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Inspiring Sustainable Growth

EFFECTS OF PLANTING DATE AND GENOTYPES ON GROWTH, DEVELOPMENT, YIELD, AND OIL CONTENT OF SAFFLOWER UNDER IRRIGATED CONDITIONS IN SEMI-ARID SOUTH-EAST BOTSWANA

A Thesis submitted to the Department of Crop and Soil Sciences

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STATEMENT OF ORIGINALITY

The author's research for this dissertation was conducted between 2020 and 2023 at the Botswana University of Agriculture and Natural Resources. To the best of my knowledge, this work does not contain any content that has already been published by another person or material that has been acknowledged by another degree, certificate, or diploma from another University, unless appropriate acknowledgement and reference have been made in the text.

Author's signature

05/09/2023

Date

DEDICATION

I would like to express my heartfelt gratitude to God for His intervention, which empowered me to successfully complete my thesis. I wholeheartedly dedicate this dissertation to Him as a testament to His grace and guidance. In addition, I extend my dedication to my beloved family, friends and especially to my mother, Mrs. Kgomotso Korononeo, whose unwavering support has been my pillar both materially and emotionally. I also dedicate this work to my esteemed brother, Dr. Tebogo Korononeo, whose guidance and encouragement have been invaluable to me. Furthermore, I want to convey my deepest appreciation to my best friend, Gaogalalwe Mokgatitswane, for his constant encouragement and motivation throughout my educational journey. His unshakeable belief in me has been a driving force and I am truly grateful for the support.

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ABSTRACT

Safflower (*Carthamus tinctorius* L.) is an annual oil plant belonging to the Compositae or Asteracea family that can be grown as a summer or winter crop. One of the most important criteria for maximising safflower production is choosing the right planting date. Therefore, the objective of this study was to evaluate how safflower growth, development, yield, and oil content were affected by planting date and genotype. The Botswana University of Agriculture and Natural Resources content farm served as the site of field studies. Three replications of a 4 x 4 factorial in randomised blocks made up the experimental design. The treatments were planting dates (15^{th} of December, January, March, and May) and safflower four genotypes (Sina, PI537636, Gila, and PI527710). The results showed that planting date and genotype significantly ($P < 0.05$) interacted to influence phenological variables (days to 50% flowering and physiological maturity), vegetative growth (LAI, LAD, NAR, CGR, and leaf chlorophyll content), yield components (seed number/capitulum, 1000-seed weight, biological yield, and harvest index), and oil content with the genotype Sina when planted in May producing the highest variables. Planting date and genotypes independently significantly ($P < 0.05$) influenced also vegetative growth (plant height, primary branch number, and plant stem diameter), yield components (capitula diameter and capitula number/plant), seed yield, and oil yield with genotype Sina planted in May producing the highest variables. The other genotypes PI57636, PI527710 and Gila were also recommended for commercial growing due to their high seed yield and oil content above 28% (threshold hold for commercial oil production) under favourable growing conditions, and multiple uses of safflower. For early planting in summer, January planting was recommended because it was the second-best planting date. Planting in March was highly discouraged as plant performance was drastically reduced due to unfavourable chilling temperatures converging at a sensitive phenological stage (onset of flowering)

CHAPTER 1 : INTRODUCTION

1.1. Background information

Safflower (*Carthamus tinctorius* L.) is an annual oil plant that belongs to the Compositae or Asteracea family and can be grown as a summer or winter crop (Oz, 2016). As a xeric crop, safflower is drought tolerant because it can survive in arid conditions by drawing water from depths of up to 2-3 metres owing to its strong deep taproot system (Emongor, 2010; Ahadi et al., 2011) and makes it possible for cereal crops to use nutrients from below the root zone (Dajue & Mündel, 1996). Safflower is propagated by seed and germination takes place within 3-10 days, depending on temperature (Emongor, 2010; Emongor & Oagile, 2017; Emongor & Emongor, 2022). For the development of their roots and rosette stage, safflower seedlings in their early stages of growth require cool temperatures of 15-20°C, whereas high temperatures (20-30°C) are necessary for stem elongation and reproduction (Li, 1989; Mündel et al., 1992; Li et al., 1997; Carapetian, 2001; El-Bassam, 2010, Emongor, 2010; Emongor & Oagile, 2017). Following seedling emergence, a rosette stage occurs during which no long stems develop but numerous leaves are generated close to the ground and a strong taproot form (Dajue & Mündel, 1996; Emongor, 2010; Emongor & Oagile, 2017). Young safflower plants can withstand cold and frost at this stage of development (Li, 1989; Mündel et al., 1992; Li et al., 1997; Carapetian, 2001; El-Bassam, 2010, Emongor, 2010; Emongor & Oagile, 2017; GRDC, 2017; OECD, 2020), but very susceptible to weeds because safflower is a poor competitor (YazdiSamadi & Zali, 1979; Dajue & Mündel, 1996; Kandel & Bergman, 2019). The duration of the rosette stage is dependent on the environment and genetic factors (Zimmerman, 1976; Zimmerman & Buck, 1977; Emongor, 2010). Depending on cultural practices, temperature, and photoperiod, the duration of rosette stage ranges between 20- and 39-days following emergence (Emongor & Oagile, 2017). For various safflower genotypes the rosette stage is shortened from 39 to 23 days when day length is increased from 10 to 14 hours (Weiss, 2000) At high temperatures the transition from rosette stage to the stem elongation and branching may be less noticeable than at low temperatures (Dajue & Mündel, 1996; Weiss, 2000).

Extensive branching follows elongation of stems with branch to stem angle ranging from 30 to 75º, thus branching habit in safflower is classified as narrow and is controlled both genetically and environmentally (Singh & Nimbkar, 2005). Depending on the growing conditions, each branch develops a globular flower capitulum where flowering starts and the complete bloom stage may last for four weeks or longer (Dajue & Mündel, 1996; Emongor & Emongor, 2022). The petals of safflower flowers appear in a variety of colours; during early bloom, yellow, orange, and red flowers are the most common, while post-bloom colours are darker and white flowers are rare (Dajue & Mündel, 1996; Emongor & Emongor, 2022). The flower matures into an achene, a single-seeded fruit, which is commonly known as seed and 15 to 60 seeds are produced by each safflower capitulum (Singh & Nimbkar, 2005). According to Ekin (2005), mature achenes of common varieties are made up of the oil content ranging from 20 to 45% or more of the whole seed, with the hull and kernel making up 33-60% and 40-67%, respectively.

