C | 246.97 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.05 | 0.84 |
| Genotypes | 5.38 | 0.0012* |
| Irrigation Regimes*Genotypes | 0.76 | 0.61 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.49 | 430 | 394.89 | 32.76 |
| Residual | | 882.58 | 254.78 | 67.24 |

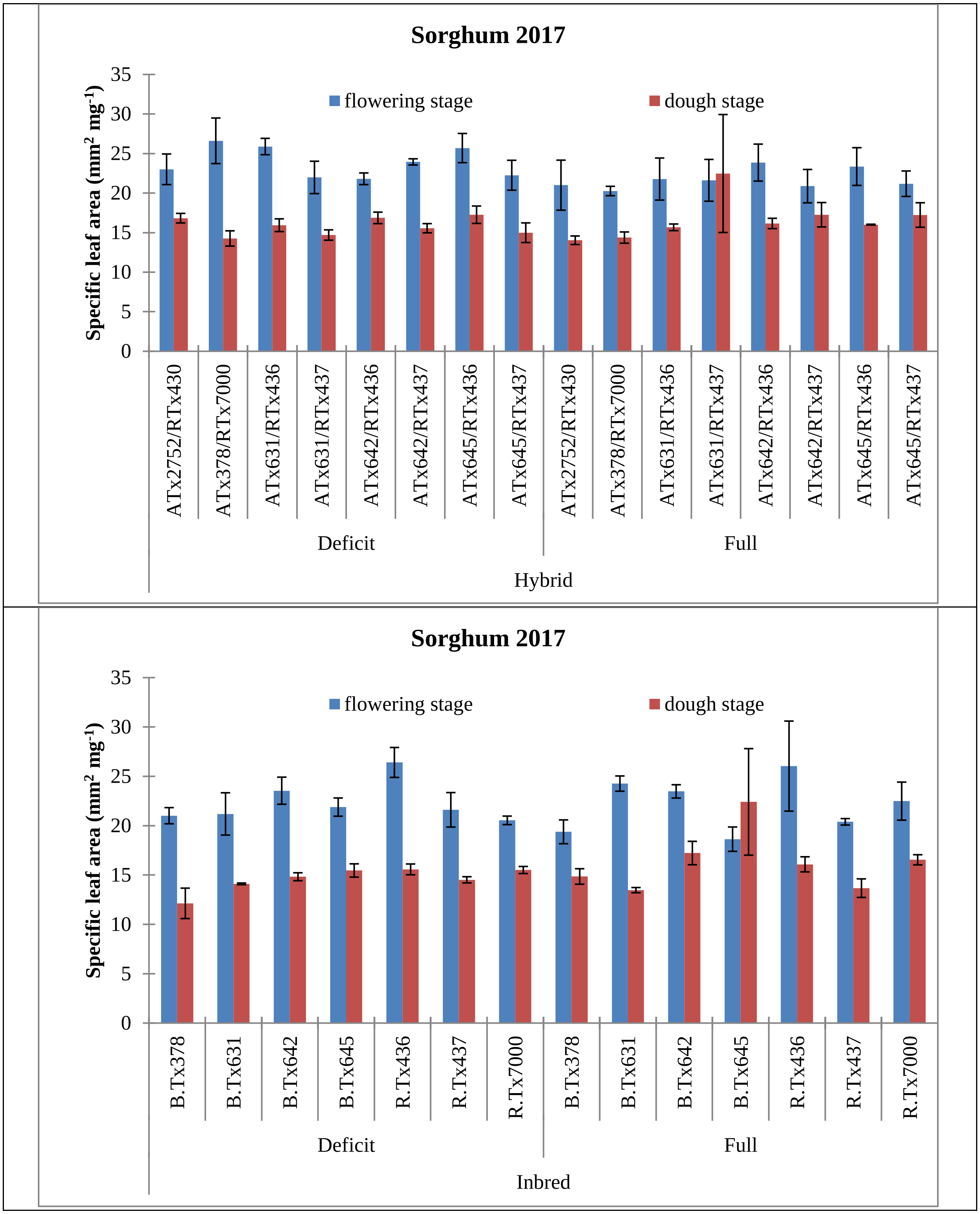


**Figure 2.27.** Specific leaf area (SLA) (mm$^2$/mg) for sorghum hybrids and inbreds in full and deficit irrigation regimes in 2017. Blue bar is SLA during flowering stage and red bar is SLA during dough stage. Standard error bar represents standard error of the mean.

**Table 2.43. Significant differences between full and deficit irrigation specific leaf area ($mm^2/mg$) of sorghum hybrids at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at $\alpha = 0.05$. Irrigation regimes connected by the same letter are not significantly different. Values with asterisk (*) shows significant main effect. Main effect of irrigation, genetic make-up, and their interaction were not significant even at dough stage.**

| Irrigation | | | Least Sq Mean |
|---|---|---|---|
| Deficit | A | | 23.9 |
| Full | | B | 21.74 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 4.42 | 0.0436* |
| Genotypes | 0.5 | 0.83 |
| Irrigation Regimes*Genotypes | 0.75 | 0.63 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 12.67 | 3.17 | 100 |

**Table 2.44. Significant differences among sorghum inbreds based on specific leaf area ($mm^2/mg$) at flowering stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at $\alpha = 0.05$. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. Main effect of genotypes was significant even at dough stage.**

| Level | | | Least Sq Mean |
|---|---|---|---|
| R.Tx436 | A | | 26.22 |
| B.Tx642 | A | B | 23.51 |
| B.Tx631 | A | B | 22.73 |
| R.Tx7000 | | B | 21.51 |
| R.Tx437 | | B | 21 |
| B.Tx645 | | B | 20.26 |
| B.Tx378 | | B | 20.19 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.05 | 0.82 |
| Genotypes | 3.08 | 0.0191* |
| Irrigation Regimes*Genotypes | 0.77 | 0.6 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 9.04 | 2.42 | 100 |

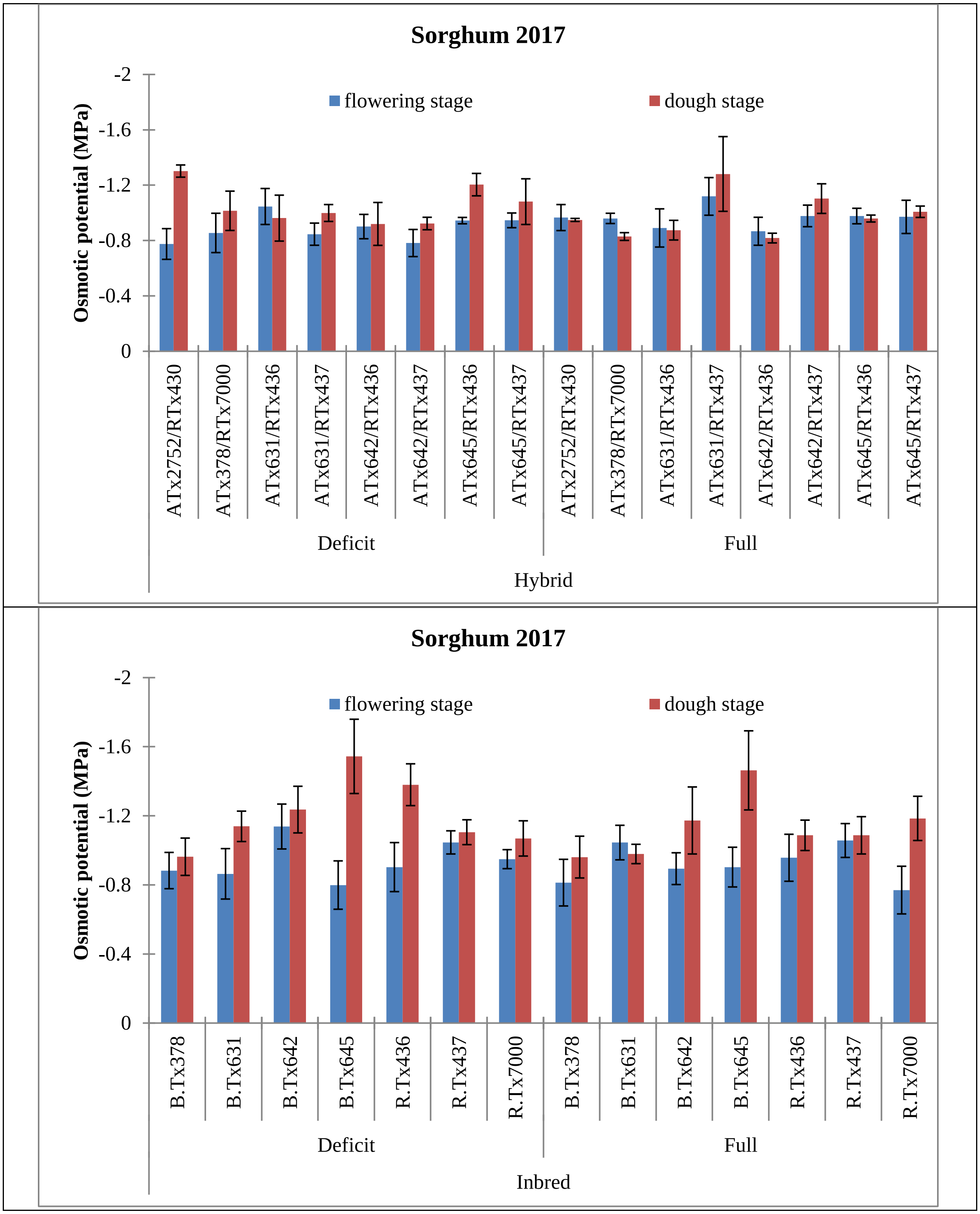


**Figure 2.28.** Osmotic potential (MPa) for sorghum hybrids and inbreds in full and deficit irrigation regimes in 2017. Blue bar is OP during flowering stage and red bar is OP during dough stage. Standard error bar represents standard error of the mean.

**Table 2.45. Fixed and random effect of different sources on osmotic potential (MPa) of sorghum hybrids under full and deficit irrigation regimes at dough stage in 2017. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Values with asterisk (*) shows significant main effect. Main effects of irrigation, genetic make-up, and their interaction were not significant even at flowering stage.**

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 1.64 | 0.21 |
| Genotypes | 1.59 | 0.17 |
| Irrigation Regimes*Genotypes | 1.72 | 0.14 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 0.04 | 0.01 | 100 |

**Table 2.46. Significant differences among sorghum inbreds based on osmotic potential (MPa) at dough stage in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Var represents variance. Values with asterisk (*) shows significant main effect. Main effects of irrigation, genetic make-up, and their interaction were not significant at flowering stage.**

| Level | | | | Least Sq Mean |
|---|---|---|---|---|
| B.Tx378 | A | | | -0.96 |
| B.Tx631 | A | B | | -1.06 |
| R.Tx437 | A | B | | -1.1 |
| R.Tx7000 | A | B | | -1.13 |
| B.Tx642 | A | B | | -1.2 |
| R.Tx436 | | B | | -1.23 |
| B.Tx645 | | | C | -1.5 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.58 | 0.49 |
| Genotypes | 3.66 | 0.0100* |
| Irrigation Regimes*Genotypes | 0.51 | 0.79 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.13 | 0.01 | 0.01 | 11.41 |
| Residual | | 0.05 | 0.01 | 88.59 |

### *Chlorophyll content and NDVI*

Not much change in chlorophyll content was observed from 35 days after sowing (vegetative stage) to 81 days after sowing (early soft dough stage) in sorghum hybrids and inbreds in 2016

(Figure 2.29). For sorghum hybrids, genetic effect was significant at 35 DAS and 81 DAS and at 41 DAS irrigation effect was significant in 2016. At 35 DAS, ATx623/RTx430 and ATx3197/RTx7000 showed significantly higher chlorophyll content compared to ATx378/RTx7000 and ATx645/RTx436 (Table 2.47). But at 81 DAS chlorophyll content was higher in ATx631/RTx436 and ATx2752/RTx430 (Table 2.48). ATx623/RTx430 showed low chlorophyll content at 81 DAS. Deficit irrigation hybrids showed significantly higher chlorophyll content compared full irrigation at 41 DAS (Table 2.49). Main effects of irrigation, genotypes, and their interaction on chlorophyll content of sorghum inbreds was not significant at 35 DAS and 41 DAS (Table 2.50). At 81 DAS, R.Tx7000 and B.Tx3197 showed significantly low chlorophyll content compared to other inbreds (Table 2.51).

In 2017, genetic effect was significant for chlorophyll content of sorghum hybrids measured at 88 DAS and 98 DAS (Table 2.52). However, in addition to genetic effect on chlorophyll content, irrigation x genotypes effect was also significant at 98 DAS in inbreds (Table 2.54). At 88 DAS, sorghum inbreds showed a significant genetic effect (Table 2.53). Not much decrease in chlorophyll content of sorghum hybrids and inbreds from 88 DAS (dough stage) to 98 DAS (dough stage) was observed (Figure 2.30). At 88 DAS, ATx642/RTx436, ATx645/RTx437, and ATx642/RTx437 showed higher chlorophyll content compared to ATx631/RTx437 and ATx378/RTx7000. Among sorghum inbreds, chlorophyll content was significantly higher in B.Tx642 and B.Tx645 compared to R.Tx436 and R.Tx437 at 88 DAS in 2017 (Table 2.53). At 98 DAS, B.Tx645 in deficit irrigation showed significantly higher chlorophyll content, whereas, low chlorophyll content was measured in R.Tx436 (deficit irrigation), R.Tx437 (deficit irrigation), and R.Tx7000 (full and deficit irrigation) (Table 2.54).

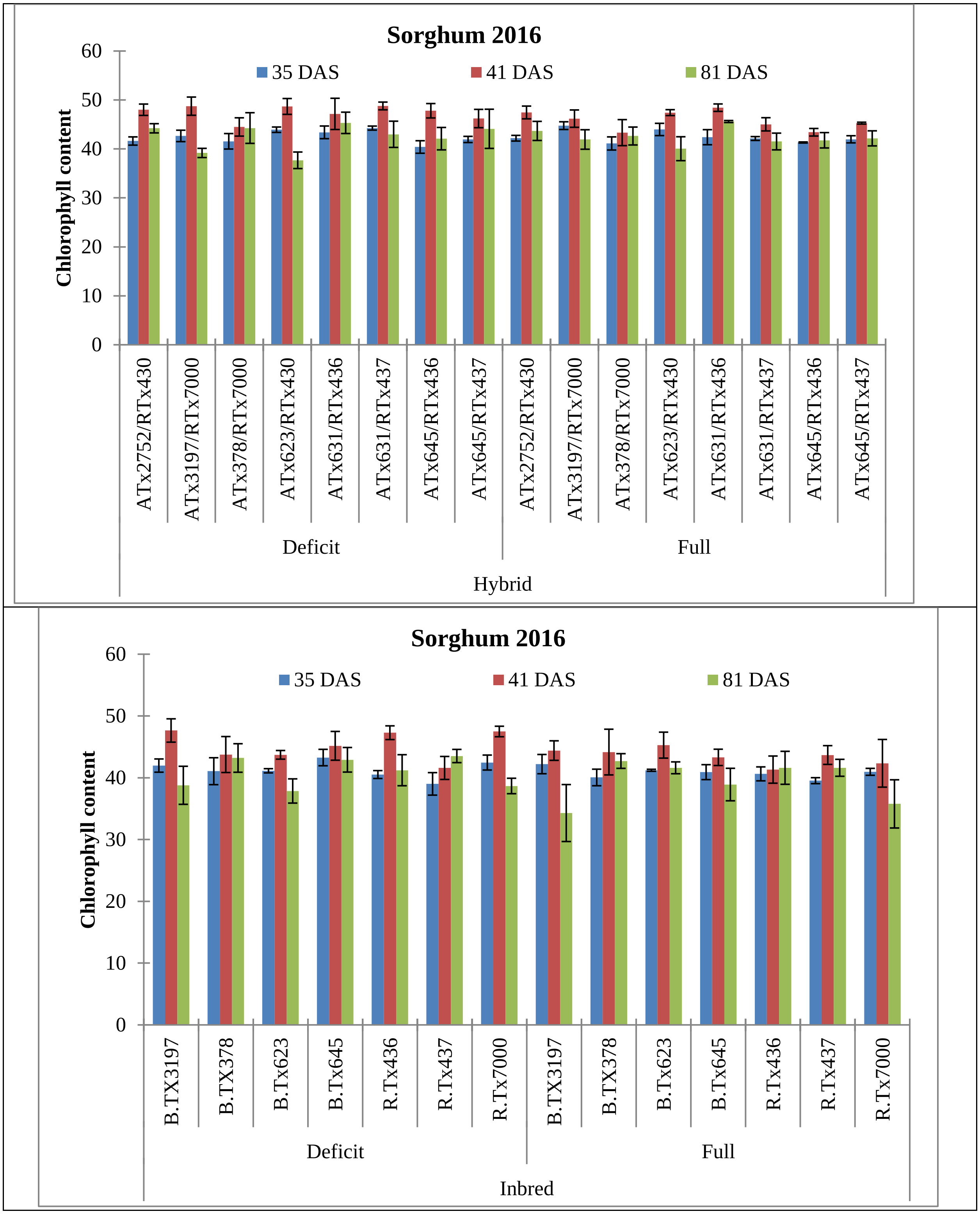


**Figure 2.29.** Chlorophyll content of sorghum hybrids and inbreds measured at 35 DAS (blue bar), 41 DAS (red bar), and 81 DAS (green bar) for deficit and full irrigation regimes in 2016. Standard error bar represents standard error of the mean.

**Table 2.47. Fixed and random effect of different sources on chlorophyll content of sorghum hybrids at 35 DAS in 2016. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| ATx623/RTx430 | A | 43.96 |
| ATx3197/RTx7000 | A B | 43.71 |
| ATx631/RTx437 | A B C | 43.2 |
| ATx631/RTx436 | A B C | 42.89 |
| ATx645/RTx437 | B C D | 41.96 |
| ATx2752/RTx430 | B C D | 41.91 |
| ATx378/RTx7000 | C D | 41.34 |
| ATx645/RTx436 | D | 40.86 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0 | 0.98 |
| Genotypes | 2.69 | 0.0277* |
| Irrigation Regimes*Genotypes | 0.85 | 0.55 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.07 | 0.19 | 0.37 | 6.4 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 2.83 | 0.73 | 93.6 |

**Table 2.48. Fixed and random effect of different sources on chlorophyll content of sorghum hybrids under full and deficit irrigation regimes at 41 DAS in 2016. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Irrigation are connected by different letters are significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Irrigation | | Least Sq Mean |
|---|---|---|
| Deficit | A | 47.48 |
| Full | B | 45.82 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 4.16 | 0.0497* |
| Genotypes | 1.56 | 0.18 |
| Irrigation Regimes*Genotypes | 0.63 | 0.73 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 8.01 | 2 | 100 |

**Table 2.49. Fixed and random effect of different sources on chlorophyll content of sorghum hybrids at 81 DAS in 2016. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| ATx631/RTx436 | A | 45.47 |
| ATx2752/RTx430 | A B | 43.95 |
| ATx378/RTx7000 | A B | 43.46 |
| ATx645/RTx437 | A B | 43.14 |
| ATx631/RTx437 | A B C | 42.25 |
| ATx645/RTx436 | A B C | 41.94 |
| ATx3197/RTx7000 | B C | 40.55 |
| ATx623/RTx430 | C | 38.87 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0 | 0.95 |
| Genotypes | 2.38 | 0.0463* |
| Irrigation Regimes*Genotypes | 0.45 | 0.86 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.28 | 2.95 | 3.62 | 21.67 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 10.65 | 2.75 | 78.33 |

**Table 2.50. Fixed and random effect of different sources on chlorophyll content of sorghum inbreds at 35 DAS in 2016. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Main effect of irrigation, genotypes, and their interaction were not significant even at 41 DAS.**

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 1.15 | 0.29 |
| Genotypes | 2.18 | 0.08 |
| Irrigation Regimes*Genotypes | 0.61 | 0.72 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.53 | 1.53 | 1.73 | 34.76 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 2.87 | 0.8 | 65.25 |

**Table 2.51. Fixed and random effect of different sources on chlorophyll content of sorghum inbreds at 81 DAS in 2016. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Inbreds connected by different letters are significantly different. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| B.TX378 | A | 42.95 |
| R.Tx437 | A | 42.57 |
| R.Tx436 | A B | 41.42 |
| B.Tx645 | A B C | 40.91 |
| B.Tx623 | A B C | 39.74 |
| R.Tx7000 | B C | 37.22 |
| B.TX3197 | C | 36.53 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 1.4 | 0.25 |
| Genotypes | 2.63 | 0.0398* |
| Irrigation Regimes*Genotypes | 0.86 | 0.54 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.29 | 4.14 | 5.17 | 22.4 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 14.34 | 3.98 | 77.6 |

**Table 2.52. Fixed and random effect of different sources on chlorophyll content of sorghum hybrids at 88 DAS in 2017. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Main effect genotypes was significant even at 98 DAS. Hybrids connected by different letters are significantly different. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| ATx642/RTx436 | A | 56.48 |
| ATx645/RTx437 | A | 55.82 |
| ATx642/RTx437 | A B | 55.57 |
| ATx2752/RTx430 | A B C | 53.68 |
| ATx645/RTx436 | A B C | 53.37 |
| ATx631/RTx436 | B C | 51.53 |
| ATx631/RTx437 | C | 50.85 |
| ATx378/RTx7000 | C | 50.67 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.17 | 0.69 |
| Genotypes | 2.66 | 0.0276* |
| Irrigation Regimes*Genotypes | 0.48 | 0.84 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 12.1 | 3.02 | 100 |

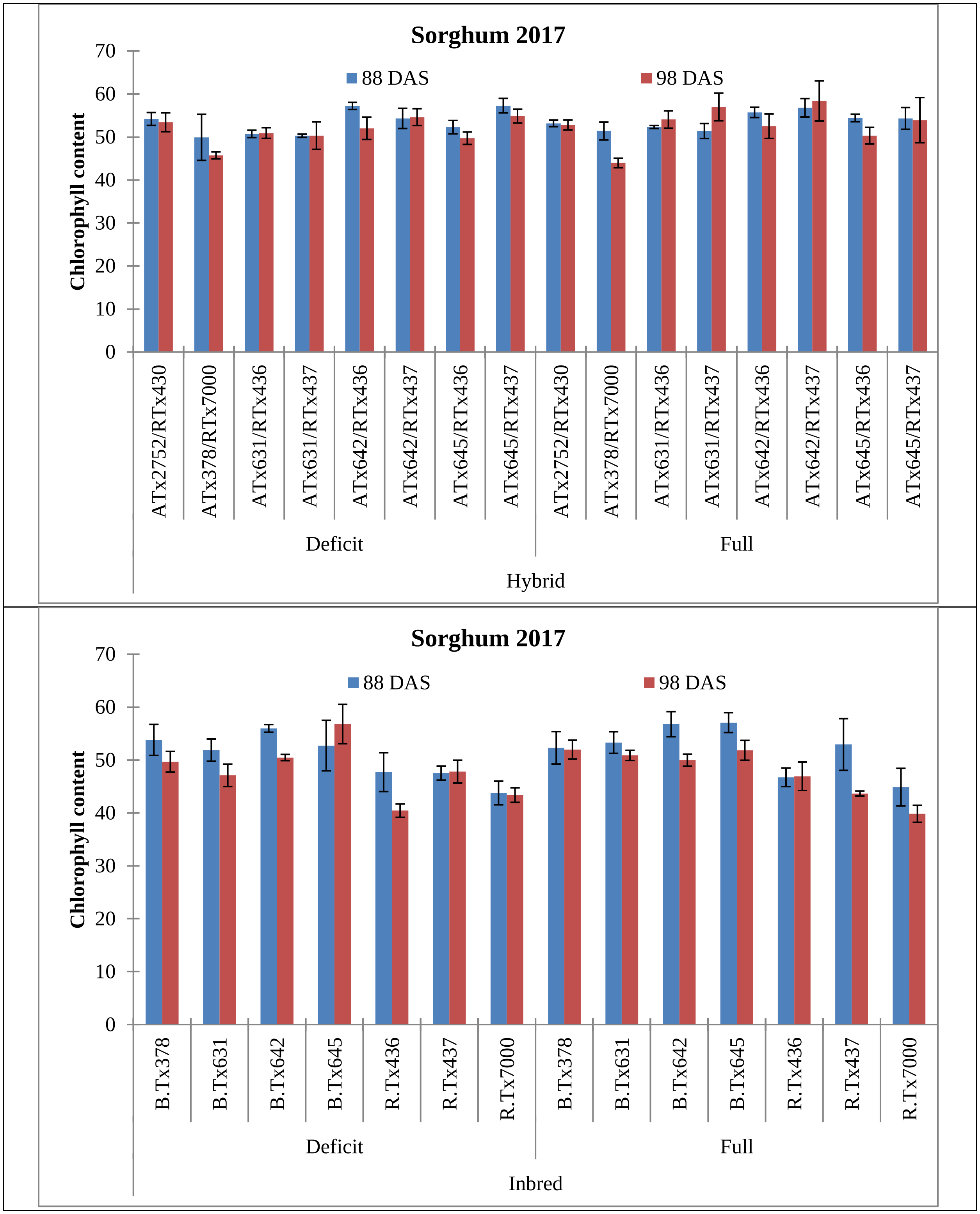


**Figure 2.30.** Chlorophyll content of sorghum hybrids and inbreds measured during 88 DAS (blue bar) and 98 DAS (red bar) for deficit and full irrigation in 2017. Standard error bar represents standard error of the mean.