The seeds are mainly used for extracting oil and for bird feed (Emongor, 2010). Oil content is determined by the types of safflower that can either be spiny or spineless. According to Oz (2016), compared to spineless varieties, the spiny types have higher oil contents. In addition to seeds, the brilliantly coloured flower petals are also harvested and used for medicinal preparations, natural food colouring and dying fabrics (Kizil et al., 2008; Kisha & Johnson, 2012; Emongor & Emongor, 2022). In recent years safflower has been considered one of the oldest crops producing oil for human consumption all around the world, commercially produced as a cut flower, vegetable, and medicinal plant (Emongor, 2010; Thalji, 2015). Also, in dry and semi-arid regions of the world, safflower is an important oilseed crop because of its capacity to withstand cold, drought, and salinity (Weiss 2000; Majidi et al., 2011). Safflower oil is one of the highest quality vegetable oils containing essential fatty acids that are important to human nutrition; linoleic (53.8-84%) which is polyunsaturated and oleic (9.5-91%) which is monounsaturated (Singh & Nimbkar, 2005; Khan et al., 2009; Thalji, 2015; Killi et al., 2016; Moatshe, 2019; Moatshe et al., 2020). The benefits of these unsaturated fatty acids in terms of medical use and nutrition are well established, and they include lowering blood cholesterol and preventing coronary heart disease, arteriosclerosis, high blood pressure, and hyperlipemia (Wang & Li, 1985; Weiss, 2000; Weiss et al., 2005; Cosge et al., 2007; Mišurcová et al., 2011; Mobraten et al., 2013). Safflower petals have been shown to promote blood circulation and remove blood stasis (Li et al., 2016; Ao et al., 2018; Delshad et al., 2018; Liao et al., 2019). Modern pharmacological research and clinical trials have shown that safflower petal extracts have promising agents for ameliorating myocardial ischemia, trauma, and joint pains (Delshad et al., 2018; Liao et al., 2019).

When safflower petals are harvested at various growth stages, the yield components and fatty acid composition are altered (Dajue & Mündel, 1996; Rajvanshi, 2005). However, Kizil et al. (2008) reported that though seed yield was not significantly influenced by petal collection cycles, collecting intervals had a detrimental effect on capitula diameter size, the number of seeds per capitulum, and dry petal yield. Also contributing to the alteration in oil content and composition is the environment (Hall, 2016) and sowing date during the growth of the seed (Samanci & Ozkaynak, 2003). Genetic factors, location, season of growth, temperature, agronomic or cultural practises, planting density, and time of planting all have an impact on variations in safflower oil content, yield, and fatty acid composition (Knowles, 1989; Dajue, 1993; Velasco & Fernandez, 2001; Samanci & Ozkaynak, 2003; Cosge et al., 2007; Ensiye & Khorshid, 2010; Mouman et al., 2013; Golkar, 2014; Liu et al., 2016; Khalid et al., 2017;

Moatshe et al., 2020). The amount of linoleic acid reduced as the temperature increased during seed maturation, but the amounts of oleic, palmitic, and stearic fatty acids increased (Samanci & Ozkaynak, 2003; Cosge et al., 2007; Moatshe, 2019; Moatshe et al., 2020).

1.2. Planting date

Planting date has been reported to influence growth and yield of safflower (Yau, 2007; Koutroubas et al., 2009). Thus, choosing the appropriate planting date is one of the most critical aspects of maximising safflower productivity (Yau, 2007; Koutroubas et al., 2009). Oz (2016) reported that planting date significantly influences safflower yield. Samanci and Ozkaynak (2003) assessed how three planting dates in Turkey (25 April, 5 May, and 15 May in 1998; 30 April, 5 May, and 15 May in 1999) affected the yield of seeds, the amount of oil they contained, and the fatty acid composition of three safflower cultivars. They noted that delaying the planting date decreased the yield of seeds, oil content, palmitic acid, stearic acid, and oleic acid contents while increasing the quantity of linoleic acid (Samanci & Ozkaynak, 2003). Reduced seed yield resulted from higher air temperatures during the flowering stage when planting was postponed because they interfered with pollination and fertilization (Samanci & Ozkaynak, 2003). Ahadi et al. (2011) in Iran reported that delaying the planting date resulted in significantly longer flowering and maturation times, but reduced safflower yield components, seed yield, and harvest index. The increase in days to flowering and maturation with delayed planting date was attributed to decreased mean air temperature and day length (Ahadi et al., 2011). While the decrease in yield components (number of seed/capitulum, number of capitula/plant and 1000-seed weight), seed yield and harvest index with delayed planting date was attributed to unfavourable climatic conditions (very low temperatures) throughout the flowering and seed-filling periods. Yau (2007) reported that late planting of safflower in the spring experienced low seed yield and late flowering because of drought and high temperatures in the semi-arid and high-altitude Mediterranean climate. Si and Walton (2004) reported that early safflower planting with early maturing cultivars was essential to produce high seed yield in the low rainfall areas.

1.3. Genotype

Significant genetic diversity exists in safflower for yield and yield-related variables, plant height, flowering time, duration of rosette stage, primary branches, and other morphological traits. The impacts of additive and non-additive gene action are known to significantly influence genetic variations in vegetative and morphological features (Kotecha, 1979; Shahbazi and Saeidi, 2007; Golkar et al., 2012; Emongor et al., 2017). According to Shabana et al. (2013), temperature influences all morphological and physiological processes. The total number of cumulative degree days or heat units needed for growth, development, and maturity varies among safflower genotypes to help them improve adaptability (Shabana et al., 2013). Safflower oil quality and yield were the subjects of an investigation by Abou Chehade et al. in 2022. All six of the investigated genotypes, according to their findings, were able to adapt to the dry and hot circumstances sufficiently, but sowing time and environmental factors varied, which affected performance. Due to water scarcity, other safflower genotypes in other parts of the world have seen a decrease in yield and yield components (Kar et al., 2007, Lovelli et al., 2007) (Santos et al., 2017). However, the impact of a water deficit on productivity and growth is genotype-dependent, particularly at certain developmental phases (Bannayan et al., 2008; Ozturk et al., 2008; Santos et al., 2017).