**Table 2.53. Fixed and random effect of different sources on chlorophyll content of sorghum inbreds under full and deficit irrigation regimes at 88 DAS in 2017. Results have been obtained from standard least squares analysis using JMP 13.0 at α = 0.05. Var represents variance. Inbreds connected by different letters are significantly different. Values with asterisk (*) shows significant main effect.**

| Level | | | | | Least Sq Mean |
|---|---|---|---|---|---|
| B.Tx642 | A | | | | 56.37 |
| B.Tx645 | A | B | | | 54.9 |
| B.Tx378 | A | B | C | | 53.05 |
| B.Tx631 | A | B | C | | 52.58 |
| R.Tx437 | | B | C | D | 50.23 |
| R.Tx436 | | | C | D | 47.22 |
| R.Tx7000 | | | | D | 44.32 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.95 | 0.34 |
| Genotypes | 4.32 | 0.0033* |
| Irrigation Regimes*Genotypes | 0.38 | 0.88 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 25.46 | 6.8 | 100 |

**Table 2.54. Significant differences among sorghum inbreds in full and deficit irrigation based on chlorophyll content at 98 DAS in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| Deficit,B.Tx645 | A | 56.8 |
| Full,B.Tx378 | A B | 51.97 |
| Full,B.Tx645 | A B | 51.83 |
| Full,B.Tx631 | B | 50.87 |
| Deficit,B.Tx642 | B | 50.47 |
| Full,B.Tx642 | B | 49.97 |
| Deficit,B.Tx378 | B | 49.67 |
| Deficit,R.Tx437 | B C | 47.8 |
| Deficit,B.Tx631 | B C | 47.1 |
| Full,R.Tx436 | B C | 46.93 |
| Full,R.Tx437 | C D | 43.67 |
| Deficit,R.Tx7000 | C D | 43.37 |
| Deficit,R.Tx436 | D | 40.43 |
| Full,R.Tx7000 | D | 39.83 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0 | 0.96 |
| Genotypes | 12.93 | <.0001* |
| Irrigation Regimes*Genotypes | 3.17 | 0.0195* |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.16 | 1.49 | 2.01 | 13.98 |
| Residual | | 9.16 | 2.64 | 86.02 |

Effect of irrigation and genotypes on soft dough stage (83 DAS) NDVI and effect of irrigation, genotypes, and their interaction on hard dough stage (95 DAS) NDVI were not significant in sorghum hybrids. A significant irrigation and genetic effect on NDVI of sorghum inbreds at 83 DAS and 95 DAS were observed. ATx642/RTx436 (deficit irrigation) showed significantly higher NDVI than ATx645/RTx437 and ATx631/RTx437 under deficit irrigation at soft dough stage (83 DAS) (Table 2.55). Sorghum inbreds R.Tx436, B.Tx642, and B.Tx645 showed significantly higher NDVI compared to R.Tx7000 at 83 DAS and 95 DAS (Table 2.56 and Table 2.57). NDVI of inbreds in full irrigation was significantly higher than that in deficit irrigation at soft dough and hard dough stage.

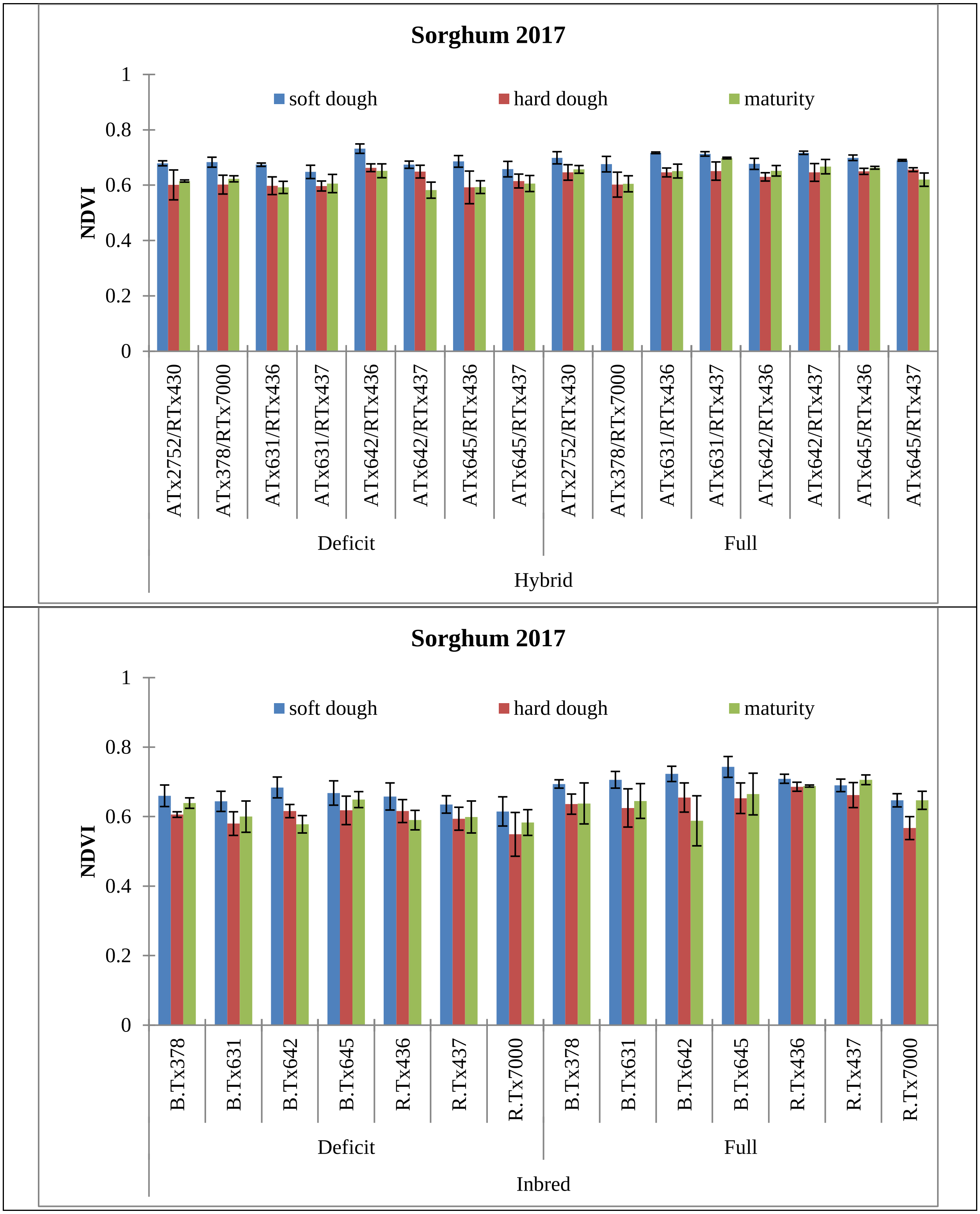


**Figure 2.31**. Normalized difference vegetation index (NDVI) of sorghum hybrids and inbreds measured during soft dough (blue bar), hard dough (red bar) and maturity (green bar) stage for deficit and full irrigation in 2017. Standard error bar represents standard error of the mean.

**Table 2.55. Significant differences among sorghum hybrids in full and deficit irrigation based on normalized difference vegetation index measured at soft dough in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect. Main effect of irrigation, genotypes, and their interaction were not significant at hard dough stage (95 DAS).**

| Level | | | | | Least Sq Mean |
|---|---|---|---|---|---|
| Deficit,ATx642/RTx436 | A | | | | 0.73 |
| Full,ATx631/RTx436 | A | B | | | 0.72 |
| Full,ATx642/RTx437 | A | B | | | 0.72 |
| Full,ATx631/RTx437 | A | B | C | | 0.71 |
| Full,ATx645/RTx436 | A | B | C | D | 0.7 |
| Full,ATx2752/RTx430 | A | B | C | D | 0.7 |
| Full,ATx645/RTx437 | A | B | C | D | 0.69 |
| Deficit,ATx645/RTx436 | | B | C | D | 0.69 |
| Deficit,ATx378/RTx7000 | | B | C | D | 0.68 |
| Deficit,ATx2752/RTx430 | | B | C | D | 0.68 |
| Full,ATx642/RTx436 | | B | C | D | 0.68 |
| Full,ATx378/RTx7000 | | B | C | D | 0.68 |
| Deficit,ATx631/RTx436 | | B | C | D | 0.67 |
| Deficit,ATx642/RTx437 | | B | C | D | 0.67 |
| Deficit,ATx645/RTx437 | | | C | D | 0.66 |
| Deficit,ATx631/RTx437 | | | | D | 0.65 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 2.45 | 0.19 |
| Genotypes | 0.9 | 0.52 |
| Irrigation Regimes*Genotypes | 2.94 | 0.0195* |

| Random Effect | % Variance |
|---|---|
| Rep | 0 |
| Irrigation Regimes*Rep | 16.79 |
| Residual | 83.21 |

**Table 2.56. Significant differences among sorghum inbreds based on normalized difference vegetation index measured at soft dough stage (83 DAS) in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes and irrigation regimes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| B.Tx645 | A | 0.71 |
| B.Tx642 | A | 0.7 |
| R.Tx436 | A | 0.68 |
| B.Tx378 | A B | 0.68 |
| B.Tx631 | A B | 0.68 |
| R.Tx437 | A B | 0.66 |
| R.Tx7000 | B | 0.63 |

| Irrigation | | Least Sq Mean |
|---|---|---|
| Full | A | 0.7 |
| Deficit | B | 0.65 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 17.15 | 0.0003* |
| Genotypes | 2.57 | 0.0433* |
| Irrigation Regimes*Genotypes | 0.25 | 0.95 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.54 | 0 | 0 | 34.86 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 0 | 0 | 65.14 |

**Table 2.57. Significant differences among sorghum inbreds based on NDVI measured at hard dough stage (95 DAS) in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes and irrigation regimes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| R.Tx436 | A | 0.65 |
| B.Tx642 | A B | 0.64 |
| B.Tx645 | A B | 0.64 |
| R.Tx437 | A B | 0.63 |
| B.Tx378 | A B | 0.62 |
| B.Tx631 | B | 0.6 |
| R.Tx7000 | C | 0.56 |

| Irrigation | | Least Sq Mean |
|---|---|---|
| Full | A | 0.64 |
| Deficit | B | 0.6 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 16.86 | 0.0004* |
| Genotypes | 4.77 | 0.0021* |
| Irrigation Regimes*Genotypes | 0.47 | 0.82 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 2.5 | 0 | 0 | 71.45 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 0 | 0 | 28.55 |

### *Linear discriminant analysis and path coefficient analysis*

Linear discriminant analysis was performed in 2017 to test the ability of different traits combinations to categorize sorghum genotypes in full and deficit irrigation regimes (Table 2.58). The combination of five traits, LT, SLA, osmotic potential, NDVI, and plant height showed the highest percentage of categorization of genotypes in full and deficit irrigation. However, NDVI was selected in all combinations. This confirmed that NDVI is an important parameter in water-stress related research. Overall, LDA results confirmed not only morphological or physiological, but morphophysiological approach and measurements are important for drought tolerance related research.

**Table 2.58. Linear discriminant analysis (LDA) of canopy and leaf traits to categorize sorghum hybrids and inbreds under full and deficit irrigation regimes in 2017. Values are in percentage. LT, LDMC, LD, SLA, OP, NDVI, LN, and height represent leaf thickness, leaf dry matter content, leaf tissue density, specific leaf area, osmotic potential, normalized difference vegetation index, number of green leaves, and plant height.**

| Traits | Deficit | Full | Overall |
|---|---|---|---|
| LT, LDMC, LD, SLA, OP, $(NDVI)^3$, $(Height)^3$, LN | 66.7 | 71.1 | 68.9 |
| LT, LDMC, SLA, OP, $(NDVI)^3$, $(Height)^3$, LN | 68.9 | 71.1 | 70 |
| LT, LDMC, LD, SLA, OP, $(NDVI)^3$, LN | 68.9 | 71.1 | 70 |
| LT, LDMC, LD, SLA, OP, $(NDVI)^3$ | 68.9 | 73.3 | 71.1 |
| LT, LDMC, OP, $(NDVI)^3$, $(Height)^3$, LN | 68.9 | 73.3 | 71.1 |
| LT, SLA, OP, $(NDVI)^3$, $(Height)^3$, LN | 68.9 | 73.3 | 71.1 |
| LT, SLA, OP, $(NDVI)^3$, $(Height)^3$ | 71.1 | 73.3 | 72.2 |
| LT, LDMC, $(NDVI)^3$, $(Height)^3$ | 68.9 | 71.1 | 70 |
| LT, OP, $(NDVI)^3$, $(Height)^3$ | 68.9 | 71.1 | 70 |
| LDMC, OP, $(NDVI)^3$, $(Height)^3$ | 68.9 | 71.1 | 70 |
| LDMC, $(NDVI)^3$, $(Height)^3$, LN | 68.9 | 71.1 | 70 |
| LT, LDMC, $(NDVI)^3$ | 68.9 | 71.1 | 70 |
| $(NDVI)^3$, $(Height)^3$ | 66.7 | 71.1 | 68.9 |
| $(NDVI)^3$ | 60 | 64.4 | 62.2 |

**Table 2.59. Direct and indirect effects of canopy and leaf traits on grain yield of sorghum hybrids and inbreds in 2016. Height, LN, LAI, and MTA represent plant height, number of green leaves, leaf area index, and mean tilt angle.**

| Hybrid/Inbred | Traits | Height | LN | LAI | MTA | Total |
|---|---|---|---|---|---|---|
| **Hybrid** | Height | -0.44 | -0.08 | 0.14 | 0.03 | -0.34 |
| | LN | 0.05 | 0.63 | -0.15 | 0.05 | 0.58 |
| | LAI | 0.09 | 0.13 | -0.7 | 0.02 | -0.47 |
| | MTA | -0.14 | 0.3 | -0.11 | 0.1 | 0.16 |
| **Inbred** | Height | 0.71 | 0 | 0 | 0.01 | 0.71 |
| | LN | 0.04 | -0.06 | 0.04 | 0 | 0.01 |
| | LAI | -0.03 | -0.03 | 0.07 | 0.01 | 0.02 |
| | MTA | -0.13 | -0.01 | -0.02 | -0.03 | -0.18 |

Path coefficient analysis was performed to study the effect of different plant traits of sorghum hybrids and inbreds on grain yield in 2016 and 2017 (Table 2.59 and Table 2.60). Values in the last column of each table are the total effect of trait present in second column on grain yield. Values in different rows are direct and indirect effect of different traits contributing to total effect of a trait in column on grain yield. The sum of these direct and indirect effects makes the total effect of trait in each row on grain yield. For example, LD showed a negative total effect of -0.36 on grain yield of sorghum inbreds (Table 2.60). This total effect was contributed by negative indirect effect of plant height (-0.02), number of green leaves (-0.1), LT (-0.38), LDMC (-0.2), SLA (-1.04), OP (-0.88), and NDVI (-0.28), direct positive effect of 2.54 by LD, and no effect by chlorophyll content.

**Table 2.60. Direct and indirect effects of canopy and leaf traits measured at flowering stage on grain yield of sorghum hybrids and inbreds in 2017. LT, LDMC, LD, SLA, OP, NDVI, LN, and height represent leaf thickness, leaf dry matter content, leaf tissue density, specific leaf area, osmotic potential, normalized difference vegetation index, number of green leaves, and plant height.**

| **Hybrid/Inbred** | **Traits** | Height | LN | Chl. | LT | LDMC | LD | SLA | OP | NDVI | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hybrid** | Height | -0.87 | 0.25 | -0.05 | 2.85 | 0.23 | -2.66 | -0.27 | 0.37 | 0.09 | -0.06 |
| | LN | -0.35 | 0.62 | 0.03 | 1.39 | 0.1 | -0.45 | -0.93 | 0.45 | -0.03 | 0.83 |
| | Chl. | 0.15 | 0.07 | 0.29 | -0.48 | 0.13 | 0.87 | -0.64 | -0.47 | 0.11 | 0.04 |
| | LT | -0.68 | 0.24 | -0.04 | 3.66 | 0.19 | -2.62 | -0.99 | 0.39 | -0.01 | 0.13 |
| | LDMC | -0.57 | 0.17 | 0.11 | 2.01 | 0.35 | -1.15 | -0.86 | -0.19 | 0.15 | 0.01 |
| | LD | 0.66 | -0.08 | 0.07 | -2.74 | -0.12 | 3.5 | -0.53 | -0.58 | -0.08 | 0.1 |
| | SLA | 0.1 | -0.26 | -0.09 | -1.65 | -0.14 | -0.84 | 2.21 | 0.18 | 0.12 | -0.35 |
| | OP | 0.31 | -0.27 | 0.14 | -1.39 | 0.07 | 1.99 | -0.4 | -1.02 | 0.13 | -0.45 |
| | NDVI | -0.24 | -0.06 | 0.11 | -0.15 | 0.17 | -0.91 | 0.88 | -0.42 | 0.3 | -0.31 |
| **Inbred** | Height | 0.9 | 0.02 | 0 | 0.35 | 0.08 | -0.05 | -0.3 | -1.03 | -0.74 | -0.78 |
| | LN | 0.09 | 0.2 | 0 | 0.53 | -0.19 | -1.32 | 0.15 | 0.94 | 0.02 | 0.41 |
| | Chl. | -0.28 | 0.02 | 0.01 | 0.27 | -0.96 | -0.05 | -0.3 | 0.34 | 1.22 | 0.27 |
| | LT | 0.42 | 0.14 | 0.01 | 0.74 | -0.52 | -1.3 | -0.08 | 0.5 | 0.13 | 0.05 |
| | LDMC | -0.06 | 0.03 | 0.01 | 0.34 | -1.13 | 0.46 | -0.62 | -0.02 | 1 | 0.01 |
| | LD | -0.02 | -0.1 | 0 | -0.38 | -0.2 | 2.54 | -1.04 | -0.88 | -0.28 | -0.36 |
| | SLA | -0.22 | 0.02 | 0 | -0.04 | 0.55 | -2.08 | 1.27 | 0.58 | 0.24 | 0.31 |
| | OP | 0.51 | -0.1 | 0 | -0.21 | -0.01 | 1.25 | -0.41 | -1.8 | -0.18 | -0.95 |
| | NDVI | -0.45 | 0 | 0.01 | 0.07 | -0.77 | -0.48 | 0.2 | 0.22 | 1.47 | 0.27 |

### *Grain starch and protein quantification, aboveground biomass accumulation, and grain yield*

Strong negative relation between grain starch and protein content was observed for sorghum hybrids (Figure 2.32 and Figure 2.34) and inbreds (Figure 2.33 and Figure 2.35) in 2016 and 2017. Only genetic effect was significant for grain starch and protein content in sorghum hybrids and inbreds in 2016 and 2017. However, irrigation x genotype effect was also found significant for grain starch content of hybrids in 2017.

In 2016, ATx645/RTx437 and ATx645/RTx436 showed significantly higher grain starch content and significantly low grain protein (Table 2.61). Grain starch was low in ATx631/RTx436 and ATx3197/RTx7000, whereas, ATx631/RTx436 showed significantly higher grain protein content. Among inbreds, R.Tx436 and R.Tx437 showed significantly high grain protein content and low grain starch content (Table 2.61). Grain protein was low in B.Tx3197. B.Tx645 showed higher grain starch content.

In 2017, ATx642/RTx437, ATx2752/RTx430, and ATx642/RTx436 showed significantly higher grain protein content, whereas, grain starch content was higher in deficit irrigation plots of ATx645/RTx436 and ATx645/RTx437 (Table 2.62). Low grain starch was found in ATx642/RTx437 and ATx642/RTx436 under deficit irrigation and ATx2752/RTx430 and ATx631/RTx436 under full irrigation. Among inbreds, B.Tx631 showed significantly low grain protein content but high grain starch, whereas, R.Tx7000 showed significantly high grain protein content but low grain starch (Table 2.62). R.Tx437 and B.Tx642 showed low grain protein as well as grain starch content.