1.4. Problem Statement

Agriculture and food security are seriously threatened by climate change, and crop yield has decreased globally because of extreme weather conditions (Majed, 2023). So, to lessen the impact of climate changes on crop production, adaptation techniques are a necessity. Generally, the development of sustainable and affordable cropping systems that offer maximum yield at a low production cost is needed for wide adoption and increased productivity. One of the best practises to attain a sufficient yield is the selection of genotypes with greater adaptability to various production systems. A key element to improving the efficiency of resource use is choosing the right planting date. With Botswana's unpredictable and unreliable rainfall, there is need to find alternative food sources that can withstand the current weather conditions. The importance of the study seeks to explore the response of safflower genotypes in relation to growth, development, and yield under various weather conditions as per planting date.

1.5. Justification of study

The productivity of agricultural lands is significantly influenced by the adoption of crop management practices like planting dates (Dai et al., 2014; Khatib et al., 2015; Srivastava & Malhotra, 2017). The ability to accumulate the necessary thermal time, which improves resource use efficiency and is necessary for the proper growth and development of agronomic crops, including safflower, depends on the timing of planting in a particular ecological zone (Khatib et al., 2015; Hasanuzzaman, 2019). The combination of a number of variables, including variety, season, temperature suitability, and water availability, influences the recommendation of optimal planting date (Balalić et al., 2012; Hasanuzzaman, 2019). Sowing date has a significant influence on safflower productivity (Samanci & Ozkaynak, 2003; Yau, 2007; Ghanbari et al., 2011; Yarnia et al., 2011; Khalil et al., 2013). Safflower, among other crops, has been shown to benefit from optimal planting dates in terms of yield components and yield (Samanci & Ozkaynak, 2003; Yarnia et al., 2011; Khalil et al., 2013; Khatib et al., 2015; Hasanuzzaman, 2019). In Botswana, safflower grown in late March and April has been observed in farmers' fields (Ramonaka) and Sebele to suffer from chilling injury because the bolling stage (just before flowering) is sensitive to low temperatures of less than 2°C (Emongor & Oagile, 2017). This stage coincides with the low night temperatures of July in Botswana. Safflower seedlings are frost tolerant, the seedlings can endure temperatures of -7 to -15°C, depending on genotype (Li, 1989; Mündel et al., 1992; Li et al., 1997; Carapetian, 2001; Ell-Bassam, 2010; Kolanyane, 2022). No known research in determining the optimum planting date to maximise safflower seed yield, oil content and fatty acid composition has been done in Botswana and Southern African Development Community (SADC).

1.6. Objectives

1.6.1. **General objective**

To evaluate the effects of planting date and genotype on growth, development, yield and oil content of safflower in semi-arid South-East Botswana with the goal to increase food security in the country.

1.6.2. **Specific Objective**

To evaluate the effects of planting date and genotype on growth, development, seed yield and oil content of safflower genotypes.

1.7. Hypothesis of the study

Ho: Planting date has no effect on the growth, development, yield, and oil content of safflower genotypes

Ha: Planting date has an effect the growth, development, yield, and oil content of safflower genotypes.

CHAPTER 2 : LITERATURE REVIEW

A broad assessment of how safflower germplasm reacts to planting date has served as the foundation for the review. It addresses how planting date affects growth, yield, yield components and oil content. The conclusion of the analysis identifies the knowledge gap in the Southern African Development Community (SADC) regarding safflower genotypes and planting date as it relates to safflower growth and development.

2.1. Factors affecting Safflower growth and development.

To research plant behaviour under a particular set of environmental variables, crop growth and development are essential (Hassan et al*.,* 2015). The growth and seed quality characteristics of safflower are influenced by factors such as genotype, environment, and agronomic practices (Koutroubas et al., 2009; Beyyavas et al., 2011; Shabana et al., 2013). Yield is a complex trait that depends on several agronomic characteristics and is significantly affected by a variety of genetic and environmental factors (Joarder et al., 1978; Emongor et al., 2017). Similarly, one of the most desired traits of a genotype is varietal stability in yield with respect to a wide range of conditions to fit the crop under the available cropping patterns (Hossain et al., 2003).

Due to its tolerance to adverse climates and salinity, safflower is a temperate zone crop that thrives in a variety of soil and climatic conditions. Koutroubas and Papakosta (2005) reported that Safflower has a great tolerance for heat, cold, and salinity, allowing it to be successfully grown in places with low temperatures and soil with poor fertility. Shabana et al. (2013) reported that safflower oil content is influenced by temperature. While Samanci and Ozkaynak (2003) reported that genotype and environment had an impact on the amount of oil and the fatty acid composition of safflower oil. During seed development, linoleic fatty acid content declined as temperature rose whereas oleic, palmitic, and stearic fatty acid amounts increased (Samanci & Ozkaynak, 2003).

2.2. Effects of planting date on growth, development, and yield of safflower cultivars.

To choose a suitable time to plant a crop in a region, several different factors should be considered such as minimum and maximum temperature (Torbaghan, 2015), daylength, radiation and moisture (Tsimba et al., 2013; Mirshekari et al., 2013). Due to unfavourable weather conditions, farmers typically plant field crops outside the ideal planting date (Baum et al., 2019). Planting time and days to physiological maturity are two essential crop adaptation and mitigation methods that can be used to deal with unfavourable conditions for growth. Planting date and crop's days to maturity decisions, set the yield potential of field crops in each environment. Together with the local weather conditions, these two factors regulate the length of the growing season during which the crop absorbs radiation that is positively correlated with grain yield (Lindquist et al., 2005; Emongor & Oagile, 2017). For field crops, early planting leads to higher yield potential than late planting (Richards, 1996), because the longer growing season allows the crop to utilise resources like radiation, water, and nutrients more efficiently than a shorter growth season (Andrade et al., 2000; Parker et al., 2016). However, during critical times, yield is extremely susceptible to partitioning and growth (Andrade et al., 2000; Vega et al., 2001). Early planting date in field crops and a lengthy growing season may not guarantee high grain yield because other aspects like drought, heat, and nutrient stressors can lower grain yield during the growth season (Edmeades et al., 2000).

Planting date and genetic make-up of safflower and other crops influences growth and development (Dajue & Mündel, 1996; Weiss, 2000; Ahmadi, 2008; Seadh et al., 2012;

Emongor et al., 2017). Seadh et al. (2012) reported that planting dates consider how edaphic factors and environmental conditions affect all field crops' growth and yield, which vary greatly from region to region. In general, the yield potential of winter safflower planting is more than spring planting because the period of growth is longer, and the plants have efficient use of climatic factors to accumulate dry matter (Nareki, 2001). However, if the cold winter is more than safflower tolerance, inevitably spring planting will have to be taken, but in areas with mild winter safflower autumn sowing is preferred than spring planting in Iran (Torbaghan, 2015).

2.2.1. **Effect of planting date and genotype on vegetative growth of safflower**

Planting date and genotypes affects safflower phenology because early and late planting contribute differently to growth and development. Early planting enables the crop to fully utilize the entire growing season, whereas late planting generally results in shorter plants, less rooting depth, decreased branching, and lower seed and oil yields (Kandel & Bergman, 2019).

2.2.1.1. Crop phenology

Crop phenology is the knowledge of progressive stages from emergence until the crop reaches physiological maturity. It is important to improve proper timing of cultural activities such as date of planting, pest and disease control, fertilizer application, irrigation regimes, to assist in prediction of crop yield (Perry et al. 1987; Shaykewich, 1995) and for evaluation of genotype adaptation to different ecological conditions (Martin et al., 1993). The recognized phenological stages of safflower are emergence, rosette, stem elongation, branching, flowering, and maturity (Mündel et al., 1y992; Dajue & Mündel, 1996; Emongor & Oagile, 2017; Emongor & Emongor, 2022).

An experiment carried out in Sanandaj in Iran revealed that delaying sowing date significantly increased the duration of flowering and maturity stages (Ahadi et al., 2011). Delay in sowing date from 25th June to 5 and 15 July contributed to prolonged vegetative growth due to the convergence of low mean temperatures and short-day length (Ahadi et al., 2011). Safflower is a long day plant, under short day conditions and low temperature the growth period is long (Ahadi et al., 2011; Emongor & Oagile, 2017; Emongor et al., 2017; Moatshe, 2019; Emongor & Emongor, 2022). Al-Doori (2017) reported similar results that late planting of safflower delayed physiological maturity because of declining mean temperature during growth which resulted in delayed flowering time induced by short photoperiod. Although the duration of stem elongation varied by cultivar and growing season, the maximum stem length was reached at the onset of flowering (Flemmer et al., 2015). However, Shabana et al. (2013) reported that in Egypt delayed planting significantly reduced days to flowering and maturity. Safflower planted on 1st of November and 1st of December flowered after 133 and 112 days, and matured after 169 and 146 days, respectively (Shabana et al., 2013). Unfavourable photoperiod and high temperatures were held responsible for the reduction in days to flowering and maturity because of late planting since they compelled the crop cycle to advance quickly to the development stage at the expense of yield and yield components (Shabana et al., 2013).

When comparing data pertaining to three cultivars' (Sina, Zarghan and 411) response to various planting dates, Ahadi et al. (2011) reported that there were significant cultivar differences of days to physiological maturity. The cultivars Sina and 411 had the longest and shortest maturity days of 112 and 105, respectively (Ahadi et al., 2011). Moatshe et al. (2020) reported that when grown in winter and summer, respectively, safflower genotypes considerably differed in the time from sowing to physiological maturity, ranging from 135 to 147 and 100 to 116 days, respectively. Similar results are reported in literature (Weiss, 2000; Golkar, 2014; Oarabile, 2017; Emongor et al., 2017; Al-Doori, 2017). However, La Bella et al. (2019) reported that in terms of days to maturity, there were no appreciable differences across safflower accessions.

2.2.1.2. Plant height

Safflower plant height is a significant morphological feature because it affects growth and development and is influenced by the action of additive genes (Kotecha, 1979; Shahbazi & Saeidi, 2007; Farooq et al., 2009; Golkar et al., 2012; Khaki-Moghadam & Rokhzadi, 2015; Emongor et al., 2017; La Bella et al., 2019; Moatshe, 2019). However, safflower plant height is also influenced by environmental and cultural factors (Zareie et al., 2013; Hamza, 2015; Killi et al., 2016; Oarabile, 2017; Emongor et al., 2017; Emongor & Oagile, 2017; Moatshe, 2019; La Bella et al., 2019). Generally early planting during the cropping season leads to taller safflower plants compared to late planting (Mirshekari et al., 2012; Omidi & Sharifmogadas 2010). In a study by Mirshekari et al. (2012), maximum plant height of safflower was obtained on the first planting date (19th April) and lower values in the late planting date (20th May). Due to an increase in air temperature during the growing season because of the delayed planting, the height of the safflower plants was reduced (Mirshekari et al., 2012). This was consistent with the earlier findings of Omidi and Sharifmogadas (2010), who reported that late planting significantly reduced safflower plant height. On the contrary, Al-Doori (2017) reported that delaying sowing date from October to November in Iraq resulted in significant increase in plant height. Similarly, Alinaghizadeh et al. (2008) reported the highest plant height on the third sowing date and explained it as due to decreased air temperature resulting in a long safflower growth duration. However, the overall effect of early or late planting of safflower on plant height was determined by the interaction of the growth stage and the prevailing climatic conditions (Alinaghizadeh et al., 2008). Al-Doori (2017) and La Bella et al. (2019) all reported that safflower plant height was significantly influenced by the interaction between the planting date and genotype.