Higher aboveground biomass accumulation led to higher grain yield in sorghum hybrids and inbreds in 2016 and 2017. This relationship was stronger in hybrids (Figure 2.36 and Figure 2.38) compared to inbreds (Figure 2.37 and Figure 2.39). Genetic effect was significant for grain yield of sorghum hybrids and inbreds in 2016 and 2017. Main effect of irrigation x genotypes was also significant for grain yield of sorghum hybrids in 2017. Effect of residual on grain yield of hybrids and inbreds was also seen in 2016 and 2017.

In 2016, ATx2752/RTx430 and ATx645/RTx437 produced significantly higher grain yield and grain yield was low in ATx378/RTx7000, ATx631/RTx436, and ATx3197/RTx7000 (Table 2.63). Among inbreds, B.Tx623, R.Tx7000, and B.Tx645 produced higher grain yield, whereas, low grain yield was found in B.Tx378 and R.Tx436 (Table 2.64).

In 2017, ATx642/RTx437 under deficit irrigation and ATx645/RTx437, ATx631/RTx437, and ATx631/RTx436 under full irrigation showed higher grain yield, while grain yield was low in ATx378/RTx7000 and ATx642/RTx436 under both the irrigation and ATx631/RTx436 under deficit irrigation (Table 2.65). Among inbreds, significantly higher grain yield was produced by R.Tx437 and B.Tx642 (Table 2.66). Interaction of irrigation x replication was also responsible for variations in grain yield of sorghum inbreds in 2017.

No significant main effects of irrigation, genotypes, and irrigation x genotypes were observed for aboveground biomass of sorghum hybrids and inbreds in 2016 and 2017.

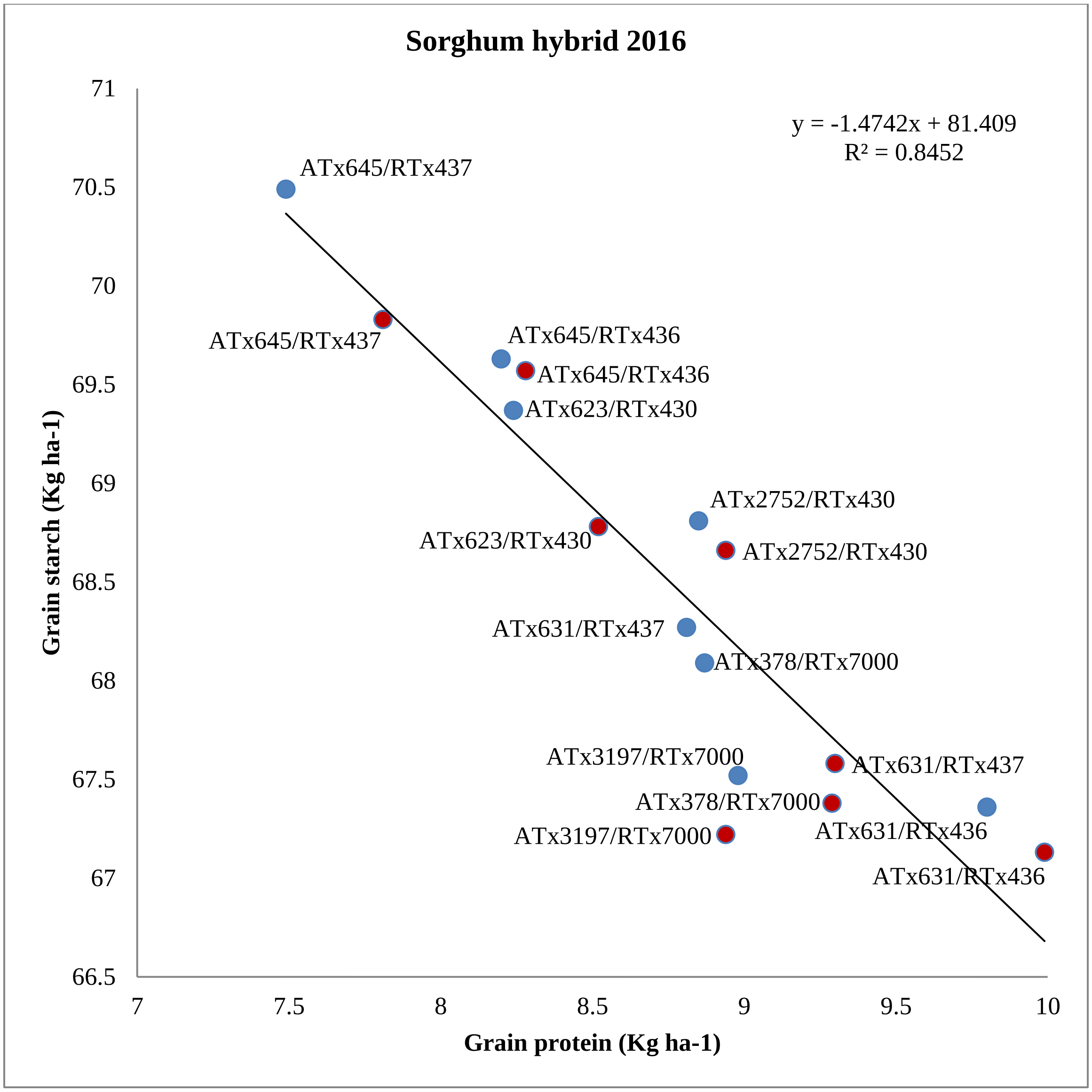


**Figure 2.32.** Scatterplot for grain starch and grain protein composition of sorghum hybrids in 2016 in deficit (red dots) and full (blue dots) irrigation regimes. Values are in percentage.

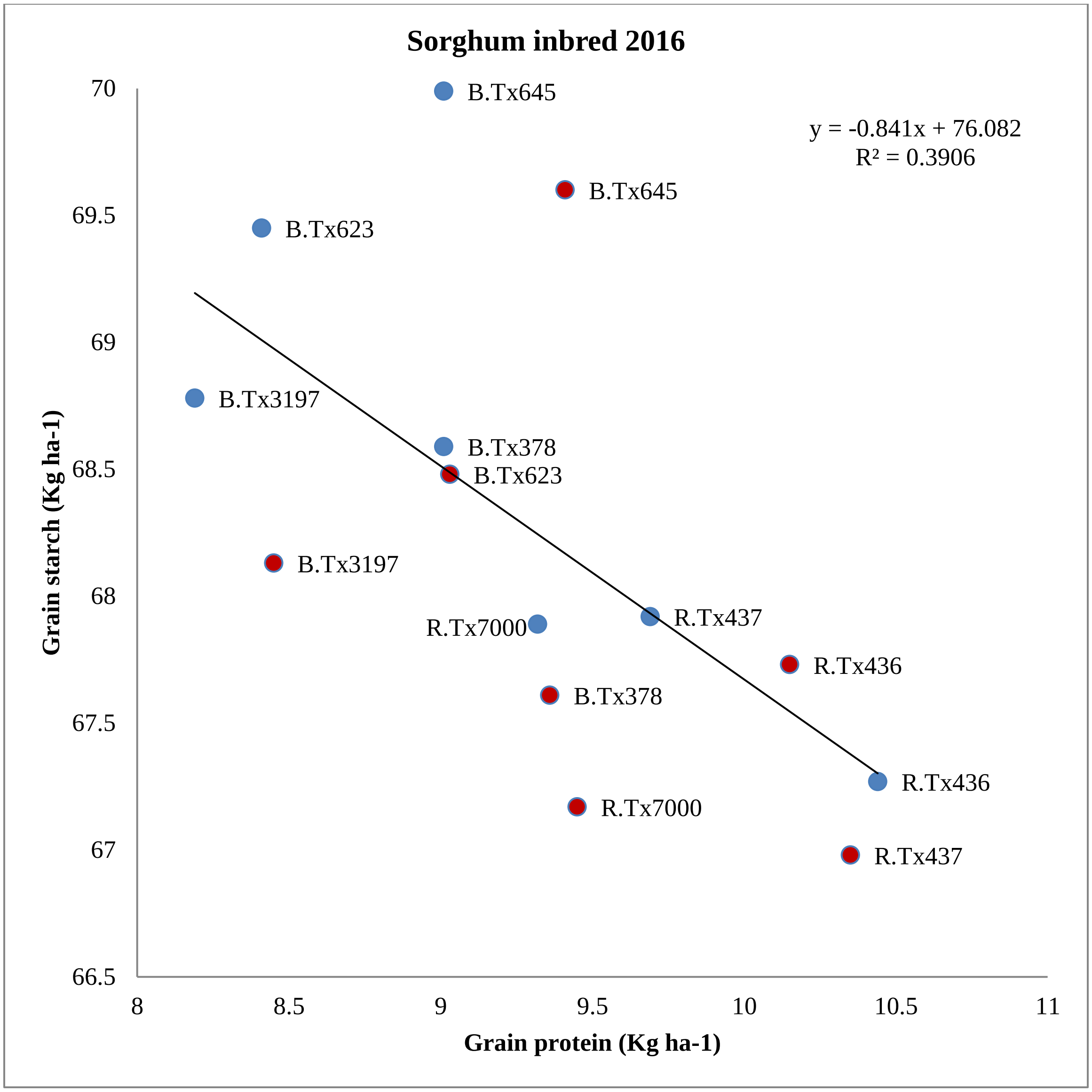


**Figure 2.33.** Scatterplot for grain starch and grain protein composition of sorghum inbreds in 2016 in deficit (red dots) and full (blue dots) irrigation regimes. Values are in percentage.

**Table 2.61. Significant differences among sorghum genotypes based on grain starch (%) and protein content (%) in 2016. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by different letters are significantly different. Values with asterisk (*) shows significant main effect.**

**Grain protein content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| ATx631/RTx436 | A | 9.9 |
| ATx378/RTx7000 | B | 9.08 |
| ATx631/RTx437 | B | 9.06 |
| ATx3197/RTx7000 | B | 8.96 |
| ATx2752/RTx430 | B | 8.89 |
| ATx623/RTx430 | C | 8.38 |
| ATx645/RTx436 | C | 8.24 |
| ATx645/RTx437 | D | 7.65 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 1.26 | 0.33 |
| Genotypes | 47.5 | <.0001* |
| Irrigation*Genotypes | 0.87 | 0.54 |

| Random Effect | % Variance |
|---|---|
| Rep | 0 |
| Irrigation*Rep | 49.33 |
| Residual | 50.67 |

**Grain starch content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| ATx645/RTx437 | A | 70.16 |
| ATx645/RTx436 | B | 69.6 |
| ATx623/RTx430 | C | 69.07 |
| ATx2752/RTx430 | C | 68.74 |
| ATx631/RTx437 | D | 67.93 |
| ATx378/RTx7000 | D | 67.73 |
| ATx3197/RTx7000 | E | 67.37 |
| ATx631/RTx436 | E | 67.25 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 1.15 | 0.34 |
| Genotypes | 75.68 | <.0001* |
| Irrigation*Genotypes | 1.15 | 0.36 |

| Random Effect | % Variance |
|---|---|
| Rep | 0 |
| Irrigation*Rep | 70.89 |
| Residual | 29.12 |

**Grain protein content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| R.Tx436 | A | 10.29 |
| R.Tx437 | A | 10.02 |
| R.Tx7000 | B | 9.38 |
| B.Tx645 | B | 9.21 |
| B.TX378 | B | 9.18 |
| B.Tx623 | C | 8.72 |
| B.TX3197 | D | 8.32 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 1.84 | 0.31 |
| Genotypes | 28.14 | <.0001* |
| Irrigation*Genotypes | 1.54 | 0.21 |

| Random Effect | % Variance |
|---|---|
| Rep | 27.43 |
| Irrigation*Rep | 27.69 |
| Residual | 44.88 |

**Grain starch content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| B.Tx645 | A | 69.8 |
| B.Tx623 | B | 68.96 |
| B.TX3197 | B C | 68.46 |
| B.TX378 | C D | 68.1 |
| R.Tx7000 | D | 67.53 |
| R.Tx436 | D | 67.5 |
| R.Tx437 | D | 67.45 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 1.37 | 0.36 |
| Genotypes | 15.03 | <.0001* |
| Irrigation*Genotypes | 1.28 | 0.31 |

| Random Effect | % Variance |
|---|---|
| Rep | 23.58 |
| Irrigation*Rep | 40.31 |
| Residual | 36.12 |

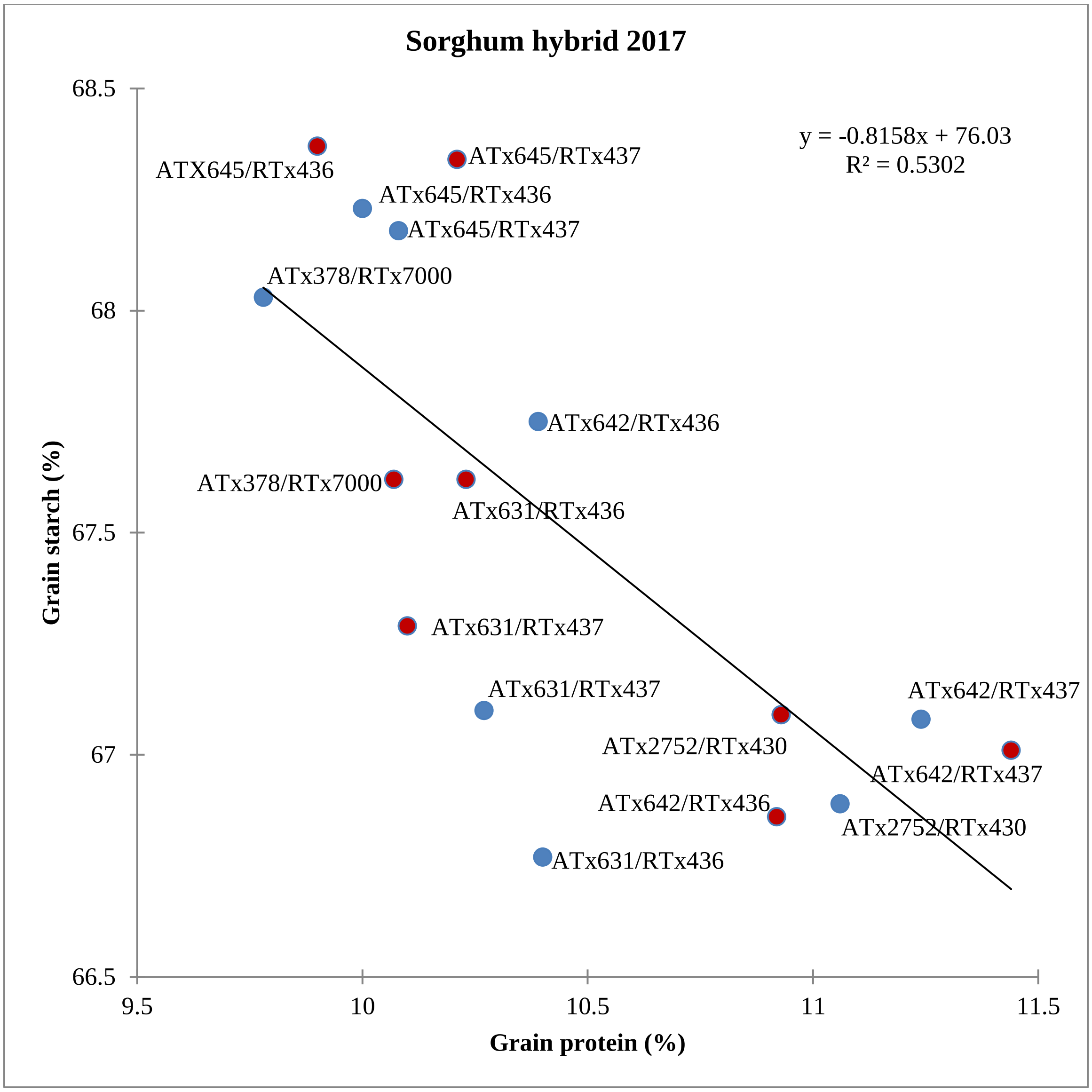


**Figure 2.34.** Scatterplot for grain starch and grain protein composition of sorghum hybrids in 2017 in deficit (red dots) and full (blue dots) irrigation regimes. Values are in percentage.

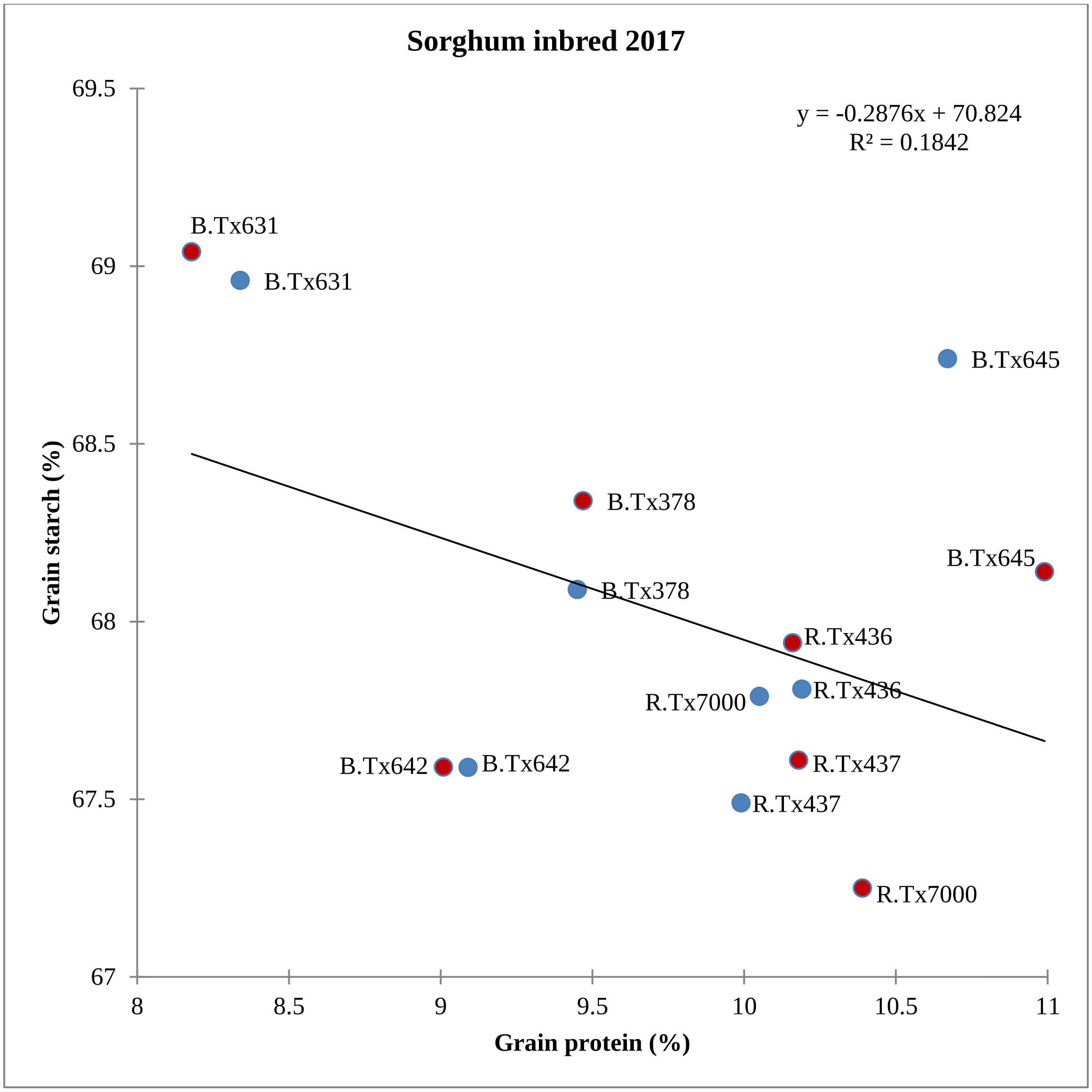


**Figure 2.35.** Scatterplot for grain starch and grain protein composition of sorghum inbreds in 2017 in deficit (red dots) and full (blue dots) irrigation regimes. Values are in percentage.

**Table 2.62. Significant differences among sorghum genotypes based on grain starch (%) and protein content (%) in 2017. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by different letters are significantly different. Values with asterisk (*) shows significant main effect.**

**Grain protein content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| ATx642/RTx437 | A | 11.34 |
| ATx2752/RTx430 | A B | 10.99 |
| ATx642/RTx436 | B C | 10.66 |
| ATx631/RTx436 | C D | 10.32 |
| ATx631/RTx437 | D | 10.19 |
| ATx645/RTx437 | D | 10.15 |
| ATx645/RTx436 | D | 9.95 |
| ATx378/RTx7000 | D | 9.92 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 0.26 | 0.66 |
| Genotypes | 12.98 | <.0001* |
| Irrigation*Genotypes | 0.81 | 0.59 |

| Random Effect | % Variance |
|---|---|
| Rep | 27.33 |
| Irrigation*Rep | 7.78 |
| Residual | 64.9 |

**Grain starch content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| Deficit,ATx645/RTx436 | A | 68.37 |
| Deficit,ATx645/RTx437 | A | 68.34 |
| Full,ATx645/RTx436 | A B | 68.23 |
| Full,ATx645/RTx437 | A B | 68.18 |
| Full,ATx378/RTx7000 | A B | 68.03 |
| Full,ATx642/RTx436 | A B C | 67.75 |
| Deficit,ATx378/RTx7000 | B C D | 67.62 |
| Deficit,ATx631/RTx436 | B C D | 67.62 |
| Deficit,ATx631/RTx437 | C D E | 67.29 |
| Full,ATx631/RTx437 | C D E | 67.1 |
| Deficit,ATx2752/RTx430 | D E | 67.09 |
| Full,ATx642/RTx437 | D E | 67.08 |
| Deficit,ATx642/RTx437 | D E | 67.01 |
| Full,ATx2752/RTx430 | E | 66.89 |
| Deficit,ATx642/RTx436 | E | 66.86 |
| Full,ATx631/RTx436 | E | 66.77 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 0.03 | 0.87 |
| Genotypes | 11.26 | <.0001* |
| Irrigation*Genotypes | 2.55 | 0.0368* |

| Random Effect | % Variance |
|---|---|
| Rep | 36.438 |
| Irrigation*Rep | 1.190 |
| Residual | 62.372 |

**Grain protein content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| B.Tx645 | A | 10.83 |
| R.Tx7000 | B | 10.22 |
| R.Tx436 | B | 10.17 |
| R.Tx437 | B | 10.08 |
| B.Tx378 | C | 9.46 |
| B.Tx642 | D | 9.05 |
| B.Tx631 | E | 8.26 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 0.96 | 0.34 |
| Genotypes | 58.63 | <.0001* |
| Irrigation*Genotypes | 0.76 | 0.61 |

| Random Effect | % Variance |
|---|---|
| Rep | 25.83 |
| Irrigation*Rep | 0 |
| Residual | 74.17 |

**Grain starch content (%)**

| Level | | Least Sq Mean |
|---|---|---|
| B.Tx631 | A | 69 |
| B.Tx645 | B | 68.44 |
| B.Tx378 | B C | 68.22 |
| R.Tx436 | C D | 67.88 |
| B.Tx642 | D | 67.59 |
| R.Tx437 | D | 67.55 |
| R.Tx7000 | D | 67.52 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation | 0.4 | 0.53 |
| Genotypes | 11.24 | <.0001* |
| Irrigation*Genotypes | 1.07 | 0.41 |

| Random Effect | % Variance |
|---|---|
| Rep | 20.8 |
| Irrigation*Rep | 0 |
| Residual | 79.2 |

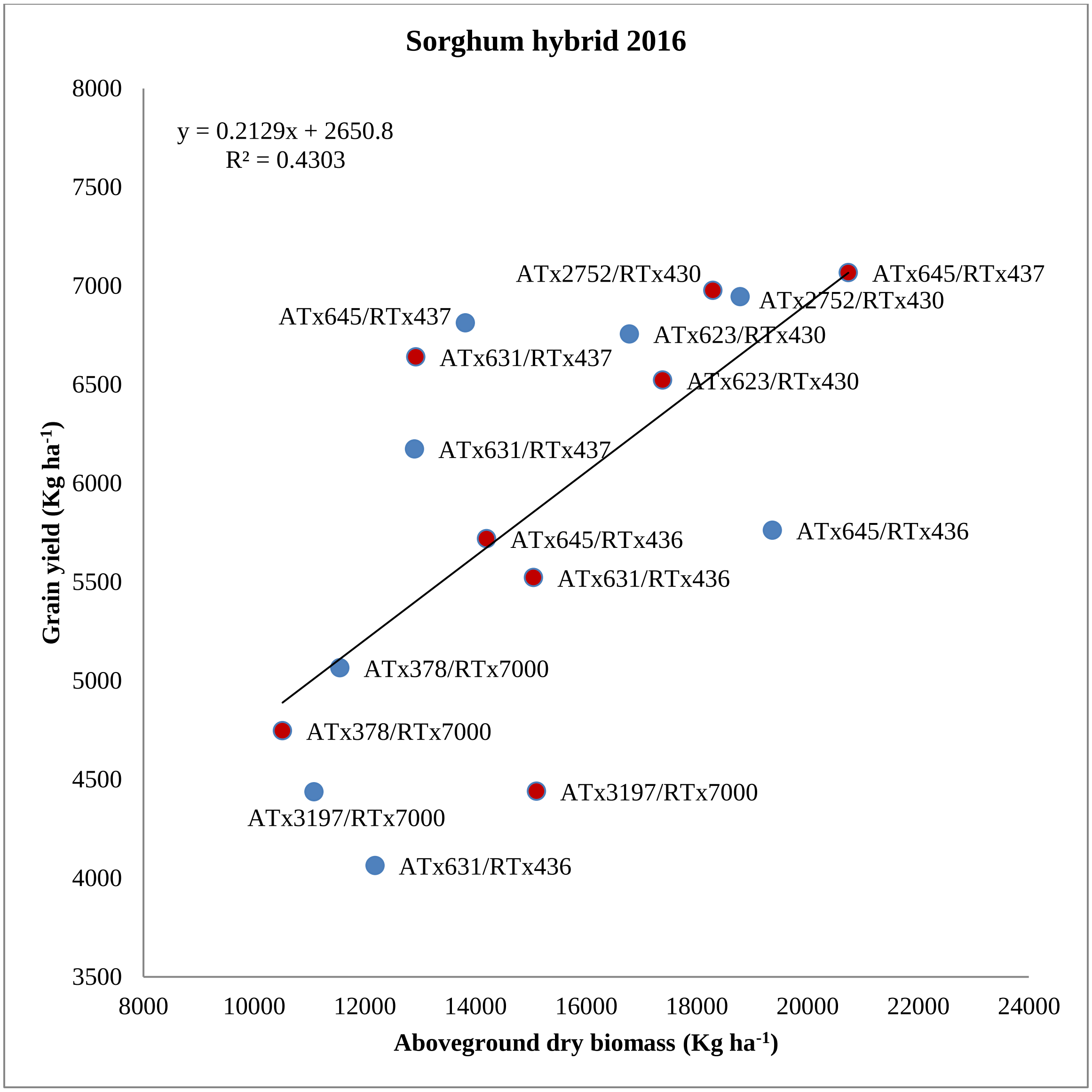


**Figure 2.36.** Scatterplot of grain yield vs. aboveground dry biomass for sorghum hybrids in 2016. Red dots represent deficit irrigation and blue dots represent full irrigation.

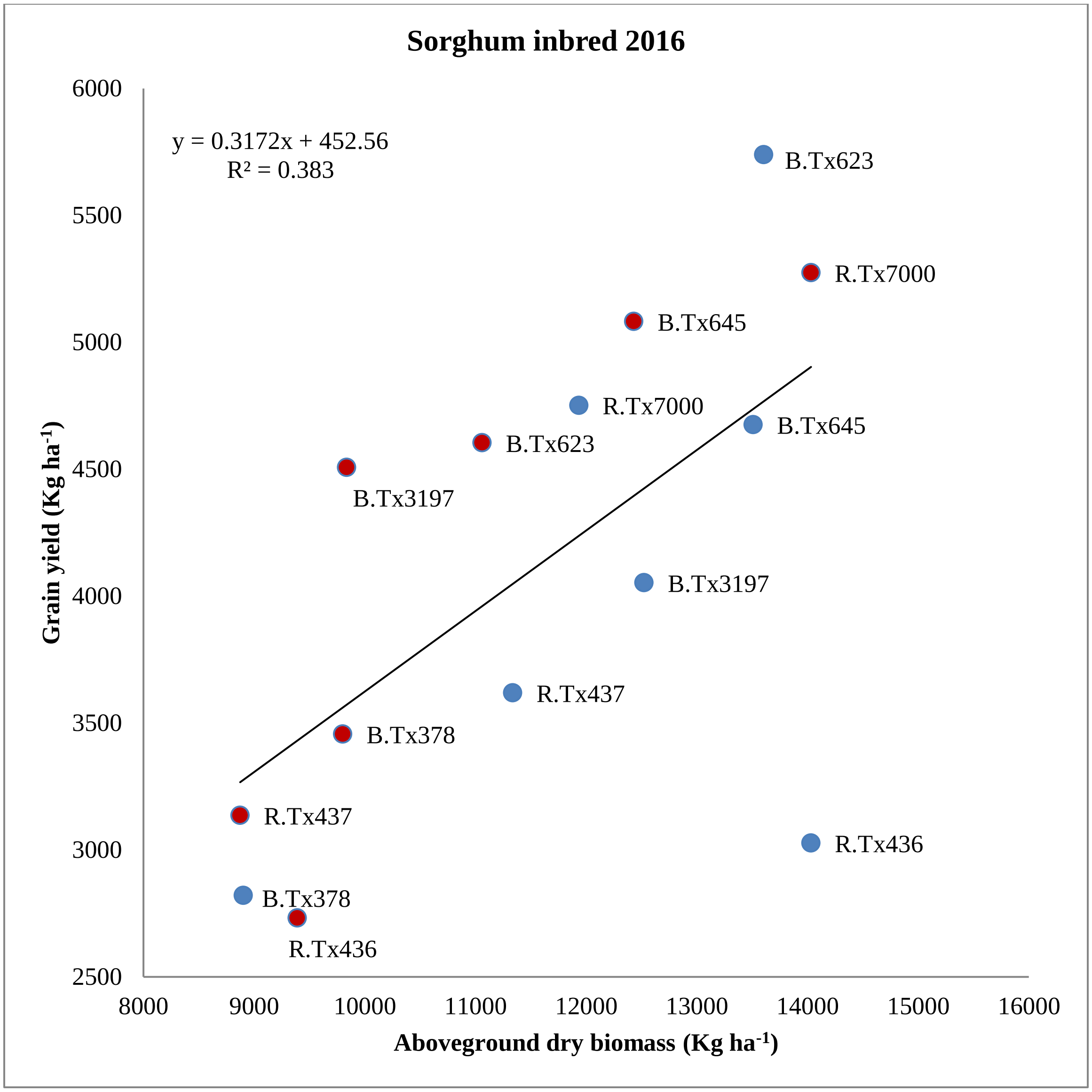


**Figure 2.37.** Scatterplot of grain yield vs. aboveground dry biomass for sorghum inbreds in 2016. Red dots represent deficit irrigation and blue dots represent full irrigation.

**Table 2.63. Significant differences among sorghum hybrids based on grain yield (Kg/ha) in 2016. Results were obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| ATx2752/RTx430 | A | 6961.59 |
| ATx645/RTx437 | A | 6940.28 |
| ATx623/RTx430 | A B | 6639.88 |
| ATx631/RTx437 | A B | 6407.71 |
| ATx645/RTx436 | B C | 5741.17 |
| ATx378/RTx7000 | C D | 4906.44 |
| ATx631/RTx436 | D | 4793.83 |
| ATx3197/RTx7000 | D | 4439.19 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.79 | 0.38 |
| Genotypes | 10.21 | <.0001* |
| Irrigation Regimes*Genotypes | 0.78 | 0.61 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0 | 0 | 0 | 0 |
| Residual | | 618543.12 | 154635.78 | 100 |

**Table 2.64. Significant differences among sorghum inbreds based on grain yield (Kg/ha) in 2016. Results have been obtained from Student's t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---|
| B.Tx623 | A | 5171.9 |
| R.Tx7000 | A | 5013.52 |
| B.Tx645 | A | 4879.02 |
| B.TX3197 | A B | 4280.23 |
| R.Tx437 | B C | 3378.04 |
| B.TX378 | C | 3139.55 |
| R.Tx436 | C | 2880.21 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0 | 0.97 |
| Genotypes | 8.47 | <.0001* |
| Irrigation Regimes*Genotypes | 1.01 | 0.44 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0.02 | 15997.93 | 128363.51 | 2.16 |
| Irrigation Regimes*Rep | 0.11 | 71334.01 | 167024.28 | 9.62 |
| Residual | | 654466.3 | 188928.15 | 88.23 |

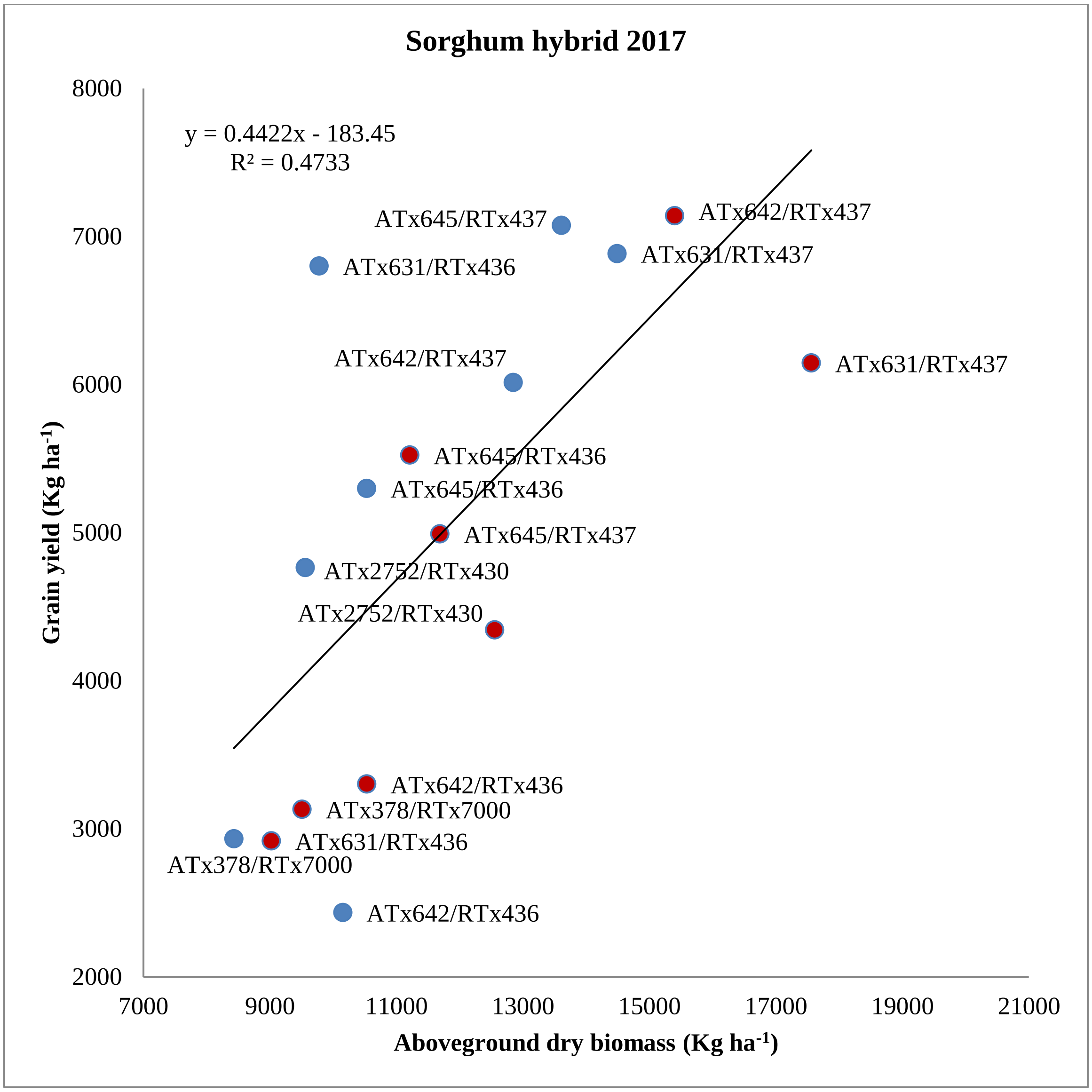


**Figure 2.38.** Scatterplot of grain yield vs. aboveground dry biomass for sorghum hybrids in 2017. Red dots represent deficit irrigation and blue dots represent full irrigation.

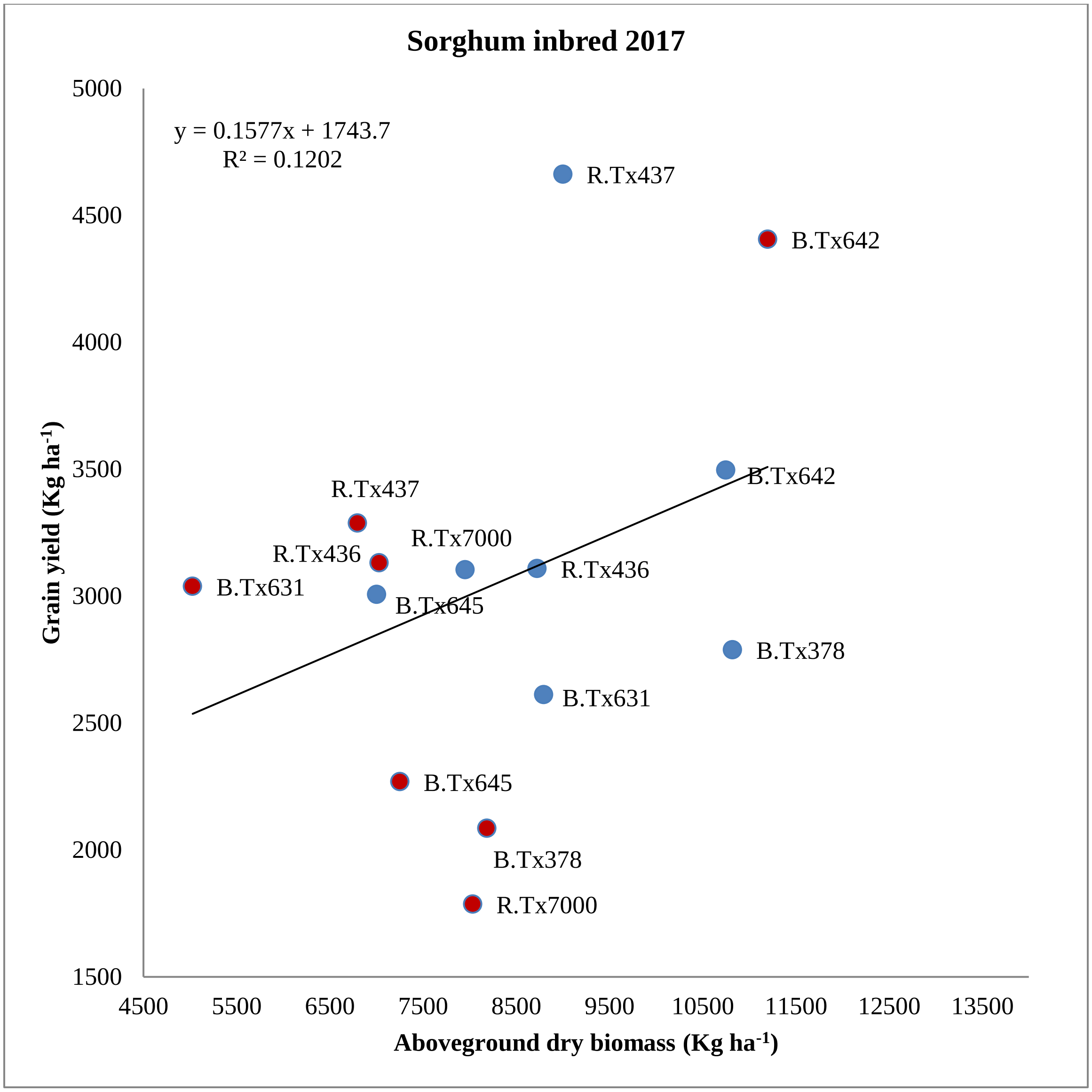


**Figure 2.39.** Scatterplot of grain yield vs. aboveground dry biomass for sorghum inbreds in 2017. Red dots represent deficit irrigation and blue dots represent full irrigation.

**Table 2.65. Significant differences among sorghum hybrids in full and deficit irrigation based on grain yield (Kg/ha) in 2017. Results have been obtained from Student’s t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | Least Sq Mean |
|---|---|---:|
| Deficit,ATx642/RTx437 | A | 7140.46 |
| Full,ATx645/RTx437 | A | 7075.98 |
| Full,ATx631/RTx437 | A B | 6885.55 |
| Full,ATx631/RTx436 | A B | 6801.52 |
| Deficit,ATx631/RTx437 | A B C | 6145.75 |
| Full,ATx642/RTx437 | A B C | 6015.46 |
| Deficit,ATx645/RTx436 | A B C | 5524.1 |
| Full,ATx645/RTx436 | A B C D | 5299.7 |
| Deficit,ATx645/RTx437 | A B C D E | 4991.25 |
| Full,ATx2752/RTx430 | B C D E | 4764.41 |
| Deficit,ATx2752/RTx430 | C D E F | 4343.37 |
| Deficit,ATx642/RTx436 | D E F | 3301.71 |
| Deficit,ATx378/RTx7000 | D E F | 3132.52 |
| Full,ATx378/RTx7000 | E F | 2933.36 |
| Deficit,ATx631/RTx436 | E F | 2918.47 |
| Full,ATx642/RTx436 | F | 2435.77 |

| Fixed Effect | F Ratio | Prob > F |
|---|---:|---:|
| Irrigation Regimes | 1.29 | 0.32 |
| Genotypes | 7.25 | <.0001* |
| Irrigation Regimes*Genotypes | 2.41 | 0.0461* |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---:|---:|---:|---:|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.11 | 188664.39 | 292324.47 | 9.82 |
| Residual | | 1732485.9 | 463026.33 | 90.18 |

**Table 2.66. Significant differences among sorghum inbreds in full and deficit irrigation based on grain yield (Kg/ha) in 2017. Results have been obtained from Student’s t-test using standard least squares analysis in JMP 13.0 at α = 0.05. Genotypes connected by the same letter are not significantly different. Var represents variance. Values with asterisk (*) shows significant main effect.**

| Level | | | Least Sq Mean |
|---|---|---|---|
| R.Tx437 | A | | 3975.62 |
| B.Tx642 | A | | 3951.94 |
| R.Tx436 | A | B | 3120.45 |
| B.Tx631 | A | B | 2825.52 |
| B.Tx645 | | B | 2637.85 |
| R.Tx7000 | | B | 2445.84 |
| B.Tx378 | | B | 2437.1 |

| Fixed Effect | F Ratio | Prob > F |
|---|---|---|
| Irrigation Regimes | 0.51 | 0.51 |
| Genotypes | 2.7 | 0.0381* |
| Irrigation Regimes*Genotypes | 1.17 | 0.35 |

| Random Effect | Var Ratio | Var Component | Std Error | % Variance |
|---|---|---|---|---|
| Rep | 0 | 0 | 0 | 0 |
| Irrigation Regimes*Rep | 0.33 | 323719 | 330096.81 | 24.88 |
| Residual | | 977309.93 | 282125.07 | 75.12 |

**Table 2.67. Correlation of grain starch content (%), grain protein content (%), grain yield (Kg/ha), and aboveground biomass (Kg/ha) of sorghum hybrids and inbreds in 2016 and 2017. Values with asterisk (*) are significant.**

| Year | Hybrid/Inbred | Variables | Grain protein | Grain starch | Grain yield |
|---|---|---|---|---|---|
| **2016** | **Hybrid** | **Grain starch** | -0.91* | | |
| | | **Grain yield** | -0.42* | 0.48* | |
| | | **Biomass** | -0.25 | 0.32 | 0.34* |
| | **Inbred** | **Grain starch** | -0.71* | | |
| | | **Grain yield** | -0.56* | 0.53* | |
| | | **Biomass** | -0.17 | 0.24 | 0.41* |
| **2017** | **Hybrid** | **Grain starch** | -0.78* | | |
| | | **Grain yield** | 0.08 | -0.13 | |
| | | **Biomass** | 0.19 | -0.07 | 0.32* |
| | **Inbred** | **Grain starch** | -0.46* | | |
| | | **Grain yield** | -0.18 | -0.19 | |
| | | **Biomass** | -0.16 | -0.07 | 0.33 |

## Discussion

The grain yield also varies based on genetic make-up of different genotypes of a crop. Grain yield might also vary for a genotype in different agronomic treatments. Studying and comparing different genotypes based on morphophysiological trait measurements will help identify genotypes yielding normal to high in deficit irrigation or water-stress conditions. When it comes to morphophysiological traits measurements, two important questions are what traits should be measured, as well as which trait(s) can explain the findings in a better way? Measuring many traits in field will be resource intensive in money and time. In addition, working with a large datasets can be difficult. It becomes important to identify some exceptional traits that can better explain drought tolerance in a crop. Linear discriminant analysis and path analysis results can be useful to identify the most important traits and importantly showed some differences between corn and sorghum based on how traits on grain yield.