2.2.1.3. Number of branches

Al-Doori (2017) reported a high number of primary branches of safflower in late planting dates of November and December in Iraq compared to safflower planted in October. Bellé et al. (2012) reported that safflower grown during the fall/winter season significantly reduced branch number by 35% compared to spring/summer grown safflower in Brazil. On the contrary, Thalji (2015) reported that in Jordan under irrigated conditions, late planting in December, significantly increased number of branches and other vegetative variables due to favourable temperatures of 12-20°C during the growth period.

2.2.1.4. Stem diameter

Safflower planted in fall/winter significantly increased stem diameter compared to spring/summer planting in Brazil (Bellé et al., 2012). The increase in stem diameter of safflower planted in fall/winter compared to spring/summer planting was attributed to a larger leaf area and longer growing period in fall/winter planting due to low temperatures than spring/summer planted safflower (Bellé et al., 2012).

2.2.1.5. Leaf area index

Leaf area in crop canopy is generally influenced by the planting date, plant density and genotypes (Omidi & Sharifmogadas, 2010; Moatshe, 2019). In a study to evaluate Iranian safflower cultivars effects to different sowing dates, Omidi and Sharifmogadas (2010) found that late planting caused a decrease in leaf area index. The decrease in leaf area was attributed to leaf shattering (Omidi & Sharifmogadas, 2010). Moatshe (2019) reported that safflower grown in winter had significantly higher leaf area index (LAI) than summer, regardless of genotype or plant density in Botswana. The high LAI in winter grown safflower was attributed to low air temperature during the growth period and short-day length which resulted in a longer growing period and delayed physiological maturity. The longer length of the growing season induced by cool air temperature and short-day length allowed the crop to use resources like radiation, water, and nutrients more efficiently (Andrade et al., 2000; Emongor et al., 2015; Parker et al., 2016; Moatshe et al., 2020).

2.2.2. **Effect of planting date and genotype on yield and yield components of safflower**

The yield components of safflower include thousand seed weight, number of primary branches per plant, capitula size, number of seed per capitulum, and number of capitula per plant (Chaundry, 1990; Gonzalez et al., 1994; Omidi & Tabrizi, 2000; Bagheri et al., 2001; Camas & Esendal, 2006; Kedikanetswe, 2012; Emongor et al., 2013; 2015; Emongor & Oagile, 2017; Emongor & Emongor, 2022). Several researchers have concluded that for selection of high yielding varieties of safflower, factors that could be utilized as the main selection criteria are the number of seeds per capitulum, the number of capitula per plant, and the weight of 1000 seeds (Chaundry, 1990; Gonzalez et al., 1994; Bagheri et al., 2001; Camas & Esendal, 2006; Ahmadzadeh et al., 2012; Emongor et al., 2013; 2015; Emongor & Oagile, 2017; Moatshe, 2019).

2.2.2.1. Capitula number per plant

The differences in planting dates have been reported to significantly influence safflower capitula number per plant (Mirzakhani et al., 2002; Ahadi et al., 2011; Shabana et al., 2013; Al-Doori, 2017). Al-Doori (2017) in Iraq, reported that late planting of safflower in December instead of October and November significantly reduced capitula number per plant. Similar results of late planting of safflower reducing capitula number per plant had been earlier reported in literature (Mirzakhani et al., 2002; Ahadi et al., 2011; Shabana et al., 2013). Low number of safflower capitula per plant was associated with lack of water, high temperatures during flowering, decrease in photosynthates, and prematurity (Hall, 2004; Tayebi et al., 2012; Shababa et al., 2013; Al-Doori, 2017). Shabana et al. (2013) reported that late planting significantly reduced yield components and seed yield of safflower due to unfavourable temperature for growth and development. In contrast in Jordan under irrigated conditions, late planting in December significantly increased capitula number per plant due to favourable temperatures of 12-20°C during the growth period (Thalji, 2015). However, a study by Nikabadi et al. (2008) found that safflower planting date did not significantly influence capitula number per plant.

2.2.2.2. Capitula diameter

A significant increase in the average capitula diameter from 1.96 to 2.45cm was reported by Al-Doori, (2017) due to delayed planting from October to November. Bellé et al. (2012) reported a difference in capitula diameter during autumn/winter and spring/summer growing seasons with values of 2.03 and 2.4 cm, respectively, although the difference was not statistically different.

2.2.2.3. Seed number per capitulum

Numerous researchers have demonstrated a significant correlation between the sowing date and genotype with the number of seeds per capitulum (Mirzakhani et al., 2002; Nikabadi et al.,2008; Ahadi et al., 2011; Khalil et al., 2013). Delaying sowing date decreased seed number per capitulum due to unfavourable climatic conditions during the stages of flowering and seed filling (Khalil et al., 2013). Mirzakhani et al. (2002) reported a significant decrease in the number of seeds per capitulum when planting was postponed to May 20th rather than sowing on the 19th of April. They concluded that the decrease in seed number per capitulum was due to the exposure of plants to chilling temperatures on late planted safflower (Mirzakhani et al., 2002). The number of seeds per capitulum drastically decreased as the sowing dates were delayed, according to research by Nikabadi et al. (2008) on the impact of sowing dates on the yield and yield components of two safflower types. Ahadi et al. (2011) and Duthion and Pigeaire (1991) reported similar results. In their findings, they explained that high temperatures during late sowing resulted in flower abortion and late pod abscission, thereby reduced seed number per plant (Duthion & Pigeaire, 1991; Ahadi et al. 2011). Khalil et al. (2013) reported that late planting of safflower in Sudan resulted in decreased seed number per capitulum. The decrease in seed number per capitulum in delayed sowing date was attributable to unfavourable climatic conditions during flowering and seed filling stages (Khalil et al., 2013).