### *Grain starch and protein composition, aboveground biomass accumulation, grain yield, and canopy and leaf traits*

As explained earlier, grain starch content showed positive correlation with grain yield (Triboi and Triboi-Blondel, 2002) and also with increased grain carbon (C), grain nitrogen (N) decreases (Canevara et al., 1994; Duvick and Cassman, 1999). $CO_2$ absorbed from the atmosphere during photosynthesis is the major source of C that contributes to grain starch in higher proportion and grain protein. N absorbed from soil contributes to grain protein. $CO_2$ absorption by plants increases with increasing photosynthesis. In full irrigation, prolonged photosynthesis with delayed wilting points or senescence is normal, but in deficit irrigation where plants try to conserve water by reducing its LAI or leaf angle (MTA), reducing the number of leaves on its stem, etc. having a low osmotic potential and high NDVI always helps. Low osmotic potential allows the root to absorb water from soil depth for a longer time and high NDVI even at dough stage explains the drought tolerance ability of plants. Due to the competition between C and N for energy (Munier-Jolain and Salon, 2005), carbon covers the major portion of grains and grain nitrogen shows negative correlation with grain yield (Lam et al., 1996). Based on above discussion, with increase in grain starch and decrease in grain protein, grain yield in corn and sorghum should increase.

Results reaffirmed the finding by Canevara et al. (1994) and Duvick and Cassman (1999). Grain starch content of corn and sorghum showed significant negative correlation with grain protein content in 2016 and 2017 (Table 2.24 and Table 2.67). However, the correlation was strongly negative in sorghum, whereas, in corn weak negative correlation was observed both the years. In addition, the correlation between grain starch and grain crude protein content in 2017 was not significant. One possible reason might be the prolonged staygreen period of sorghum (Figure 2.30 and Figure 2.31) that resulted in $CO_2$ absorption by plants for a longer period and the carbon absorbed increased starch content of grains, thereby reducing its nitrogen (protein) content. Corn hybrids tend to lose its greenness early as compared to sorghum genotypes (Figure 2.12 and Figure 2.13). Early drying of corn leaves reduces the photosynthetic period of plants that might result in a weak negative correlation between grain starch and crude protein content. Plant biomass accumulation depends on photosynthetic efficiency of crop/genotype.

Grain yield also showed significant negative correlation with grain protein for corn and sorghum genotypes in 2016 and 2017 that confirmed the finding by Lam et al. (1996) (Table 2.24 and Table 2.67). However, this relationship was not significant for corn hybrids in 2016 and sorghum genotypes in 2017. In addition, sorghum inbreds in 2017 showed almost no correlation with grain protein content. As suggested by Triboi and Triboi-Blondel (2002), grain starch content for sorghum genotypes showed significant positive correlation with grain yield for sorghum genotypes in 2016, but the relationship was negative for sorghum genotypes in 2017 and not significant for corn hybrids in 2016 and 2017 (Table 2.24 and Table 2.67). This contradicts the finding by Triboi and Triboi-Blondel (2002). A significant positive correlation was observed between grain yield and aboveground biomass accumulation in corn and sorghum in 2016 and 2017 suggesting that increase in plant biomass results in grain yield increment.

Corn hybrids Tx149/Tx775 and Tx775/Tx777 in 2016 and Tx775/GP474GT, Tx775/Tx777, and Tx772WRS/LH195 in 2017 with low biomass also showed reduced grain yield. Corn hybrids NP2643GT/Tx777, Tx781/Tx777, SGI890/Tx777, and GP7169GT/Tx777 produced higher grain yield with no significant difference observed among their aboveground biomass (Figure 2.16 and Figure 2.17). TR8145/Tx777 also showed higher grain yield with higher aboveground biomass in full irrigation but low grain yield in deficit irrigation. It can be speculated that plants must have reduced its stomatal aperture in deficit irrigation, thus reducing photosynthesis and grain yield. Most of the hybrids showing higher grain yield are commercial inbreds crossed with Tx777 and are 50% temperate 50% tropical derived, except Tx781/Tx777 (Table 2.1). Tx773/LH195 in 2016 and Tx150/Tx777 in 2017 also showed reduced grain yield. Commercial corn hybrids performed better than experimental hybrids in terms of yield and biomass. SGI890/Tx777 and TR8145/Tx777 were significantly taller than other experimental hybrids in 2016 and 2017 but the same was not the case with NP2643GT/Tx777, GP7169GT/Tx777, and commercial hybrids. NP2643GT/Tx777 and GP7169GT/Tx777 yielded high in 2016 and 2017 but did not showed significantly higher plant height in both the years (Table 2.2 and Table 2.3). Commercial hybrids REV28HR20 and BH8732VTTP were significantly taller in height in 2016 but not in 2017. In addition, plant height of commercial hybrid DKB64-69 and experimental height Tx775/Tx777 were similar (Table 2.2 and Table 2.3). Both were shorter in height but DKB64-69 yielded high both the years. Result contradicts the observation of  Farfan et al. (2013).

Sorghum showed no significant difference among genotypes or irrigation regimes based on aboveground biomass. However, ATx2752/RTx430 and ATx645/RTx437 in 2016 and ATx642/RTx437 and ATx631/RTx437 in 2017 showed higher grain yield (Table 2.63 and Table 2.65). ATx378/RTx7000 in 2016 and 2017, ATx631/RTx436 and ATx3197/RTx7000 in 2016, and ATx642/RTx436 yielded low. ATx378/RTx7000 and ATx3197/RTx7000 are early maturity hybrids. Among inbreds, B.Tx623, R.Tx7000, and B.Tx645 yielded high in 2016 but low yield was seen in B.Tx645 and R.Tx7000 in 2017 (Table 2.64 and Table 2.66). B.Tx378 yielded low in 2016 but higher significantly yield was seen in 2017. One of the reason might be the terminal plant height of these three sorghum inbreds. R.Tx7000 was significantly taller than B.Tx378 in 2016 but significantly shorter in 2017 (Table 2.26 and Table 2.28). B.Tx645 was also taller in 2016 compared to 2017. But among hybrids, ATx631/RTx436 and ATx378/RTx7000 significantly taller than ATx2752/RTx430 and ATx645/RTx437 yielded low in 2016 (Table 2.25 and Table 2.63). In 2017, ATx642/RTx436 and ATx631/RTx437 were significantly taller but ATx642/RTx436 yielded low (Table 2.27 and Table 2.65). This contradicts the finding by Farfan et al. (2013) in corn that plants taller at the end of the season tend to yield high.

In high density planting, greater number of leaves with higher leaf area index increases the number of shade leaves in a plot (Drewry et al., 2010a; b), thus affecting its photosynthetic efficiency that might reduce its grain yield. Most of the corn hybrids with fewer number of leaves at 83 DAS in 2016 and at 93 DAS in 2017 showed higher grain yield (Table 2.4 and Table 2.5). Not all the sorghum hybrids and inbreds behaved in similar fashion in 2016 (Table 2.29 and

Table 2.30) and 2017 (Table 2.31 and Table 2.32). A sorghum hybrid or an inbred with greater number of leaves not necessarily yielded low and vice versa. It confirms that higher energy investment towards vegetative development reduces grain yield in corn, but it may not be true for sorghum. High yielding corn hybrids had LAI comparatively lower than those that yielded low (Table 2.6). Low LAI reduces the plant water-use. Blum (2011) stated that crop/genotype with low water-use might show a reduction in grain yield, but a contradictory result was obtained in corn. Such genotypes might perform well in water-stress condition. However, not all the low yielding sorghum hybrids and inbreds had higher LAI (Table 2.33 and Table 2.35). Higher LAI was found in high yielding sorghum inbreds B.Tx623, R.Tx7000, and B.Tx645. One of the reason might be, higher LAI contributed to higher photosynthetic efficiency that proved to be an advantage for grain yield.

Leaf thickness (LT), leaf dry matter content (LDMC), leaf tissue density (LD), specific leaf area (SLA), and osmotic potential are all related to each other. They play a great role in maintaining drought tolerance in a crop/genotype. Thickness of leaf is positively related to its ability to capture solar radiation and atmospheric $CO_2$ and water use efficiency of that plant (Givnish, 1979). Higher leaf thickness more efficiently absorbs solar radiation and increases photosynthesis. Sun leaves have been found to be thicker than shade leaves (Popma and Bongers, 1988; Cornelissen, 1992; Dong, 1993; Hodgson et al., 2011). One of the reasons is higher photosynthetic efficiency of sun leaves. To conserve water and withstand limited soil-water availability, some genotypes with high LT in deficit irrigation might undergo some changes such as increase in LDMC and closure of stomata. As explained earlier, LDMC is the cell wall material and the higher the cell wall material the more rigid the cell wall will be; this will increase relative water content in leaves during permanent wilting point (Bartlett et al., 2012a; b) and help the plant to survive in water stress or drought condition. Compared to high yielding corn hybrids, LDMC was higher in low yielding hybrids at flowering and dough stage (Table 2.9). SLA is an inverse function of LT and LDMC, so corn hybrids with low LDMC showed higher SLA (Table 2.11). Specific leaf area is the leaf area per unit leaf biomass. Higher SLA means less biomass accumulation per unit leaf area. Plants spend energy in biomass accumulation. Corn hybrids with higher SLA spend less energy in vegetative development that increased their grain yield. Sorghum hybrids did not show any significant difference based on their SLA values (Table 2.39). High yielding sorghum inbreds B.Tx642 and R.Tx437 showed comparatively low LDMC than low grain yielding B.Tx645 and B.Tx378 at dough stage (Table 2.40). This confirms that genotypes although genotypes with low LDMC tend to have late wilting stage but that might not be an advantage for their grain formation. $CO_2$-$H_2O$ exchange is needed for higher grain yield. Moreover, having significantly higher SLA in deficit irrigation confirms drought tolerance nature of sorghum hybrids (Table 2.43). Most of the sorghum inbreds were not significantly different based on SLA (Table 2.44).

Osmotic potential is related to water-use and drought tolerance nature of a crop/genotype. Lower osmotic potential means higher accumulation of solutes in vacuoles/cells (Bartlett et al., 2012a). Higher accumulation of solutes in plant cells/vacuoles is responsible for continuous uptake of soil-water by roots to leaves, thus maintaining water use of genotypes (Basu et al., 2016). This water use contributes to grain yield and total plant biomass. However, no significant difference between osmotic potential values of corn and sorghum hybrids with low grain yield and high grain yield was observed in 2017 (Table 2.12 and Table 2.45). Not much difference in osmotic potential of sorghum inbreds was observed. B.Tx645 as well as B.Tx378 showed low grain yield but osmotic potential of B.Tx645 at flowering stage was significantly lower than B.Tx378 (Table 2.46).

Chlorophyll is an important component found in thylakoid sacs of chloroplast that participate in photosynthesis. Chlorophyll pigment absorbs solar radiation and uses this in photosynthesis to form photoassimilates that is transported to different parts of plants. This photoassimilates add up to vegetative part to form biomass and to reproductive part for grain yield. Higher chlorophyll content in full irrigation increases the photosynthetic efficiency of plants, resulting in higher grain yield and/or biomass accumulation. In deficit irrigation, genotypes showing higher chlorophyll content are drought tolerant. However, water efficient nature of a genotype can only be confirmed from grain yield data. Deficit irrigation genotypes showing high chlorophyll content producing normal to high grain yield can be considered as water efficient. Sometimes plant water use of a genotype showing high chlorophyll content is high, but it add up more to vegetative biomass accumulation rather than grain filling. However, in 2016 chlorophyll content in corn hybrids did not showed any significant difference at 34 DAS and 40 DAS, i.e., vegetative stage (Table 2.13). One of the reason might be that at vegetative stage both the irrigation regimes received equal amount of water to meet their evapotranspirative demand. Yield cannot be predicted from chlorophyll content of sorghum hybrids measured at 35 DAS, reason being that not every hybrid with low chlorophyll content yielded low and vice versa (Table 2.47). Even at 81 DAS, most of the sorghum hybrids did not show any significant differences (Table 2.49). Sorghum inbreds B.Tx623 and R.Tx7000 with high grain yield showed comparatively low chlorophyll content than B.Tx378 and R.Tx436 with low grain yield at 81 DAS (Table 2.51). Corn hybrids producing high grain yield with low chlorophyll content confirmed their water efficient behavior (Table 2.14). Sorghum inbred B.Tx642 yielded high with higher chlorophyll content because of its prolonged staygreen period, but high yielding R.Tx437 with low chlorophyll content can be considered as water efficient (Table 2.53).

Normalized difference vegetation index (NDVI) measures the greenness of complete plot, whereas, in field condition chlorophyll content of a plot was estimated from representative plants/plot. This might be a reason behind the difference in chlorophyll and NDVI results of corn and sorghum in 2017. NDVI of corn hybrids was significantly higher under full irrigation than under deficit irrigation. Results were not similar in sorghum hybrids and inbreds. It might be because sorghum has been known to be more drought tolerant compared to corn, with prolonged staygreen period. Corn hybrids are affected by water-stress condition, thus shortens their staygreen period to prevent excess water loss in the form of transpiration. Full irrigation NDVI was higher than that in deficit irrigation for sorghum inbreds but only R.Tx7000 showed significantly low NDVI at 83 DAS and 95 DAS (Table 2.56 and Table 2.57).

Grain yield of corn being higher than sorghum reaffirmed the finding of Assefa et al. (2014b), that taller plants with greater number of leaves are responsible for higher grain yield of corn compared to grain sorghum. The study by Assefa et al. (2014b) was conducted in Kansas. In addition, corn shows comparatively higher NDVI than sorghum at 83 DAS (milk stage in corn and soft dough in sorghum), but a sharp decrease in NDVI can be seen in corn at later stage (Table 2.13 and Table 2.31). NDVI in sorghum does not change much at later stage. This confirms that higher greenness in corn close to flowering stage might result in higher grain yield compared to sorghum, but prolonged greenness of sorghum results in higher water use from emergence to harvest. Water-use efficiency is the ratio of grain yield and evapotranspiration, corn with higher grain yield and less evapotranspiration would be more water efficient compared to sorghum. The similar result has been discussed in chapter III as well. Comparing sorghum hybrids to inbreds, range of chlorophyll content and NDVI is similar, but osmotic potential of sorghum inbreds ranges from -0.96 to -1.5 MPa, whereas, for sorghum hybrids it ranges from -0.87 to -0.98 MPa. Low osmotic potential is related to higher water use, thus based on results obtained water use in sorghum inbreds was higher than hybrids.

Corn and sorghum yielded high in 2016 compared to 2017. In 2017, plots of corn and sorghum were infested by pigweed (Amaranthus spp.) and johnson grass (Sorghum halepense (L.) Pers.). Crop-weed competition might be a reason for reduction of grain yield in 2017. Late planting and early harvesting in 2017 compared to 2016 might be another reason for grain yield reduction.

### *Linear discriminant analysis and path coefficient analysis*

Linear discriminant analysis result showed that some combinations of five traits (leaf thickness (LT), leaf dry matter content (LDMC), leaf tissue density (LD), normalized difference vegetation index (NDVI), and number of green leaves (LN)) showed highest percentage of correct classification of genotypes in full and deficit irrigation regimes in corn. There were three combinations with highest classification percentage in Table 2.17 but LDMC and LD shows positive correlation and LD involves LT that changes with light intensity. Thus, the combination of four traits (LT, LDMC, NDVI, and LN) showing a correct classification percentage very close to five traits combinations classification percentage can be considered as important traits in drought tolerance study in future. In sorghum, a five traits combination (LT, SLA, OP, NDVI, and Height) showed highest percentage of classification of genotypes into full and deficit irrigation regimes (Table 2.58). LT is affected by light intensity, so a four traits combination (LDMC, OP, NDVI, and Height) was considered as best combination to be focused on in future. Overall, morphophysiological traits can explain drought tolerance research better than morphological or physiological traits alone.

Path coefficient analysis showed some differences in corn and sorghum. Number of green leaves showed a negative direct and total effect on grain yield in 2016 and 2017 in corn (Table 2.18 and Table 2.19). However, a positive direct and total effect of number of green leaves on grain yield was observed in 2016 and 2017 in sorghum (Table 2.59 and Table 2.60). Osmotic potential showed no direct and indirect effect but a weak positive total effect on grain yield of corn hybrids, whereas, for sorghum hybrids and inbreds a negative direct effect and a strong negative total effect of osmotic potential on grain yield was observed. This clearly indicates that greater number of green leaves results in low grain yield in corn hybrids but high grain yield in sorghum hybrids and inbreds. This can be supported by the fact that corn is taller than sorghum and in high density planting greater number of leaves increases the number of shade leaves that affects photosynthesis in corn. Sorghum maintains its greenness for a longer period and is shorter in height compared to corn. Greater number of green leaves increases photosynthesis in sorghum that results in increased grain yield. The negative relationship between osmotic potential and grain yield in sorghum can be linked to its water use. Low osmotic potential can be defined as increase in solute concentration in vacuoles/cells. This increased solute concentration builds a pressure on roots due to which continuous absorption of soil-water by roots takes place. Water use of sorghum hybrids and inbreds increases and that contributes to grain yield increment.

# CHAPTER III

# SOIL-WATER WITHDRAWAL PATTERN AND WATER-USE EFFICIENCY OF SELECTED CORN AND SORGHUM GENOTYPES

## Introduction

Soil-water availability plays an important role in determining growth, development, and yield of crops. Water stress or water deficit is a condition that arises when there is limited extractable soil-water to meet evapotranspiration demand (Jaleel et al., 2009; Chai et al., 2014). Limited soil-water availability affects grain formation in crops resulting in yield reduction (Claasen and Shaw, 1970; Çakir, 2004) but it also depends on development stage (Claasen and Shaw, 1970; Doorenbos and Kassam, 1979). Not only crops morphology but also the environment where they are grown, such as, temperature, rainfall, wind speed, solar radiation, etc., also determines soil-water availability. In addition, various soil properties, such as soil type, soil texture, soil structure, soil porosity, etc., act as determining factor for water input to soil as well as soil-water uptake by plants (Childs, 1940; Childs and Collis-George, 1950; Vogel, 2000; O'Geen, 2012). Clay soil (fine textured) has higher number of small pores with low rate of infiltration but high water holding capacity (WHC), whereas, sandy soil (coarse textured) has large pores with high rate of infiltration but low WHC (O'Geen, 2012). The experiment was conducted at Uvalde, Texas and soil at the experimental site is clay loam. Although clay soil has high WHC, the presence of very small sized pores lowers the water uptake rate by plants in deficit irrigation, especially when soil-water content (θ) is close to permanent wilting point (approximately 17%). Field capacity and permanent wilting point are the two extremes of θ. When soil pores are filled completely filled with water and air such that further infiltration as well as percolation is not possible, soil is said to have reached field capacity (Rab et al., 2011; Kirkham, 2014). Permanent wilting point is the soil water content under and beyond which most plants are no longer able to continue absorbing water from soil due to soil dryness (Rab et al., 2011; Kirkham, 2014). Soil water between these two extreme water contents is the water available to plants (O'Geen, 2012). Plants with shallow roots might show low water uptake in deficit irrigation, especially under soils with small sized pores holding water tightly. Biomass accumulation in plants is accompanied with water loss in the form of transpiration (Lopes et al., 2011). As stated by Blum (2011) low water uptake results in low water loss or water use and that might affect biomass accumulation as well as grain yield. With low soil evaporation and deep root penetration, crops/genotypes can absorb water even in deficit irrigation or water stress condition and use them effectively for grain yield formation and biomass accumulation. This is also known as effective use of water (Blum, 2011). Deeper root penetration is an example of drought avoidance. In addition, genotypes with larger root area also play an important role in capturing water and nutrients distributed in soil heterogeneously. Although, deeper roots capture water from deeper soil depth but it might not work in case of prolonged drought or water stress for longer periods. There are crops/genotypes having shallow roots but might be drought tolerant and/or water efficient. At the crop level, water-use efficiency (WUE) can be defined as grain yield formation and/or biomass accumulation per unit evapotranspiration (Vadez, 2016). At plant level, it is known as transpiration efficiency or intrinsic WUE (iWUE) (Vadez et al., 2014). From this definition, for a plant to be water efficient, it should tend to transpire less water thereby contributing to higher yield or biomass. Crops/genotypes showing higher yield with less water utilization might be suitable for growing in water deficit or drought stress areas. Agriculture in Texas have faced serious drought time-to-time and corn and sorghum being major cereal crops of

Texas were grown in an experimental field at Texas A&M AgriLife Research Center, Uvalde in 2016 and 2017 to identify water efficient and/or drought tolerant genotypes and compare the tolerance level of the two crops. Measuring soil-water loss to atmosphere is not an easy task, biasness occurs in data due to several factors in soil, and atmosphere that cannot be controlled, so water loss was verified by two different measurements – transpiration and soil-water withdrawal-based evapotranspiration. Analyzing all three data, best has been presented as result.

The objective of this study was:

i) To study the rate of water uptake by selected genotypes of corn and sorghum and compare genotypes as well as crops based on their water-use efficiency for yield and aboveground biomass.

## Materials and Methods

Soil-water availability and sap-flow rate are the important parameters in identifying crops and/or genotypes that show better growth and development even in water-limited condition. To confirm the accuracy of result, rate of water loss from plants and soil in the form of transpiration and evapotranspiration were quantified in two different ways – (a) soil-water withdrawal-based evapotranspiration (*ET*) (b) sap-flow based transpiration (T). To quantify the rate of water loss from soil and plants, selected genotypes from 15 entries of corn and sorghum were studied at Texas AgriLife Research Center, Uvalde in 2016 and 2017 (Table 3.1 and Table 3.2).

### *Sap-flow measurement*

Sap-flow rate in selected genotypes of corn and sorghum were measured using a set of Dynagage Flow32-1K system. Sap-flow sensors, SGB25 were installed in one section each of full and deficit irrigation regimes at 20 days after sowing (DAS), at 2/3-leaf stage in corn and sorghum in 2016 and at 60 days after sowing (DAS), at 10-leaf stage in corn and flag-leaf stage in sorghum in 2017. In 2016, sap-flow rate in two selected hybrids each in corn and sorghum were measured (Table 3.1). Table 3.1 shows selected genotypes for sap-flow measurements in 2017. To estimate transpiration rates, four healthy and representative plants per plot were selected. A sap-flow sensor was installed near each plant, making four sensors per plot. In total there were 16 sensors/crop deployed each year {4 sensors/genotype x 2 sections of irrigation treatment (1 full and 1 deficit irrigation) x 2 genotypes/crop}. In corn and sorghum experimental plots, sensors were installed early in 2016, but sap-flow data were collected from 106 DAS (1/2 maturity) to 120 DAS (physiological maturity). In 2017, a weed infestation in the corn and sorghum experimental plots during the vegetative stage resulted in late installation of sensors. Sap-flow measurements in 2017 started at 63 DAS (10/12-leaf stage in corn and booting stage in sorghum) but the malfunctioning of sensors resulted in consideration of collected data from 80 DAS (blister stage in corn and early soft dough stage in sorghum) to 94 DAS (dent stage in corn and hard dough stage in sorghum). Data collected after 94 DAS was found to be inconsistent, hence not considered for further analysis. Spurious data resulted in consideration of only 9 sensors out of 16 for corn and 15 sensors out of 16 for sorghum in 2016, whereas, 13 sensors out of 16 for corn and 11 sensors out of 16 for sorghum in 2017 for further analysis. Transpiration is maximum during daytime, thus diurnal sap-flow rates (6:00 AM to 7:00 PM) were considered for further analysis in both the crops for 2016 and 2017.

**Table 3.1. Corn and sorghum genotypes selected for sap-flow measurements in 2016 and 2017.**

| Crops | Irrigation Regimes | Genotypes (2016) | Genotypes (2017) |
|---|---|---|---|
| Corn | Deficit | Tx781/Tx777 (25% temperate, 75% tropical derived) | SGI890/Tx777 (50% temperate, 50% tropical derived) |
| Corn | Full | Tx781/Tx777 (25% temperate, 75% tropical derived) | NP2643GT/Tx777 (50% temperate, 50% tropical derived) |
| Corn | Deficit | Tx773/LH195 (50% temperate, 50% tropical derived) | Tx149/LH195 (50% temperate, 50% tropical derived) |
| Corn | Full | Tx773/LH195 (50% temperate, 50% tropical derived) | Tx775/Tx777 (25% temperate, 75% tropical derived) |
| Sorghum | Deficit | ATx378/RTx7000 (Hybrid) | B.Tx378 (Inbred line) |
| Sorghum | Full | ATx378/RTx7000 (Hybrid) | ATx631/RTx436 (Hybrid) |
| Sorghum | Deficit | ATx645/RTx437 (Inbred line) | R.Tx437 (Inbred line) |
| Sorghum | Full | ATx645/RTx437 (Inbred line) | R.Tx436 (Inbred line) |

Data collected from sap-flow sensors contained noises. Factors such as high temperature, wind, solar radiation, etc. result in overestimation of transpiration rates by sap-flow sensors (Wang et al., 2017). This overestimated transpiration rate for a genotype might be higher than the estimated evapotranspiration rate calculated using soil-water data. To bring this overestimated transpiration rate to evapotranspiration level or lower, adjustment of sap-flow rates was done by calibrating with soil-water based evapotranspiration, as in equation 3.1 to get a calibration coefficient and then multiplying the calibration coefficient with per day sap-flow rates for all sensors.

$$k = \frac{0.85x}{y} \qquad \textbf{...3.1}$$

where $k$ is the calibration coefficient, $x$ is the soil-water based evapotranspiration (mm/day) for the period in which first measurement of sap-flow based transpiration considered in calculation lies, $y$ is the sap-flow based transpiration (mm/day) for first day of measurement used in calculation, and 0.85 is assumed as soil-water based transpiration (Saxton et al., 1974). $k$ has been calculated for soil-water based evapotranspiration at 97-113 DAS in corn and at 100-113 DAS in sorghum with sap-flow based transpiration on 106 DAS in both corn and sorghum. Sensors did not overestimate sap-flow rates for 2017 in both the crops, so no adjustment of transpiration rates was needed. Conversion of sap-flow rate unit from g plant$^{-1}$ day$^{-1}$ to mm/day gives a better idea of amount of water transpired per plot.

### *Soil-water withdrawal measurement*

A neutron moisture probe (CPN 503 Hydroprobe) was used to measure soil-water content at different depth of 10 cm, 20 cm, 40 cm, 60 cm, 80 cm, 100 cm, and 120 cm. One access tube per selected plot was installed in each section of deficit and full irrigation regimes (Table 3.2). Through the access tube, the source tube of the probe was lowered down in the soil. High speed neutrons hits the hydrogen atom present in water and this collision results in loss of energy by neutrons and these neutrons are reflected back to the probe, which are then counted and available soil-water is determined (Gardener and Kirkham, 1952; Chanasyk and Naeth, 1996). In 2016, two genotypes each for corn and sorghum were selected to study soil-water withdrawal pattern but in 2017 due to some miscommunications, different genotypes in different sections were selected to study soil-water withdrawal pattern and evapotranspiration (Table 3.2).

**Table 3.2. Selected corn and sorghum genotypes for soil-water related measurements in 2016 and 2017.**

| Crops | Genotypes (2016) | | Genotypes (2017) | |
|---|---|---|---|---|
| | Deficit irrigation | Full irrigation | Deficit irrigation | Full irrigation |
| Corn | Tx773/LH195 (50% temperate, 50% tropical derived) | Tx773/LH195 (50% temperate, 50% tropical derived) | REV26V21 (temperate derived commercial hybrid) | NP2643GT/Tx777 (50% temperate, 50% tropical derived) |
| | Tx781/Tx777 (25% temperate, 75% tropical derived) | Tx781/Tx777 (25% temperate, 75% tropical derived) | SGI890/Tx777 (50% temperate, 50% tropical derived) | REV26V21 (temperate derived commercial hybrid) |
| | | | Tx149/LH195 (50% temperate, 50% tropical derived) | SGI890/Tx777 (50% temperate, 50% tropical derived) |
| | | | Tx781/Tx777 (25% temperate, 75% tropical derived) | TR8145/Tx777 (50% temperate, 50% tropical derived) |
| | | | Tx773/LH195 (50% temperate, 50% tropical derived) | Tx149/LH195 (50% temperate, 50% tropical derived) |
| | | | Tx775/GP474GT (75% temperate, 25% tropical derived) | Tx775/Tx777 (25% temperate, 75% tropical derived) |
| Sorghum | ATx378/RTx7000 (Hybrid) | ATx378/RTx7000 (Hybrid) | ATx645/RTx436 (Hybrid) | B.Tx631 (Inbred line) |
| | ATx645/RTx437 (Hybrid) | ATx645/RTx437 (Hybrid) | ATx645/RTx437 (Hybrid) | R.Tx436 (Inbred line) |
| | | | B.Tx378 (Inbred line) | R.Tx7000 (Inbred line) |
| | | | B.Tx631 (Inbred line) | R.Tx7000 (Inbred line) |
| | | | B.Tx642 (Inbred line) | ATx631/RTx436 (Hybrid) |
| | | | R.Tx437 (Inbred line) | ATx631/RTx436 (Hybrid) |

Soil-water data in 2016 was collected from 22 DAS (4-leaf stage in corn; 3-leaf stage in sorghum) to 119 DAS (physiological maturity in corn and sorghum). In 2017, soil-water data were collected from 48 DAS (8-leaf stage in corn; growing point differentiation stage in sorghum) to 104 DAS (physiological maturity in corn and sorghum). Because of malfunctioning of tube in 2017, data collected from corn hybrid Tx781/Tx777, a deficit irrigation plot was not considered for further analysis. Therefore, 11 access tubes were in good condition. Because of pesticide spraying in the field, soil-water from six tubes out of 11 were not measured on 62 DAS. In addition, spurious data found on 96 DAS in corn 2017 were excluded in further analysis. Soil-water data collected using the neutron probe in percentage was converted in mm by multiplying with the difference in depth at which soil-water is stored and previous depth, for example, soil-water data at depth 40 cm was multiplied by depth difference 400 - 200 mm. Both sap-flow based water loss with soil-water based water loss were changed into the same unit for comparison. Therefore, soil-water stored at different depth was added separately for each day and evapotranspiration (mm/day) was calculated at every DAS measured (equation 3.2).

$$ET = \frac{(SW_1 - SW_2 + I + R - SR)}{DI} \qquad \textbf{…3.2}$$

Where $ET$ is evapotranspiration in mm/day, $SW_1$ is soil-water stored during first DAS measured, $SW_2$ is soil-water stored during second DAS measured. Irrigation ($I$) and rainfall ($R$), both in mm received by field plots between first and second DAS were added to $SW_2$. Surface runoff (SR) occurred because of rainfall was subtracted from rainfall received. The overall water loss was divided by day interval (DI) between first and second DAS to get daily ET (mm/day). The amount of rainfall lost because of surface runoff was determined by extrapolating the runoff as a function of rainfall curve (Campbell and Diaz, 1988)  based on the work of Stewart et al., 1976. Because the experimental plot has approx. 50% of clay soil (Table 3.3) this resulted in assumption of surface storage (S) value of 0.08 while extrapolating the curve. While calculating ET, amount of percolation was considered zero because the soil-water content at different depths in 2016 and 2017 were higher than that calculated at -15 bar water potential (wilting point). In addition, in most of the cases soil-water content was lower than that calculated at -1/3 bar water potential (field capacity) confirming the availability of water to plants at different soil depths. Soil-water content at field capacity and wilting point was calculated as in equation 3.3.

$$\theta = \theta_r + (\theta_s - \theta_r)[1 + |\alpha h|^n]^{-m} \qquad \textbf{...3.3}$$

Where $\theta$ is soil-water content at field capacity (-1/3 bar) and wilting point (-15 bar), $\theta_s$ and $\theta_r$ are saturated and residual water contents ($m^3/m^3$), $\alpha$, $n$, and $m$ are empirical fitting parameters with $m = 1-1/n$ (van Genuchten, 1980). The value of $h$ is negative in unsaturated soil, measured in meters, so absolute value of $\alpha h$ is used (Table 3.3).

**Table 3.3. Physical parameters of soil in the corn/sorghum plots at Uvalde. BD is bulk density, $K_C$ is saturated hydraulic conductivity and $\theta_s$, $\theta_r$, $\alpha$, and $n$ same as in equation 3.3). (Xuejun Dong and Jianchu Shi, unpublished data).**

| Depth (cm) | Sand (%) | Silt (%) | Clay (%) | BD (g cm$^{-3}$) | θr (m$^3$ m$^{-3}$) | θs (m$^3$ m$^{-3}$) | α (cm$^{-1}$) | n | Kc (cm day$^{-1}$) | θ (field capacity of -1/3 bar) | θ (wilting point of -15 bar) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-30 | 29 | 23 | 48 | 1.39 | 0.096 | 0.467 | 0.0179 | 1.305 | 13.99 | 0.306 | 0.163 |
| 30-80 | 28 | 22 | 50 | 1.45 | 0.094 | 0.451 | 0.0183 | 1.278 | 10.63 | 0.304 | 0.168 |
| 80-140 | 24 | 24 | 51 | 1.58 | 0.09 | 0.416 | 0.0182 | 1.238 | 5.45 | 0.297 | 0.176 |

The estimated ET in mm/day was used to calculate water-use efficiency (WUE) for selected corn and sorghum genotypes in 2016 and 2017, based on grain yield (Kg/ha) and/or dry biomass (Kg/ha) (equation 3.4). The equation was derived based on the work of Passioura (1977). The estimated ET and WUE were compared with estimated transpiration and transpiration efficiency to get an idea of water loss through plants at different growth stages. Patterns of water uptake by plants at different soil depths (Rose and Stern, 1967) (equation 3.4) in 2016 and 2017 for different periods were estimated from soil-water content measured at different DAS. Periods in which experimental plots did not receive any rainfall or irrigation were selected to study water uptake patterns. While no such period for corn and sorghum was found in 2017 but in 2016 a period from 34 to 48 DAS was selected to study water-uptake pattern in selected corn and sorghum genotypes.

$$Daily\ water\ uptake = \frac{(SW_1 - SW_2)_X}{DI} \qquad \textbf{...3.4}$$

where daily water uptake is in mm/day, $SW_1$ and $SW_2$ are soil-water content (mm) measured on first DAS and second DAS at a depth $X$, and $DI$ is day interval between first and second DAS.

## Results

Sap-flow rate, soil-water withdrawal rate and pattern, and lysimeter-based evapotranspiration are three ways to verify crop-water use efficiency but might not always agree.

### *Sap-flow measurement*

The transpiration rate was more similar between the two genotypes in both corn and sorghum than it was between crops or between 2016 and 2017 (Figure 3.1). Combining transpiration in 2017 with 2016 better explains the difference in rate of water loss by corn, sorghum, and their genotypes. In corn, at 80 DAS experimental hybrids SGI890/Tx777 (deficit irrigation), Tx149/LH195 (deficit irrigation), NP2643GT/Tx777 (full irrigation), and TX775/Tx777 (full irrigation), show transpiration rate of 3.3 to 4.3 mm/day that decreases at continuous rate to 0.9 to 2.45 mm/day on 94 DAS in 2017. Transpiration rate was higher (6.0 to 9.0 mm/day) on 82 DAS because of heavy rainfall of 11 mm from 80 DAS to 82 DAS. In 2016, on 106 DAS, transpiration rate in corn experimental hybrids Tx773/LH195 and Tx781/Tx777, in two different irrigation regimes were 2.01 to 2.3 mm/day. A continuous decrease in transpiration rate occurred ending at 0.33 to 0.78 mm/day on 120 DAS. Overall, corn showed a continuous decrease in similar pattern of transpiration from 80 DAS to 119 DAS. In sorghum 2017, at 80 DAS, a hybrid ATx631/RTx436 (full irrigation) and 3 inbreds B.Tx378 (deficit irrigation), R.Tx437 (deficit irrigation), and R.Tx436 (full irrigation) showed transpiration rate of 2.6 to 2.9 mm/day. The transpiration rate increased to 4.1 to 6.9 mm/day on 82 DAS, the period when experimental plots received high rainfall of 11.44 mm and then all four genotypes maintained a constant transpiration of 4.0 to 7.0 mm/day from 82 to 94 DAS. Hybrid ATx631/RTx436 showed an increase in transpiration rate to 8 mm/day from 91 to 94 DAS. On 106 DAS, the first day of sap-flow measurement in 2016, the transpiration rate of sorghum hybrids ATx378/RTx7000 and ATx645/RTx437, in two different irrigation regimes were 2.66 to 2.95 mm/day. Transpiration decreased to a rate of 1.9 to 2.2 mm/day on 116 DAS, and further maintained a value of 2.0 to 2.5 mm/day from 116 to 120 DAS, except for ATx645/RTx437 (full irrigation) that increased to a value of 2.8 mm/day on 120 DAS. Overall, the decrease in transpiration rate of sorghum from 80 to 94 DAS and from 116 to 120 DAS was not as steep as in corn.

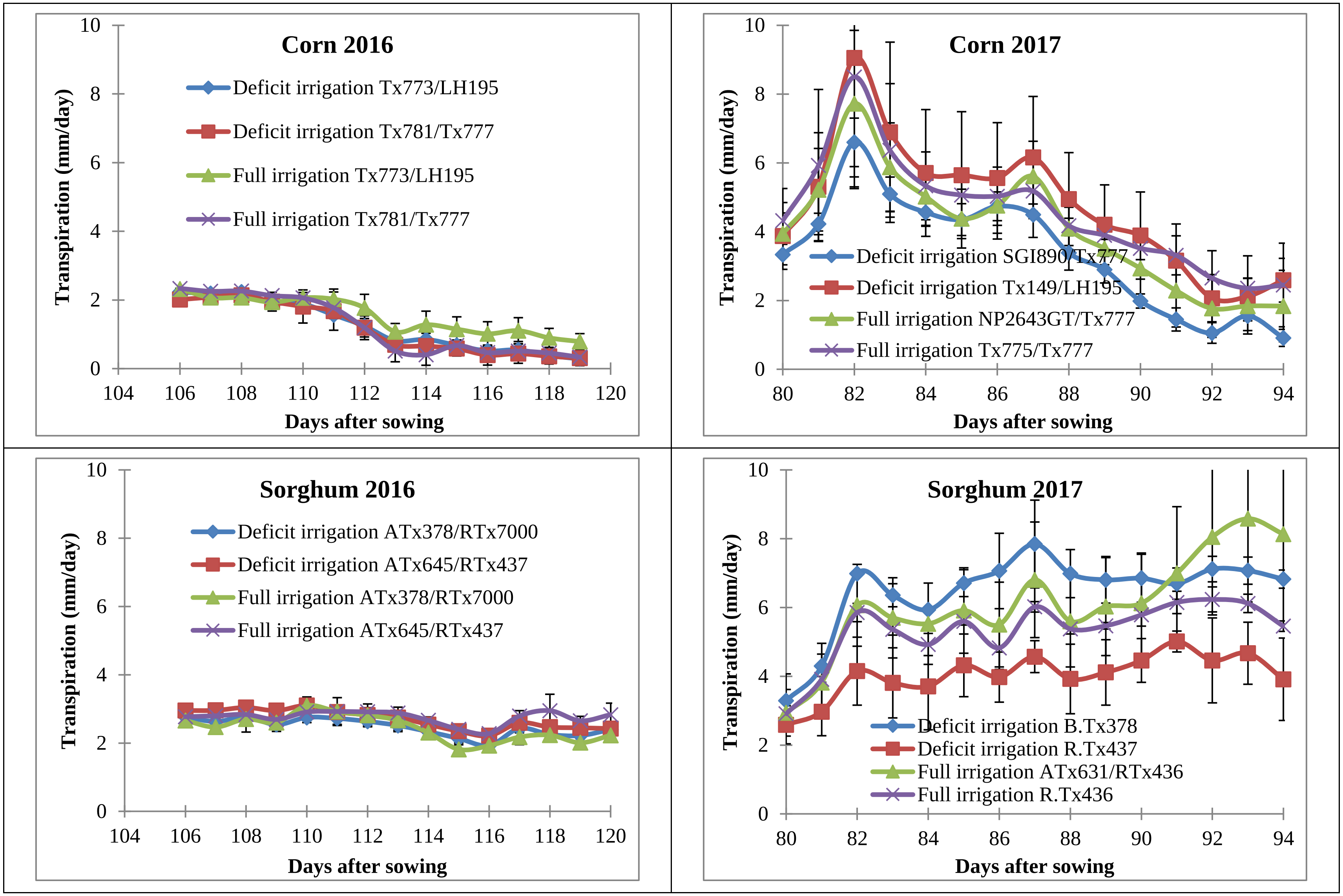


**Figure 3.1.** Transpiration rate (mm/day) of corn and sorghum genotypes in 2016 (106 to 120 DAS) and 2017 (80 to 94 DAS) in full and deficit irrigation regimes. Standard error bar represents standard error of the mean.

**Table 3.4. Comparison of genotypes based on plant density, grain yield/ha, aboveground biomass/ha, and transpiration in 2016 and 2017. Each genotype plot had four rows, but plant density was considered only for the two harvested middle rows. A single plot per genotype was used to measure sap-flow rate, so there was no standard error.**

| Year | Crops | Genotypes | Irrigation Regimes | Plants/2 rows of a plot | Yield/ha (Kg/ha) | Dry biomass (Kg/ha) | Transpiration (mm) from 106 to 120 DAS (2016) and 80 to 94 DAS (2017) |
|---|---|---|---|---|---|---|---|
| 2016 | Corn | Tx773/LH195 | Deficit | 55 | 7725.074 | 15681.808 | 17.323 |
| | | | Full | 67 | 8479.891 | 25418.891 | 21.548 |
| | | Tx781/Tx777 | Deficit | 66 | 11191.362 | 22355.457 | 16.284 |
| | | | Full | 66 | 10086.627 | 22493.994 | 17.349 |
| | Sorghum | ATx378/RTx7000 | Deficit | 141 | 3604.71 | 9874.553 | 37.017 |
| | | | Full | 117 | 4673.376 | 6333.617 | 36.613 |
| | | ATx645/RTx437 | Deficit | 185 | 6328.116 | 23584.015 | 40.518 |
| | | | Full | 174 | 7105.034 | 11110.527 | 41.298 |
| 2017 | Corn | SGI890/Tx777 | Deficit | 47 | 5256.612 | 13904.209 | 50.62 |
| | | NP2643GT/Tx777 | Full | 60 | 6011.997 | 11398.062 | 60.791 |
| | | Tx149/LH195 | Deficit | 47 | 3952.968 | 12524.058 | 71.158 |
| | | Tx775/Tx777 | Full | 56 | 5100.949 | 8588.073 | 68.067 |
| | Sorghum | B.Tx378 | Deficit | 171 | 3282.354 | 11333.122 | 96.827 |
| | | ATx631/RTx436 | Full | 120 | 3956.25 | 7632.723 | 91.777 |
| | | R.Tx437 | Deficit | 171 | 2118.846 | 7427.18 | 60.641 |
| | | R.Tx436 | Full | 122 | 3070.752 | 7410.614 | 79.988 |

### ***Soil-water withdrawal measurement***

Soil-water withdrawal rate was estimated by utilizing soil-water content data for a period between 34 to 48 DAS in 2016 (Figure 3.2). In corn, water uptake rate of two experimental hybrids Tx773/LH195 (deficit irrigation), Tx781/Tx777 (deficit irrigation), Tx773/LH195 (full irrigation), Tx781/Tx777 (full irrigation) at a depth of 10 cm from soil surface was 0.11-0.18 mm/day. Continuous decrease in water uptake rate of corn experimental hybrids occurred from 20-60 cm soil depths. Water uptake rate of Tx781/Tx777 (full irrigation) was 1.6 times higher than Tx773/LH195 (deficit irrigation), Tx781/Tx777 (deficit irrigation), and Tx773/LH195 (full irrigation) at 20-40 cm soil depth. Water uptake from 0-60 cm decreased faster compared to the 60-120 cm soil depth. Water uptake rate of Tx781/Tx777 was found to be higher in full irrigation, whereas, water uptake rate of Tx773/LH195 was higher in deficit irrigation for soil depth 0-60 cm. For 60-100 cm soil depth, experimental hybrids in both the irrigation regimes had approximately similar water uptake rate of 0.1-0.3 mm/day. For 100-120 cm soil depth, the experimental hybrids in both the irrigation regimes had minimum water uptake rate. In sorghum, water uptake rate was higher than corn at the 0-120 cm soil depth. Although, decrease in water uptake rate was seen with increase in soil depth for sorghum hybrids ATx378/RTx7000 (full and deficit irrigation) and ATx645/RTx437 (full and deficit irrigation), the rate was higher from 0-80 cm making a steep slope (Figure 3.2). From 80-120 cm, water uptake rate remained high. Water uptake rate at soil depth 80-120 cm was five times lower than that at 10-60 cm soil depth. Hybrid ATx645/RTx437 (full irrigation) maintained higher water uptake rate compared to others at soil depth 20-120 cm, while ATx645/RTx437 (deficit irrigation) maintained the lowest rate. Variations in water uptake rate were high at each level of soil depth in ATx378/RTx7000 (full and deficit irrigation). One of the reasons might be malfunctioning of soil-moisture measurement tubes in ATx378/RTx7000 plots that collected biased or spurious data at some level of soil depths. Overall, water uptake rate of sorghum was higher than corn and sorghum continued to withdraw water from soil even at 100 cm soil depth.