2.2.2.4. Thousand seed weight

Al-Doori (2017) reported that delaying planting from either October or November to December in Iraq reduced 1000-seed weight of safflower. The reduction in 1000-seed weight, yield and other yield components was attributed to low chilling temperatures during seed filling stage and shortening of photoperiod (Al-Doori, 2017). In Sudan, late planting of safflower decreased a 1000-seed weight due to unfavourable climatic conditions (high temperatures of above 31°C) during flowering and seed filling stages (Khalil et al., 2013). Ahadi et al. (2011) reported that late planting of safflower on 25th June in Iran, significantly reduced 1000-seed weight. Similar results were reported earlier in Iran by Nikabadi et al. (2008) when they reported that late planting of safflower after 21st March significantly reduced 1000-seed weight. Reduction in 1000-seed weight of safflower due to late planting has been documented by other researchers and the reduction was credited to unfavourable temperature and photoperiod during the seed filling stage (Cazzato et al., 1997; Özel et al., 2004; Dadashi & Khajehpour 2004, Yau, 2007; Mirshekari et al.,2012; Khalil et al., 2013). Safflower is a long day plant, so when grown under short-day conditions, days to physiological maturity increases due to slow growth (Zimmerman, 1972; Dajue & Mündel, 1996; Emongor & Oagile, 2017: Emongor & Emongor). Mirshekari et al. (2012) and Munier and Ney (1998) found that high temperatures during the reproductive phase of grain crops negatively affected cell division and expansion hence a reduction in seed filling rate resulting in decreased seed weight per plant.

2.2.2.5. Dry matter/ Biological yield

Mirshekari et al. (2012) studied the effects of sowing date and water stress from limited irrigation on spring safflower and discovered that planting dates significantly affected dry matter. The results showed that delaying planting date reduced the biological yield due to a shorter development period caused by high temperatures. Similarly, Tayebi et al. (2012) reported that late planted safflower had a lower plant dry weight than early planted safflower in Iran. Alinaghizadeh et al. (2008) reported a significant interaction between genotype and sowing date on biological yield of safflower. Late planting date significantly reduced biological yield of safflower grown in Iran, though influenced by genotype (Alinaghizadeh et al., 2008). In contrast, Bellé et al. (2012) reported dry matter accumulation in safflower was not significantly influenced by planting date in Brazil.

2.2.2.6. Harvest index

Delaying planting date has been reported to decrease safflower harvest index (Ahadi et al., 2011; Mirshekari et al*.,* 2012). In an experiment by Ahadi et al. (2011) on the impact of planting density and date on the development and production of safflower cultivars as a second crop, late planting date significantly decreased the harvest index (HI). Previous literature reported similar results (Alinaghizadeh et al., 2008; Mirshekari et al., 2012). The reduced HI was attributed to an increase in terminal temperature stress throughout grain development which resulted in irregular growth and poor production (Alinaghizadeh et al., 2008; Mirshekari et al., 2012). The highest HI attained on the correct planting date was due to optimum environment temperature which was best for the translocation of photosynthates from source to sink (Alinaghizadeh et al., 2008).

2.2.2.7. Seed yield

Safflower planting date and genotype have been reported to significantly influence seed yield (Zimmerman, 1972; Kaffka & Kearney 1998; Samanci & Ozkaynak, 2003; Nikabadi et al*.,* 2008; Omidi & Sharifmogadas, 2010; Tayebi et al., 2012; Khalil et al., 2013; Torbaghan, 2015; Al-Doori, 2017). Late planting of safflower has been reported to significantly decrease seed yield (Nikabadi et al., 2008; Ahadi et al., 2011; Khalil et al., 2013; Torbaghan, 2015; Al-Doori, 2017). Al-Doori (2017) reported that late planted safflower produced 1,490 kg/ha of seed compared to 1,630 kg/ha in early planted safflower. Similar results were reported by Samanci and Ozkaynak (2003) who found that seed yield was reduced from 1875kg ha^{-1} to 1176 kg ha^{-1} by delayed safflower planting. The decrease in yield was attributed to the obstruction of pollination and fertilization due to high air temperatures at the time of flowering ultimately sinking the final yield (Samanci & Ozkaynak, 2003). Planting safflower early in the cropping season increases seed yield because of high capitulum number per plant, number of seeds per capitulum, and 1000-seed weight mainly due to favourable crop growth conditions which allows a complete physiological maturity of the crop (Mirshekari et al.,2012). Additionally, safflower seed yield generally has been reported to have a direct relationship with length of growth period due to variations in maturation time that can range from 110 to 183 days depending on the genotype, location, planting tie and growing conditions (Tayebi et al., 2012; Moatshe et al., 2016; Moatshe, 2019). High air temperature during the growth of safflower, shortens the time of growth of all the phenological stages of safflower resulting in low seed yield (Mirshekari et al.,2012; Emongor & Oagile, 2017; Emongor et al., 2017; Moatshe et al., 2020). Also in other field crops, early planting results in higher yield potential than late planted crops due to the increased ability to employ resources necessary for growth and development owing to the longer length of the growing period (Richards, 1996; Andrade et al., 2000; Parker et al., 2016).

2.2.3. **Effect of planting date on oil yield and oil content of safflower**

Oil yield is a function of grain yield and grain oil content (Koutroubas et al., 2009; Emongor et al., 2017; Santos et al., 2018; Moatshe, 2019). Several studies have indicated that safflower oil yield had a similar response pattern with that of grain yield irrespective of dependent variables investigated (Sharifmoghaddassi & Omidi, 2009; Emami et al., 2011; Sharifi et al., 2012; Shakeri-Amoghein et al., 2012; Vaghar et al., 2014; Emongor et al., 2017; Sampaio et al., 2017; Moatshe, 2019).

2.2.3.1. Oil content

Oil content is the percentage of oil in safflower seeds, and the sowing date is one of the major factors affecting safflower's oil content and fatty acid composition (Samanci & Ozkaynak, 2003). Several authors have reported that planting date, genotype, and the interaction of genotype and planting date significantly influenced safflower oil content (Çama et al., 2007; Yau, 2007; Alinaghizadeh et al., 2008; Hall, 2016; Oz, 2016; La Bella et al., 2019). Late planting of safflower reduced seed oil content (Samanci & Ozkaynak, 2003; Alinaghizadeh et al., 2008; Oz, 2016; Al-Doori, 2017). Al-Doori (2017) reported that November and December planted safflower had an oil content of 29.2 and 27.8%, respectively. A study by Oz (2016) reported that early planting of safflower in autumn obtained a higher oil content of 27.42% compared to spring planted safflower which had oil seed content of 26.10%. Similarly, in Turkey, Samanci and Ozkaynak (2003) investigated the impact of three planting dates on the seed yield, oil content, and fatty acid composition of three safflower cultivars. They reported that the oil content decreased with delayed planting date from 38.07 to 35.57%. While Jajarmi et al. (2008) reported that was a significant interaction of planting time and genotype on safflower oil content in Iran. Early planted safflower had high seed oil content, irrespective of genotype (Jajarmi et al., 2008). However, Torbaghan (2015) and Zamani and Javadi (2019) reported that planting date had no significant effect on safflower oil content. However, Zamani and Javadi (2019) concluded that early planting (17th October) was the best planting date compared to 1st November 16th November, or 1st December for Birjand region of eastern Iran because all safflower yield components were significantly higher than the other planting dates.