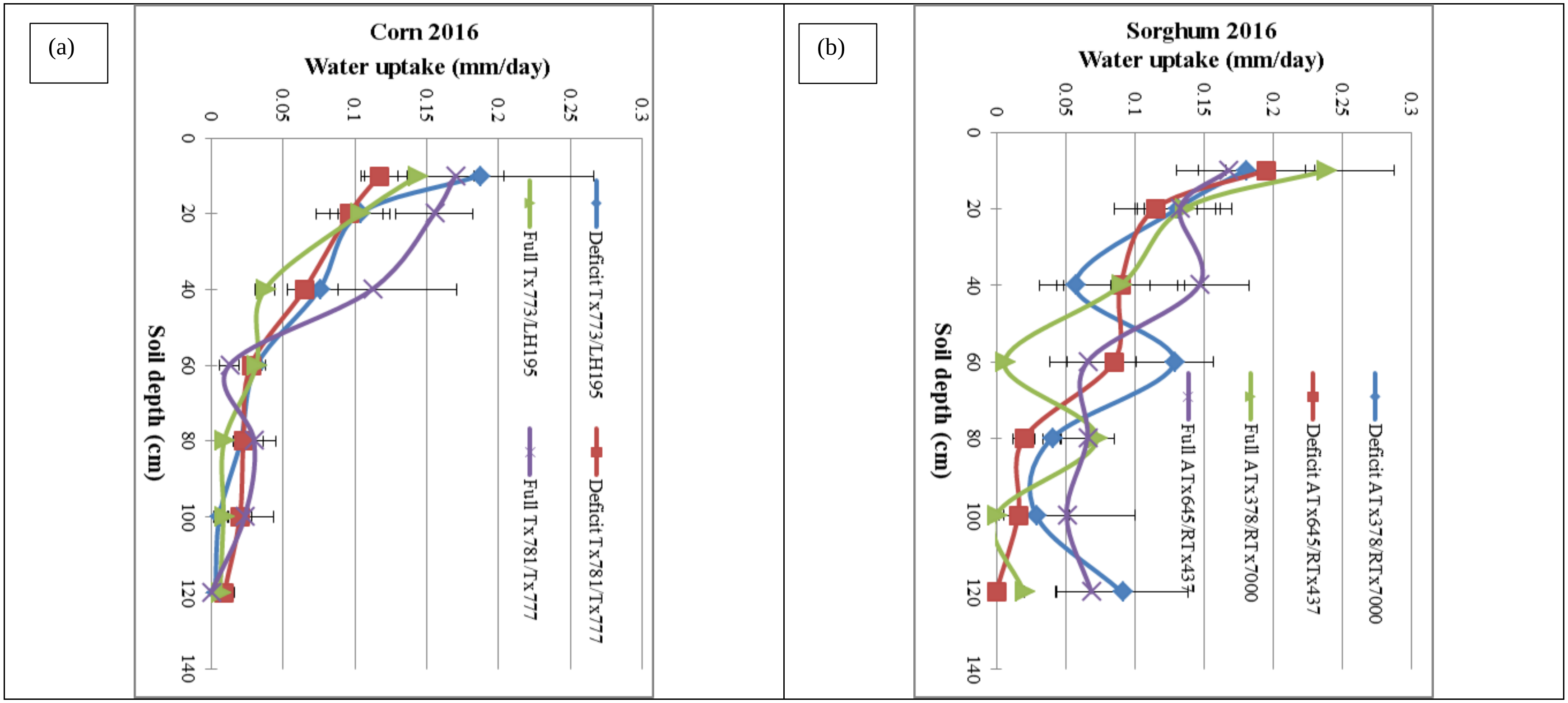


**Figure 3.2.** Typical profiles of rate of water withdrawal (mm/day) by genotypes of (a) corn and (b) sorghum at different soil depths (cm) in 2016 in full and deficit irrigation regimes. Standard error bar represents standard error of the mean.

The patterns of evapotranspiration (mm/day) for selected corn and sorghum genotypes were different as were the differences between the years of 2016 and 2017 (Figure 3.3). For example, ET displayed on 34 DAS was calculated for 22-34 DAS; ET displayed on 76 DAS was calculated for 68-76 DAS, and so on. In 2016, ET was estimated from 22-119 DAS (3-leaf stage to physiological maturity in corn and sorghum) of soil-water content measurement, whereas, in 2017 ET was estimated from 48-104 DAS (8-leaf stage to ½ maturity in corn and growing point differentiation to hard dough stage in sorghum). ET in 2016 showed a sudden decrease from 22-34 DAS to 34-48 DAS.

In corn 2016, experimental hybrids Tx773/LH195 and Tx781/Tx777, both grown in deficit and full irrigation followed a similar pattern of ET. Also, ET increased by three times for both the experimental hybrids from 34-48 DAS (4-leaf stage to 8-leaf stage) to 48-55 DAS (8-leaf stage 10-leaf stage). From 55 DAS to 85 DAS (10-leaf stage to blister formation stage), increase in ET was 1/3 of the increase during 48 DAS to 55 DAS. The ET curve at 55 DAS to 85 DAS was smooth, with slight difference in ET of experimental hybrids in two different irrigation regimes. Tx773/LH195 and Tx781/Tx777, both in full irrigation regimes had slightly higher ET than in deficit irrigation regimes during 55 DAS to 85 DAS. A sharp decrease in ET occurred after 85 DAS for both the experimental hybrids, with the values falling below 1 mm/day on 119 DAS.

In sorghum 2016, the selected hybrids ATx378/RTx700 and ATx645/RTx437, both grown in full and deficit irrigation regimes showed a similar pattern of ET from 22 DAS to 119 DAS (3-leaf stage to physiological maturity). Like corn, there was a sharp increase (three times) in ET of sorghum hybrids from a period 34-48 DAS (5-leaf stage to late growing point differentiation) to 48-55 DAS (late growing point differentiation to flag leaf stage). But approximate increase in ET of corn was from 1.5 mm/day to 5 mm/day, whereas, in sorghum it increased from 1.3 mm/day to 4.4 mm/day. Sorghum hybrids showed a smooth curve from 55 DAS to 92 DAS (flag leaf stage to soft dough stage), for a longer time but 1.1 times lower ET value compared to corn. Full irrigation hybrids had slightly higher ET than those in deficit irrigation at 55 DAS to 92 DAS. A sharp decrease in ET occurred after 92 DAS, but at 119 DAS ET values (2.1-2.3 mm/day) for both the sorghum hybrids was higher than those in corn.

Most of the genotypes in two different irrigation regimes followed a similar ET pattern but differences among ET of different genotypes were visible in both corn and sorghum (Figure 3.3). ET calculated for the 48-103 DAS in corn and 48-104 DAS in sorghum showed a sharp increase followed by a sharp decrease in both corn and sorghum without showing a smooth pattern. In corn 2016, most of the genotypes in full and deficit irrigation showed a sharp increase in ET from 68 DAS (3.1-4.1 mm/day) to 76 DAS (5.0-6.3 mm/day) (Table 3.5). Hybrids NP2643GT/Tx777, Tx149/LH195, and Tx775/Tx777, all in full irrigation regimes that showed an increase in ET from 68 DAS (3.7-4.9 mm/day) to 82 DAS (6.0-6.7 mm/day), followed by a sharp decrease to 1.8-2.7 mm/day on 103 DAS. In sorghum 2017, large variations in ET occurred at each period. However, most of the genotypes showed a similar pattern of increase and decrease in ET. No smooth curve was observed. However, inbreds in full irrigation had higher ET from 68 DAS to 104 DAS compared to inbreds in deficit irrigation and hybrids in full and deficit irrigation (Table 3.6). Hybrids in full irrigation showed higher ET than in deficit irrigation. ET was highest during 75-81 DAS (late flowering period) and was 2-2.5 times of that during 48-62 DAS and 1.5 times of that during physiological maturity. Inbreds had lowest ET in deficit irrigation from flowering to physiological maturity.

In 2017, ET values for both the experimental corn hybrids were averaged to get the values for full and deficit irrigation regimes (Figure 3.4). ET in both the irrigation regimes showed similar pattern. Overall, corn experimental hybrids under deficit irrigation showed lower ET compared to those in full irrigation. In addition, full irrigation maintained a higher ET value for a period of 76-82 DAS, whereas, a sharp increase in ET till 76 DAS followed by sharp decrease was seen in deficit irrigation.

In sorghum, the 2017 ET values showed lot of variations for each period from 48-104 DAS. However, hybrids and inbreds under full irrigation showed a sharp increase in ET until 68 DAS, which was followed by constant ET values until 75 DAS and again a sharp increase until 81 DAS. Similar pattern was seen in deficit irrigation inbreds, but with large variations from one period to another. Overall, higher ET was observed in corn and sorghum during the flowering stage in 2016 and 2017. Corn showed ET 1.1-1.2 times higher than sorghum in 2016 and 2017 during the flowering period. In both 2016 and 2017, hybrids under full irrigation showed higher ET than deficit irrigation in corn and sorghum genotypes.

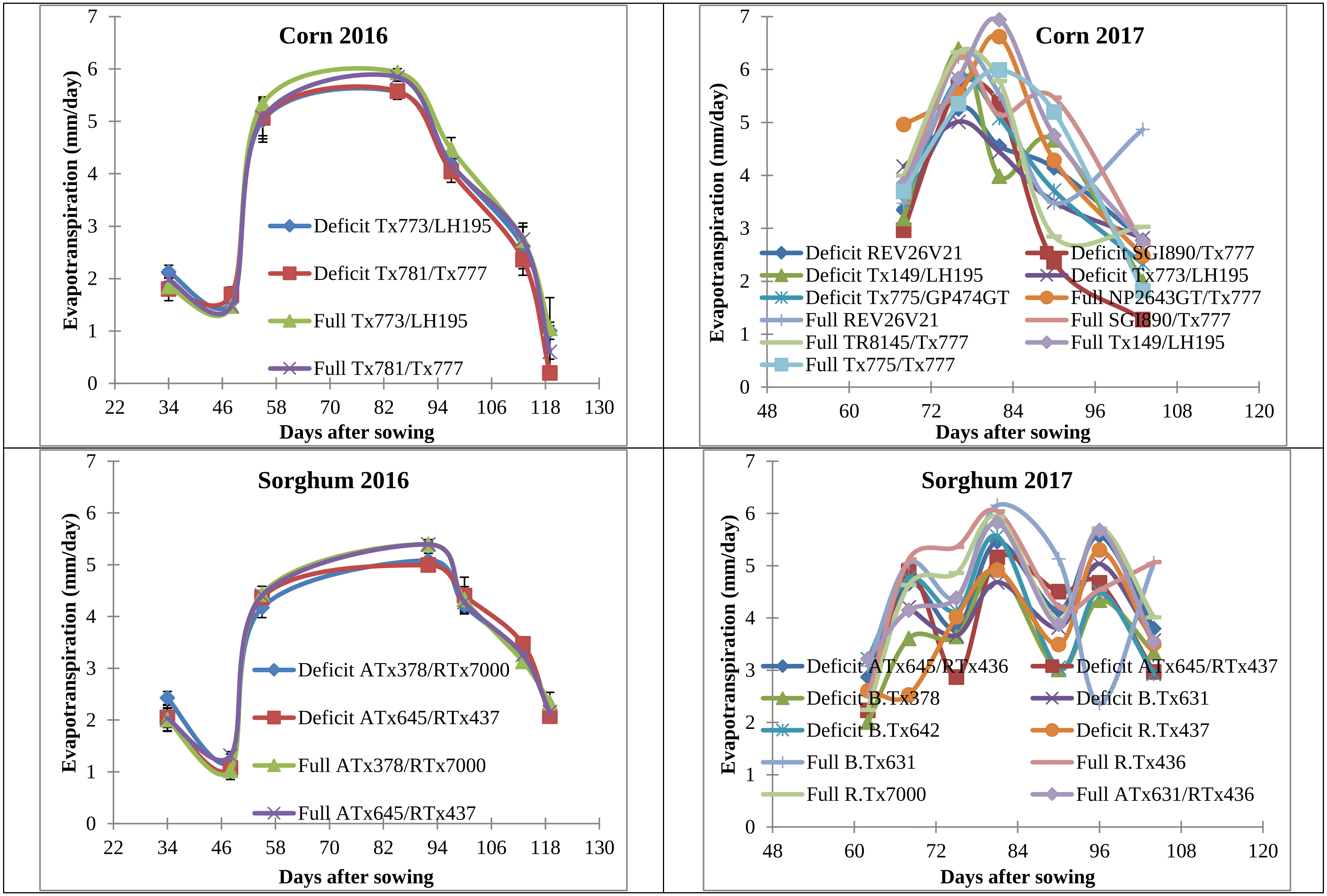


**Figure 3.3.** Evapotranspiration for selected genotypes of corn and sorghum at different day intervals during a period of 22-119 DAS (2016) and 48-104 DAS (2017) in full and deficit irrigation regimes. Standard error bar represents standard error of the mean.

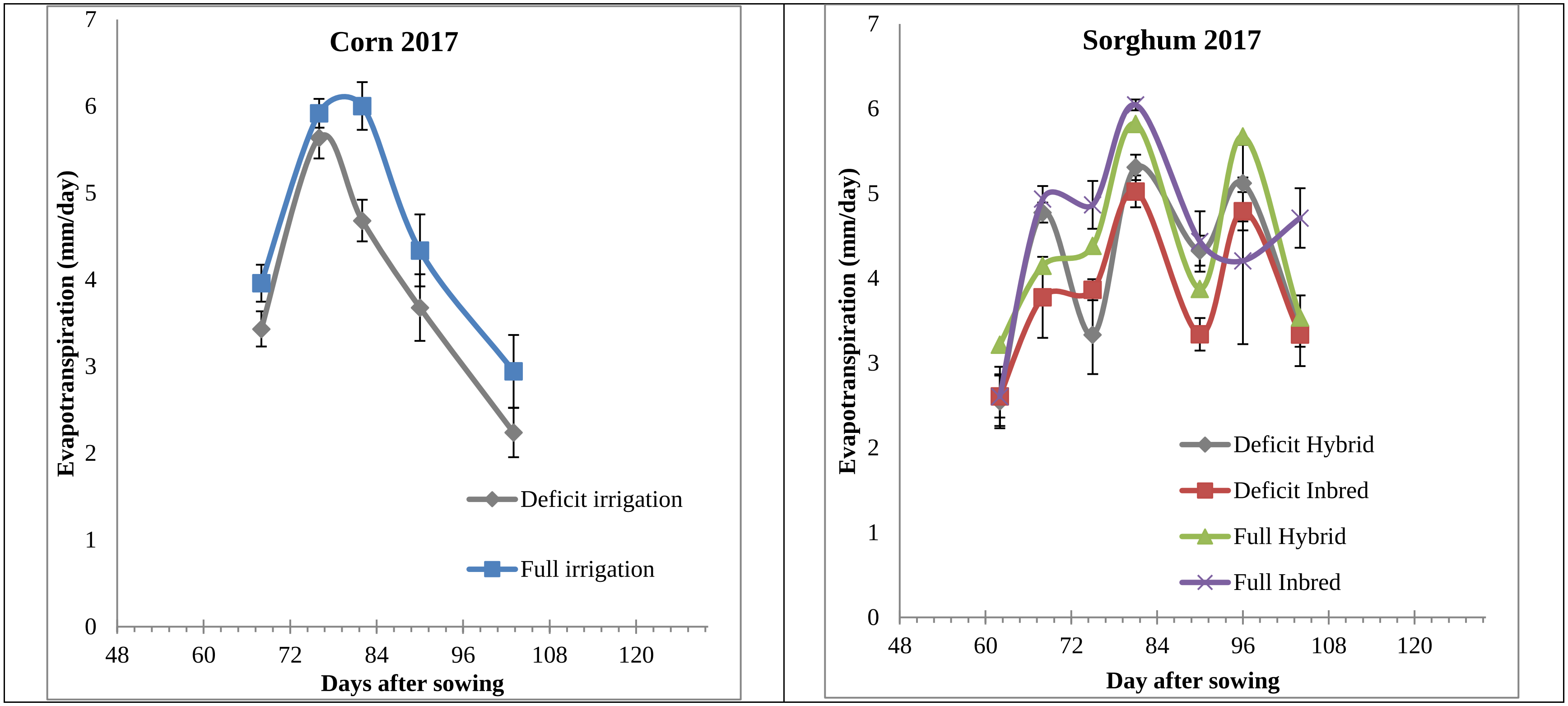


**Figure 3.4.** Comparison of full and deficit irrigation ET obtained by averaging the ET of genotypes present in those regimes in 2017. Standard error bar represents standard error of the mean.

**Table 3.5. Soil-moisture based ET (mm/day) for different day intervals during a period from 48-103 DAS in corn 2017.**

| Corn 2017: Soil-moisture based ET (mm/day) | | | | | | |
|---|---|---|---|---|---|---|
| **Irrigation Regimes** | **Genotypes** | **48-68 DAS** | **68-76 DAS** | **76-82 DAS** | **82-90 DAS** | **90-103 DAS** |
| Deficit | REV26V21 | 3.34 | 5.25 | 4.55 | 4.14 | 2.78 |
| | SGI890/Tx777 | 2.97 | 5.7 | 5.35 | 2.37 | 1.28 |
| | Tx149/LH195 | 3.19 | 6.39 | 3.99 | 4.67 | 2.0 |
| | Tx773/LH195 | 4.17 | 5.02 | 4.44 | 3.5 | 2.81 |
| | Tx775/GP474GT | 3.5 | 5.82 | 5.08 | 3.72 | 2.33 |
| Full | NP2643GT/Tx777 | 4.96 | 5.55 | 6.62 | 4.29 | 2.48 |
| | REV26V21 | 3.48 | 6.24 | 5.54 | 3.48 | 4.87 |
| | SGI890/Tx777 | 3.78 | 6.22 | 5.14 | 5.47 | 2.71 |
| | TR8145/Tx777 | 4.0 | 6.32 | 5.79 | 2.85 | 3.03 |
| | Tx149/LH195 | 3.85 | 5.83 | 6.94 | 4.75 | 2.75 |
| | Tx775/Tx777 | 3.7 | 5.35 | 5.99 | 5.2 | 1.82 |

**Table 3.6. Soil-moisture based ET (mm/day) for different day intervals during a period from 48-103 DAS in sorghum 2017.**

| Sorghum 2017: Soil-moisture based ET (mm/day) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Irrigation regimes** | **Genotypes** | **48 DAS to 62 DAS** | **62 DAS to 68 DAS** | **68 DAS to 75 DAS** | **75 DAS to 81 DAS** | **81 DAS to 90 DAS** | **90 DAS to 96 DAS** | **96 DAS to 104 DAS** |
| Deficit | ATx645/RTx436 | 2.87 | 4.66 | 3.79 | 5.46 | 4.15 | 5.57 | 3.8 |
| | ATx645/RTx437 | 2.23 | 4.89 | 2.87 | 5.16 | 4.5 | 4.67 | 2.96 |
| | B.Tx378 | 2.0 | 3.61 | 3.64 | 4.94 | 3.01 | 4.34 | 3.34 |
| | B.Tx631 | N/A | 4.21 | 3.66 | 4.68 | 3.81 | 5.04 | 3.57 |
| | B.Tx642 | 3.21 | 4.76 | 4.13 | 5.56 | 3.04 | 4.49 | 2.93 |
| | R.Tx437 | 2.61 | 2.53 | 4.02 | 4.92 | 3.49 | 5.3 | 3.51 |
| Full | B.Tx631 | 3.08 | 5.05 | 4.38 | 6.16 | 5.13 | 2.36 | 5.06 |
| | R.Tx436 | 2.49 | 5.12 | 5.36 | 6.04 | 4.22 | 4.54 | 5.07 |
| | R.Tx7000 | 2.24 | 4.63 | 4.86 | 5.94 | 3.96 | 5.72 | 4.0 |
| | ATx631/RTx436 | 3.22 | 4.15 | 4.38 | 5.82 | 3.88 | 5.68 | 3.54 |

WUE has been estimated for grain production (Kg/ha) and aboveground dry biomass (Kg/ha) per mm of ET. For corn 2016, $WUE_{yield}$ of Tx773/LH195 and Tx781/Tx777 in full and deficit irrigation was not significantly different (Figure 3.5). However, significant differences exist between full and deficit irrigation regimes for $WUE_{yield}$ but not for $WUE_{biomass}$. No significant differences exist between Tx773/LH195 and Tx781/Tx777 for $WUE_{biomass}$ in both the irrigation regimes (Figure 3.5). In addition, $WUE_{biomass}$ in full irrigation was not significantly different from deficit irrigation.

For sorghum 2016, no significant differences were observed between full and deficit irrigation regimes for $WUE_{yield}$ and $WUE_{biomass}$ of both the genotypes (Figure 3.5). Compared to ATx378/RTx7000, ATx645/RTx437 showed significantly higher $WUE_{yield}$ and $WUE_{biomass}$ in deficit irrigation regime.

Overall, corn showed 1.5 times higher $WUE_{yield}$ and 1.1 to 1.7 times higher $WUE_{biomass}$ compared to sorghum.