2.2.3.2. Oil yield

Late planting of safflower has been reported to reduce safflower oil yield (Alinaghizadeh et al., 2008; Omidi & Sharifmogada, 2010; Shabana et al., 2013; Al-Doori, 2017). Al-Doori (2017) reported that in Iraq, safflower planted in November and December had an oil yield of 475 and 410 kg/ha, respectively. Shabana et al. (2013) reported that in Egypt, safflower planted on 1st of November 15th November, and 1st December had an oil yield of 186, 182 and 166 kg/ha, respectively. Omidi and Sharifmogadas (2010) reported that planting safflower on 20th September and October had an oil yield of 855 and 736 kg/ha, respectively. Similar results on the reduction of safflower oil yield with late planting is reported in literature (Zakeri, 1996; Koutroubas et al., 2004; Yau, 2007; Alinaghizadeh et al., 2008; Soleymani & Shahrajabian, 2011). Reduction in oil yield was mainly attributed to a decrease in seed yield induced by late planting than oil content (Koutroubas et al., 2004; Yau, 2007; Alinaghizadeh et al., 2008; Mirshekari et al., 2013). Thakare et al. (2018) suggested that increased oil yield during early planting may be influenced by improved root and plant development due to a long, convenient temperature favourable for vegetative and reproductive growth of plants.

2.2.4. **Effect of cultivar and growing season on the development and yield of safflower in Botswana**

In Botswana effects of cultivar and growing season on the general development and growth of safflower have been reported (Emongor et al*.,* 2013; Emongor et al*.,* 2017; Oarabile, 2017; Emongor et al., 2017; Moatshe, 2019). In a study by Moatshe (2019), growing period significantly influenced phenological stages, vegetative growth, yield, and yield components of safflower. Winter grown safflower took longer to reach successive development stages than summer grown safflower. The winter and summer seasons in Botswana, triggered safflower genotypes to attain physiological maturity in 126–147 and 90–116 days, respectively, after planting (Emongor et al., 2013; Emongor et al., 2017; Moatshe, 2019; Moatshe et al., 2020).

Emongor et al. (2013) reported that safflower that was planted in winter had a longer growth cycle, thus translated to extended leaf area duration (LAD) than safflower that was produced in summer, therefore accounts for the increased vegetative development, yield, and yield-related components of the safflower that was grown in winter as opposed to summer. The variation between night and day temperatures (DIF) was thought to be the cause of the variation in safflower plant height due to the growth season (Emongor et al*.,* 2013). Compared to summer (116 days after emergence), winter has a longer maturity time (138 days). As influenced by temperature, winter-grown safflower plants had higher accumulations of dry matter (plant biomass), flower heads per plant, achenes per flower head, and achene weight than summer-grown plants (Emongor et al*.,* 2013).

Literature revealed that there was no known research on the effects of planting date on vegetative growth, yield components, yield and oil content of safflower that has been carried out in SADC countries including Botswana. Internationally results on seed yield, seed oil content and oil yield as influenced by planting date and safflower genotypes were very variable depending on climatic conditions. Majority of literature reported decrease in vegetative growth, yield components, seed yield, seed oil content, and oil yield due to late planting of safflower (Samanci & Ozkaynak, 2003; Yau, 2007; Alinaghizadeh et al., 2008; Jajarmi et al., 2008; Omidi & Sharifmogada, 2010; Shabana et al., 2013; Al-Doori, 2017; Sampaio et al., 2017; Zamani & Javadi, 2019). Other authors reported no effect of planting date on vegetative growth, yield components, yield, seed oil content, and oil yield of safflower (Nikabadi et al*.,* 2008; Bellé et al., 2012; Torbaghan, 2015). Therefore, the current study is important because the climatic conditions of Botswana are different from majority of countries where safflower is grown either as a spring or autumn crop. This current study seeks to generate information on the best planting date for safflower growing bearing in mind of the winter season since some phenological stages of safflower are sensitive to chilling temperatures.

CHAPTER 3 : MATERIALS AND METHODS

3.1. Experimental site

Field studies were conducted at the Botswana University of Agriculture and Natural Resources content farm, located at latitude 24^o 34’, 25” S and longitude 25^o, 58’, 00’’E and 993 m altitude. Planting was done during the 2019/2020 and 2020/2021 growing seasons in summer (December & January) and winter (March & May) under supplemental irrigation (12 mm/day, twice and once a week in summer and winter, respectively). The temperatures recorded during the experimental period ranged from minimum 2.08 to maximum 35°C on average for the months of July and December, respectively. Summer, which often begins in late October and lasts through March or April, is when it rains the most. The soils are medium to coarse grained sandy loams with a limited water retention capacity and low phosphorus levels. They are shallow, ferruginous tropical soils (De Wilt & Nachtengale, 1996). The mean rainfall is 538 mm per annum. The total rainfall received during the experimental period was an average maximum of 136.7 and the minimum 1.1 mm. Extreme temperature swings can be experienced all year long. Temperatures in winter (mid-May to mid-August) can vary from -6.3°C in the morning to 30°C in the afternoon. Temperatures in the summer (mid-September to late mid-May) range from 20°C in the morning to 37°C in the evening (Burgess, 2006; Kolanyane, 2022).