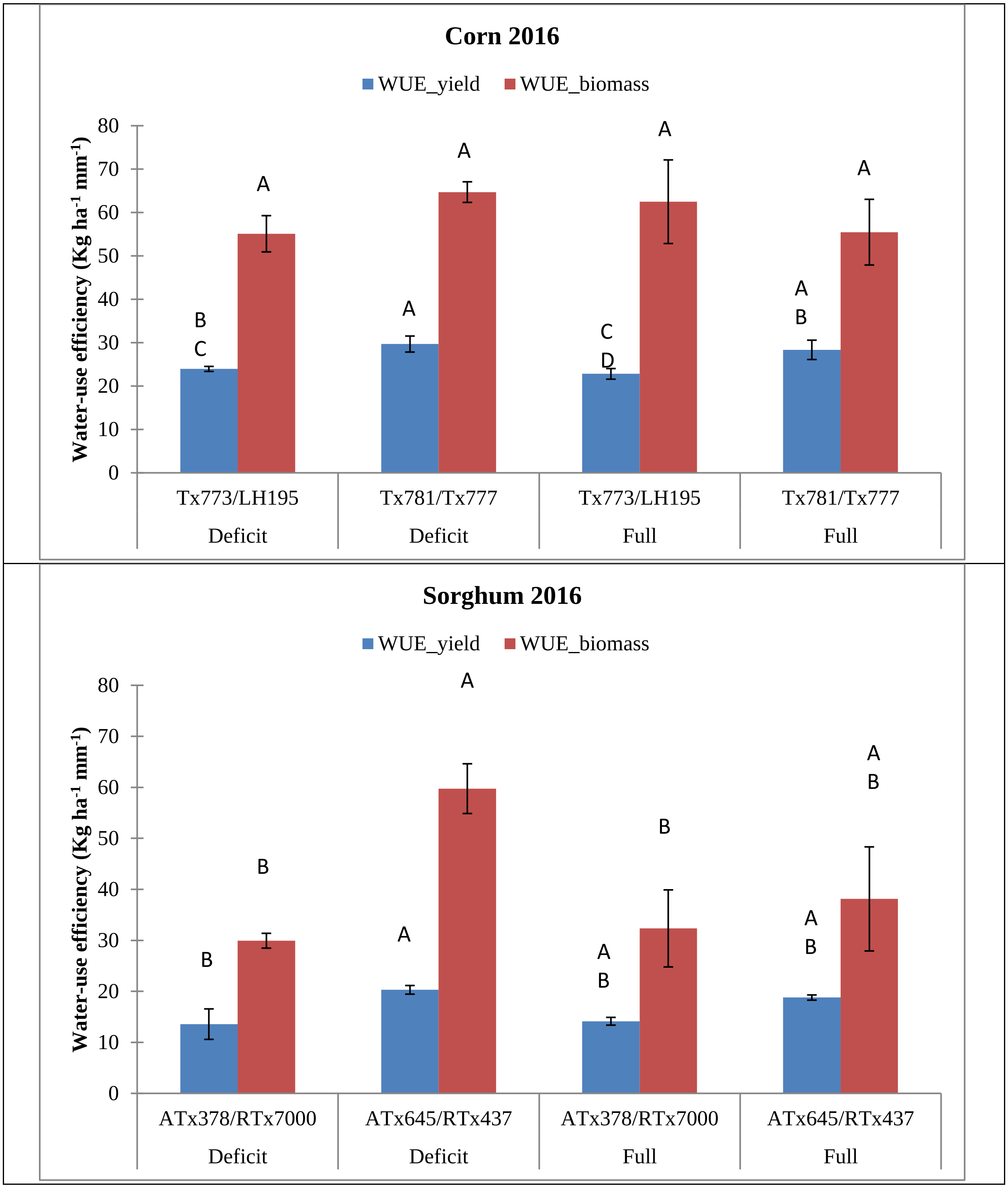


**Figure 3.5.** Water-use efficiency for yield (blue bars) and accumulated biomass (red bars) of selected corn and sorghum hybrids 2016. WUE have been calculated based on soil-water measured from 22-119 DAS. Bars connected with different letters are significantly different. The letters showing significant difference among genotypes have been obtained from student's t-test in JMP 13.0 software. Standard error bar represents standard error of the mean.

Among deficit irrigation, commercial hybrid REV26V21 showed higher $\mathrm{WUE}_{\mathrm{yield}}$ and $\mathrm{WUE}_{\mathrm{biomass}}$ (Table 3.7). Among experimental hybrids in deficit irrigation, SGI890/Tx777 showed higher $\mathrm{WUE}_{\mathrm{yield}}$ and $\mathrm{WUE}_{\mathrm{biomass}}$. Low $\mathrm{WUE}_{\mathrm{yield}}$ and $\mathrm{WUE}_{\mathrm{biomass}}$ in deficit irrigation were seen in Tx149/LH195. In full irrigation, REV26V21 as commercial hybrid and SGI890/Tx777 as experimental hybrid had highest value for $\mathrm{WUE}_{\mathrm{yield}}$, whereas TR8145/Tx777 showed highest value for $\mathrm{WUE}_{\mathrm{biomass}}$. Tx775/Tx777 performed poor in full irrigation in terms of $\mathrm{WUE}_{\mathrm{yield}}$ and $\mathrm{WUE}_{\mathrm{biomass.}}$

In sorghum, ATx645/RTx437 was found to be more water efficient in terms of grain yield and aboveground dry biomass compared to ATx645/RTx436 in deficit irrigation in 2017 (Table 3.8). Among inbreds in deficit irrigation, B.Tx631 was found to be more water efficient in terms of grain yield and B.Tx378 in terms of aboveground dry biomass. $\mathrm{WUE}_{\mathrm{biomass}}$ of B.Tx378 was even higher than both the hybrids in deficit irrigation. ATx631/RTx436 being the only hybrid in full irrigation was less water efficient compared to the inbred B.Tx631 in terms of grain yield and R.Tx7000 in terms of aboveground dry biomass. R.Tx437 showed poor $\mathrm{WUE}_{\mathrm{yield}}$ in deficit irrigation and R.Tx436 in full irrigation. $\mathrm{WUE}_{\mathrm{biomass}}$ was low for B.Tx642 in deficit irrigation and R.Tx436 in full irrigation.

**Table 3.7. Water-use efficiency (WUE) of selected corn hybrids for yield and biomass in 2017. WUE was calculated based on soil-water measured from 48-103 DAS. In 2017, due to some miscommunication different genotypes were selected in different replications, so there is no standard error for any value.**

| Corn 2017: Water-use efficiency (Kg/ha $mm^{-1}$) | | | |
|---|---|---|---|
| **Irrigation regimes** | **Genotypes** | **WUE_yield (Kg/ha $mm^{-1}$)** | **WUE_biomass (Kg/ha $mm^{-1}$)** |
| Deficit | REV26V21 | 36.83 | 106.66 |
| | SGI890/Tx777 | 30.47 | 80.6 |
| | Tx149/LH195 | 19.56 | 61.96 |
| | Tx773/LH195 | 24.87 | 73.93 |
| | Tx775/GP474GT | 26.52 | 68.38 |
| Full | NP2643GT/Tx777 | 24.06 | 45.61 |
| | REV26V21 | 32.66 | 46.06 |
| | SGI890/Tx777 | 28.89 | 67.2 |
| | TR8145/Tx777 | 27.11 | 113.88 |
| | Tx149/LH195 | 26.3 | 73.85 |
| | Tx775/Tx777 | 23.39 | 39.39 |

**Table 3.8. Water-use efficiency (WUE) of selected sorghum genotypes for yield and biomass in 2017. WUE was calculated based on soil-water measured from 48-104 DAS. In 2017, due to some miscommunication different genotypes were selected in different replications, so there is no standard error for most of the genotypes. Two replications of ATx631/RTx436 and R.Tx7000 were selected in full irrigation, however, one plot of ATx631/RTx436 showed high grain yield loss due to bird damage resulting in only one plot to be considered for water-use efficiency for yield. The values in '±' are the standard error of the mean.**

| Sorghum 2017: Water-use efficiency (Kg/ha $mm^{-1}$) | | | |
|---|---|---|---|
| **Irrigation regimes** | **Genotypes** | **WUE_yield (Kg/ha $mm^{-1}$)** | **WUE_biomass (Kg/ha $mm^{-1}$)** |
| Deficit | ATx645/RTx436 | 22.22 | 33.69 |
| | ATx645/RTx437 | 32.81 | 48.41 |
| | B.Tx378 | 17.77 | 61.36 |
| | B.Tx631 | 22.4 | 34.51 |
| | B.Tx642 | 19.35 | 32.37 |
| | R.Tx437 | 10.57 | 37.04 |
| Full | ATx631/RTx436 | 16.86 | 30.94 |
| | B.Tx631 | 19.74 | 34.88 |
| | R.Tx436 | 12.53 | 30.23 |
| | R.Tx7000 | 13.43 ± 3.12 | 40.64 ± 5.19 |

**Table 3.9. Parameters contributing to WUE of selected corn and sorghum hybrids in 2016. Plant density shown is for middle two harvested rows per plot. The values in '±' are the standard error of the mean.**

| **Crops (2016)** | **Irrigation** | **Genotypes** | **Plant density** | **Total ET (mm) from 22-119 DAS** | **Yield/ha (Kg/ha)** | **Dry biomass (Kg/ha)** |
|---|---|---|---|---|---|---|
| **Corn** | Deficit | Tx773/LH195 | 62.33 ± 3.71 | 347.61 ± 6.58 | 8330.08 ± 318.46 | 19204.5 ± 1768.13 |
| | | Tx781/Tx777 | 62.67 ± 2.03 | 335.78 ± 3.63 | 9972.85 ± 672.75 | 21744.18 ± 1022.94 |
| | Full | Tx773/LH195 | 66.00 ± 1.00 | 361.99 ± 2.61 | 8263.07 ± 492.31 | 22595.92 ± 3415.84 |
| | | Tx781/Tx777 | 62.00 ± 4.00 | 355.34 ± 7.34 | 10051.01 ± 651.56 | 19692.66 ± 2649.36 |
| **Sorghum** | Deficit | ATx378/RTx7000 | 130.67 ± 10.84 | 351.97 ± 6.69 | 4747.33 ± 974.99 | 10513.41 ± 320.99 |
| | | ATx645/RTx437 | 185.67 ± 6.36 | 347.81 ± 4.46 | 7067.7 ± 380.28 | 20737.89 ± 1425.31 |
| | Full | ATx378/RTx7000 | 123.33 ± 6.33 | 358.47 ± 2.84 | 5065.54 ± 252.27 | 11551.52 ± 2634.63 |
| | | ATx645/RTx437 | 167.67 ± 9.49 | 362.63 ± 0.31 | 6812.86 ± 189.86 | 13820.95 ± 3689.49 |

**Table 3.10. Parameters contributing to WUE of selected corn and sorghum genotypes in 2017. Plant density shown is for middle two harvested rows per plot. Standard error of the mean in '±' is missing because genotypes were not selected in replications.**

| Crops (2017) | Irrigation Regimes | Genotypes | Plant density | Total ET (mm) from 48-104 DAS | Yield/ha (Kg/ha) | Dry biomass (Kg/ha) |
|---|---|---|---|---|---|---|
| **Corn** | Deficit | REV26V21 | 63 | 205.48 | 7567.73 | 21917.08 |
| | | SGI890/Tx777 | 47 | 172.51 | 5256.61 | 13904.21 |
| | | Tx149/LH195 | 47 | 202.14 | 3952.97 | 12524.06 |
| | | Tx773/LH195 | 57 | 214.62 | 5336.74 | 15866.13 |
| | | Tx775/GP474GT | 55 | 207.03 | 5490.23 | 14156.14 |
| | Full | NP2643GT/Tx777 | 60 | 249.90 | 6012 | 11398.06 |
| | | REV26V21 | 64 | 243.77 | 7960.97 | 11227.21 |
| | | SGI890/Tx777 | 56 | 235.14 | 6792.09 | 15801.77 |
| | | TR8145/Tx777 | 61 | 227.35 | 6163.33 | 25891.84 |
| | | Tx149/LH195 | 62 | 239.11 | 6287.4 | 17658.32 |
| | | Tx775/Tx777 | 56 | 218.04 | 5100.95 | 8588.07 |
| **Sorghum** | Deficit | ATx645/RTx436 | 184 | 228.52 | 5078.29 | 7698.69 |
| | | ATx645/RTx437 | 168 | 203.90 | 6689.20 | 9870.23 |
| | | B.Tx378 | 171 | 184.71 | 3282.35 | 11333.12 |
| | | B.Tx631 | 90 | 172.03 | 3853.34 | 5936.71 |
| | | B.Tx642 | 150 | 213.64 | 4134.57 | 6915.50 |
| | | R.Tx437 | 171 | 200.51 | 2118.85 | 7427.18 |
| | Full | ATx631/RTx436 | 123 | 232.74 | 3956.25 | 7203.71 |
| | | B.Tx631 | 107 | 241.81 | 4772.52 | 8433.31 |
| | | R.Tx436 | 122 | 245.13 | 3070.75 | 7410.61 |
| | | R.Tx7000 | 142 | 230.75 | 3094.65 | 9384 |

## Discussion

The experiment at Uvalde focused on studying variations in corn and sorghum, their selected genotypes, and their performance in two different irrigation regimes, based on sap-flow rate and crop water-use efficiency in 2016 and 2017. Various factors, such as atmospheric temperature ($T_{air}$), wind speed, rainfall, irrigation, stomatal activity, leaf area, crop canopy size, soil structure and texture, soil-water availability, and root area and rooting depth are responsible for rate of water uptake and loss from plants (Kramer and Boyer, 1995). Water loss from crops contribute to grain yield and biomass accumulation (Passioura, 1977; Morison et al., 2008). Water loss in agriculture can be measured in transpiration or evapotranspiration, where evapotranspiration comprises of both soil evaporation and plant transpiration. Water loss by plants due to transpiration or evapotranspiration, contributing to grain yield or aboveground dry biomass accumulation is transpiration efficiency (TE) or water-use efficiency (WUE). Transpiration rate in 2016 was studied for 106-120 DAS (1/2 maturity to physiological maturity), whereas, in 2017 it was studied for 80-94 DAS (blister to dough in corn and soft dough to hard dough in sorghum).

### *Sap-flow rate in selected corn and sorghum genotypes*

During 80-119 DAS, selected corn genotypes first showed a higher transpiration rate of 3.3-4.3 mm/day on 80 DAS (blister stage), and then a gradually decreased transpiration of 1-2.45 mm/day on 94 DAS. In 2016, transpiration rate was 2.0-2.3 mm/day on 106 DAS, and then decreased steadily to 0.3-0.7 mm/day on 119 DAS. An overall decreasing trend of transpiration from blister stage to physiological maturity can be explained by the decreased soil water availability and leaf drying. $T_{air}$ in 2017, for 80-94 DAS was almost constant at 29 °C to 30.4 °C, with solar radiation showing a decrease from 273.9 to 251.7 W $m^{-2}$, with daily variations. The decrease in solar radiation might be a reason for the decrease in transpiration rate from 80 DAS to 94 DAS. Although, $T_{air}$ and $R_s$ increased to 31.17 °C and 297.2 W $m^{-2}$ on 119 DAS, transpiration was low as plants reached physiological maturity with minimum or no green leaves.

Selected sorghum genotypes showed a higher transpiration rate of 4.0-7.0 mm/day on 80 DAS and maintained approx. same rate until 94 DAS. One of the reasons for maintaining constant transpiration rate for 80-94 DAS and only slight decreases transpiration during 106-120 DAS was longer staygreen period in sorghum. Sorghum maintained greenness of leaves even during physiological maturity, and that was responsible for the higher transpiration rate compared to corn. In addition, water uptake in sorghum is possible till soil depth 100 cm, whereas uptake in corn only extended to 60 cm soil depth and this might be due to greater rooting depth of sorghum, which further explains its higher transpiration rate compared to corn (Figure 3.2). On 94th DAS in 2017, transpiration rate in sorghum genotypes was 4.0-8.0 mm/day but on 106th DAS in 2016 it was lower (2.8-2.9 mm/day). One of the reasons might be $T_{air}$ value that was 30.41 °C on 94th DAS in 2017 and 28.03 °C on 106th DAS in 2016. In 2016, corn showed lower transpiration in deficit irrigation than in full irrigation, although not significantly different, reason being higher soil-water availability in full irrigation regimes. Experimental hybrid Tx781/Tx777 in full and deficit irrigation showed lower transpiration rate compared to Tx773/LH195.

In 2016, sorghum hybrids ATx378/RTx7000 and ATx645/RTx437 had similar transpiration rate. However, variations in transpiration rate were seen among hybrids. ATx645/RTx437 showed higher transpiration rate in full and deficit irrigation regimes compared to ATx378/RTx7000. One of the reasons might be higher planting density in ATx645/RTx437 plots resulting in higher transpiration rate, but even at per plant level ATx645/RTx437 had higher transpiration than

ATx378/RTx7000. Although, in full and deficit irrigation ATx645/RTx437 had higher transpiration rate compared to ATx378/RTx7000 but 1.5 times higher yield and 2.5 times higher aboveground biomass accumulation. Also, water uptake by ATx645/RTx437 in full irrigation and ATx645/RTx437 in deficit irrigation (Figure 3.2) extended to 120 cm and 100 cm soil depth, suggesting higher rooting depth.

In 2017, corn hybrid Tx149/LH195 (deficit irrigation) showed highest transpiration rate, whereas, SGI890/Tx777 (deficit irrigation) showed lowest transpiration rate among all the selected hybrids in full and deficit irrigation regimes, even the plant density in both the deficit regimes was same. NP2643GT/Tx777 (full irrigation) had higher transpiration rate compared to SGI890/Tx777 (deficit irrigation), but this is possible because of high soil-water availability and higher plant density.

In 2017, sorghum inbred line B.Tx378 (deficit irrigation) showed highest transpiration rate, whereas, inbred line R.Tx437 (deficit irrigation) shows least transpiration rate among all selected sorghum genotypes. Both, B.Tx378 (deficit irrigation) and R.Tx437 (deficit irrigation) had equal and highest plant density.  B.Tx378 (deficit irrigation) showed grain yield less than ATx631/RTx436 (full irrigation) and high aboveground biomass accumulation. A possible reason for low yield in B.Tx378 compared to ATx631/RTx436 is that the latter is hybrid and under full irrigation. Grain yield and aboveground biomass for B.Tx378 (deficit irrigation) was approx. 1.5 times higher than R.Tx437 (deficit irrigation) and so was the transpiration rate.

For corn and sorghum, transpiration in 2016 was lower than in 2017 because sap-flow rate measured in 2017 was during staygreen period when leaves were in maximum expansion stage. Larger is the leaf area, more is the plant transpiration. In 2016, sap-flow rate measurement started at ½-maturity stage when leaves start drying. In 2017, late planting followed by early harvesting resulted in less biomass accumulation compared to 2016. In addition, weeds infestation were seen in corn and sorghum plots in 2017, resulting in yield reduction due to competition for water by weeds.

### ***Soil-water withdrawal by selected corn and sorghum genotypes***

The soil of experimental plots at Uvalde are mostly clayey loam (Table 3.3). Clayey loam soil has higher water holding capacity (WHC) and low infiltration rate due to its fine texture, it is highly porous with small pore size. In addition, presence of cliché layer at 100-120 cm soil depth in experimental plots restricted deep penetration of roots, as well as, percolation of water downwards. In addition, values soil moisture content ($\theta$) at measured depths being lower than $\theta$ (field capacity) and higher than $\theta$ (permanent wilting point) confirmed the soil-water availability for uptake by plants (Table 3.3). Water uptake by corn and sorghum hybrids at different soil depths in 2016 were different (Figure 3.2). The plant uptake was calculated for a period of 34-48 DAS, when field plots did not receive any rainfall and/or irrigation. In 2017, no such period without rainfall and/or irrigation occurred. Rainfall and/or irrigation add to extra water in soil and estimating plant-water uptake during such periods might end up with a biased outcome. Water uptake at different soil depths for a period of 34-48 DAS provides an idea about root area and rooting depth of selected corn and sorghum genotypes, which further explains water uptake pattern during a longer period. Results confirm deeper root growth in sorghum compared to corn. It can be speculated that the deeper root growth led to the higher water uptake rate in sorghum resulting in low water-use efficiency compared to corn in 2016 (Figure 3.5) and 2017 (Table 3.7 and Table 3.8). Higher water-use efficiency of corn compared to sorghum contradicts the popular knowledge. One of the possible reason might be that sorghum has low grain yield and biomass accumulation, but higher transpiration rate compared to corn.

### *Water-use efficiency in selected corn and sorghum genotypes*

For crops and/or genotypes to be identified as water efficient or having drought tolerance ability, per drop water loss must contribute to higher biomass accumulation and/or grain yield (Lopes et al., 2011). However, Blum (2011) stated that crops/genotypes having higher water-use efficiency (WUE) tends to be less yielding because water use is reduced, thus tolerance to drought is reduced. The WUE calculated for genotypes of corn and sorghum at Uvalde has been compared with that stated by Blum (2011). $WUE_{yield}$ and $WUE_{biomass}$ for corn was higher than sorghum in 2016 (Figure 3.5) and 2017 (Table 3.7 and Table 3.8). Although, evapotranspiration (*ET*) for corn and sorghum were similar but corn yielded higher than sorghum (Table 3.9 and Table 3.10). Tx781/Tx777 showed higher grain yield compared to Tx773/LH195 at equal amount of water use. Sorghum hybrid ATx645/RTx437 in deficit irrigation showed higher grain yield compared to ATx378/RTx7000 at similar water use. Overall, result confirms that at similar water use some genotypes of corn and sorghum tend to produce higher grain yield and aboveground biomass, thus contradicting the argument by Blum (2011).

### *Assumptions*

At 106-120 DAS in 2016, ET value measured using neutron moisture probe was found to be lower than transpiration (sap-flow rate) measured through Dynagage sap-flow meter. We expect the ET values should always be higher than transpiration. However, the result for 106-120 DAS did not meet that expectation. Possible reasons might be: 1) Four plants in a plot were selected to represent whole plot and soil-moisture tubes and sap-flow sensors were installed near them. The installation was done during vegetative period when all four plants were healthy and seemed to be the representative of whole plot. However, during the phase close to physiological maturity how well these four plants represented complete plot and if all the plants in a plot had similar ET and transpiration is difficult to explain. (2) The ET and transpiration value for a complete plot is just an estimated value based on performance of four representative plants selected during vegetative period. We did not have lysimeter facility in corn and sorghum field to measure exact ET and transpiration values for whole plot. (3) Although, sap-flow sensors are insulated to prevent their interaction with the outer environment, but we can never know if all sensors really work during the days when air temperatures are high. If the insulation fails during high air temperature, then shift in sap-flow rate (transpiration) can occur. Because of all these reasons, ET in 2016 was adjusted using equation 3.1. Based on different assumptions, soil-moisture based ET is more trusted compared to sap-flow based transpiration. In addition, amount of water percolated has been assumed zero in 2016 and 2017.

# CHAPTER IV

# CONCLUSION

Sorghum having deeper roots than corn confirms a drought avoidance nature. Deeper roots tend to absorb water even in deficit irrigation, even then, evapotranspiration in sorghum was lower than in corn during the flowering period. Corn was found to have higher water-use efficiency than sorghum. Commercial hybrids of corn performed better than experimental hybrids. Among experimental hybrids, NP2643GT/Tx777 and GP7169GT/Tx777 showed drought tolerant and water efficient behavior. Tx781/Tx777, TR8145/Tx777 and SGI890/Tx777 also performed good. Tx775/Tx777, Tx772WRS/LH195, Tx773/LH195, and Tx149/LH195 showed poor performance. In sorghum, ATx631/RTx437, ATx642/RTx437, B.Tx642, and B.Tx623 showed water efficient behavior. ATx645/RTx437 and ATx2752/RTx430 also performed good. Overall poor performance of ATx378/RTx7000, ATx631/RTx436, B.Tx378, and R.Tx436 was observed. A negative relationship between number of green leaves and grain yield was found in corn, whereas, in sorghum the relationship was positive. Osmotic potential had no effect on grain yield in corn but negative effect on grain yield in sorghum. Breeders and molecular biologists/physiologists can consider these traits for crop improvement research by altering their metabolism to produce a fewer number of leaves, a higher leaf dry matter content or a lower osmotic potential. Result also contradicts the finding by Triboi and Triboi-Blondel (2002) that grain starch content correlates positively with grain yield. No such correlation was observed in corn; however, sorghum showed such correlation in 2016 but a negative relationship in 2017. Linear discriminant analysis confirmed the importance of morphophysiological traits such as leaf dry matter content, osmotic potential, normalized difference vegetation index, number of green leaves, and plant height in study related to drought tolerance.

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