3.2. Experimental Design

A 4 × 4 factorial in randomized blocks with three replications made up the experimental design. The treatments were planting dates (15th December 15th January 15th March 15th May) and safflower genotypes (Sina, PI537636, Gila, and PI527710). Each genotype was planted in 3 m x 3 m plots. The plots were separated by 0.5 m and the blocks by 1 m space. The plant spacing was 40 cm (between rows) x 25 cm (within rows).

3.3. Cultural and Management Practices

The land was cleared and ploughed using a mouldboard then disc harrowed to give the soil a fine tilth. Basal fertilizer application was done at 80 kg N/ha and 20 kg P/ha using the fertilizer formulation 2:3:2. Two seeds of safflower were directly sowed in each hole, and depending on the season, the safflower was thinned 15 to 20 days following emergence. Irrigation was immediately performed then 2 to 3 times a week thereafter to avoid visible symptoms of drought stress. The average water recommendation for safflower depends on the climate and duration period of plant growth and ranges between 600 - 1200 mm (FAO, 2011). All relevant management practices, such as pest, disease, and weed control, were carried out to promote the growth and development of safflower plants. During flowering aphids were controlled using a systemic insecticide (Bandit 350 SC).

3.4. Data Collection

The dependent variables determined were days to flowering, days to maturity, leaf area index, leaf area duration, net assimilation rate, crop growth rate, chlorophyll content, plant height, number of primary branches/plant, number of capitulum/plant, stem diameter, capitulum diameter, number of seeds/capitulum, 1000-seed weight, total dry matter, harvest index, seed yield/ha, oil content, and oil yield.

3.4.1. Plant Phenological stages

3.4.1.1. Days to 50% flowering and physiological maturity

Days to 50% flowering and physiological maturity were determined by recording the number of days from planting to flowering when 50% of plants had flower blossoms and when 80% of the capitula were brown and the stem was dry, respectively. These were determined on 10 tagged plants per experimental unit.

3.4.2. Vegetative growth variables

3.4.2.1. Leaf area index (LAI)

Ten leaves were sampled on ten random plants for each treatment per replicate to determine the average leave area (cm^2) at branch initiation and 50% flowering (DAS). A leaf area meter (Li-3100, Nebraska-USA) was used to measure the leaf area, thereafter, leaf area index (LAI) was calculated as the ratio of the leaf area to the crop ground area.

LAI = Total leaf area of plant/ Ground area occupied by each plant

3.4.2.2. Leaf area duration (LAD)

This was determined according to the method of Hunt (1978):

$$LAD = \frac{LAI_1 + LAI_2}{2} \times (t_2 - t_1)$$

Where: LAI_1 = Leaf area index at branch initiation

LAI_2 = Leaf area index at 50% flowering

t_1 = number of days at branch initiation, t_2 = number of days at 50% flowering

3.4.2.3. Net assimilation rate (NAR)

Was determined by using the formula according to Hunt (1978).

$$NAR\ (gm^{-2}\ day^{-1}) = \frac{TDM}{LAD}$$

Where: TDM is total dry matter and LAD is leaf area duration

3.4.2.4. Crop growth rate (CGR)

Ten whole plants were sampled, and oven dried at 66ºC to constant weight for 72 hours at branch initiation and 50% flowering. Crop growth rate was calculated according to method by Hunt (1978).

$$CGR = \frac{W_2 - W_1}{t_2 - t_1}$$

Where: W_2 and W_1 is total dry weight harvested at branch initiation t_1 and 50% flowering t_2, respectively.

3.4.2.5. Chlorophyll content

Five leaves per plant, from ten randomly selected plants per treatment, were used to calculate the average amount of leaf chlorophyll. A portable chlorophyll meter (Minolta- SPAD-502, Tokyo, Japan) was used to measure the amount of chlorophyll in the leaves. The leaf chlorophyll content was determined at branch initiation and 50% flowering.

3.4.2.6. Plant height (cm)

At 80% flowering, plant height was measured from the ground up using a measuring tape from 10 randomly selected plants per treatment.

3.4.2.7. The number of primary branches

The number of primary branches were determined by counting primary branches from 10 randomly selected plants per treatment.

3.4.3. Yield and yield components

3.4.3.1. Capitula number/plant

The number of capitula were determined by counting the number of capitula per plant from 10 randomly selected plants per treatment.

3.4.3.2. Capitulum diameter (mm)

Capitulum diameter was determined at 50% flowering by measuring the diameter of 10 randomly selected heads per plant on 10 selected plants using a digital vernier calliper.

3.4.3.3. Stem diameter (mm)

Diameter of the stem was determined by measuring stems of 10 randomly selected plants just above the ground using a digital vernier calliper.

3.4.3.4. Number of seeds/Capitulum

Total number of seed in each capitulum were counted from 50 capitula collected from 10 randomly selected plants using a seed counter.

3.4.3.5. 1000-seed weight (g)

Thousand seed weight was determined by counting one thousand seeds (seed count machine) and weighing them using a digital laboratory balance (model 8800- Chicago, USA).

3.4.3.6. Total dry matter (Biological yield)

Biological yield was determined after harvesting by adding seed and dry straw yield.

3.4.3.7. Seed yield

Plants growing in a 4 m^2 area (the plot's centre) provided an estimated amount of seed yield. The sample of seeds was manually threshed and winnowed, and the seed yield per unit area was calculated. A digital laboratory balance (model 8800-Chicago, USA) was used to weigh the seeds.

3.4.3.8. Harvest index

Harvest index was computed by dividing seed yield with biological yield.

3.4.4. Oil content and oil yield

3.4.4.1. Oil content

Oil content was determined using ANKOM, 2009 method.

Seeds were ground using a seed grinder then moisture content was measured. Labelled filter bags were weighed. Then ground samples weighing 2g were put into the bags and weighed(W1). Sample bags with sample were heat sealed and placed in an oven at 100°C for 3 hours then cooled in a desiccator, weighed, and recorded (W2). Sample bags were placed into Teflon Insert and then in the extractor allowing the extraction process to continue for 40 minutes at 90°C. When the extraction process was complete the samples were put in the oven at 90^0C for 30minutes then cooled to room temperature in the desiccator and weighed (W3). The percentage (%) oil content of the samples was calculated as:

$$\% \text{ Oil content} = \frac{100(W_2 - W_3)}{W_1}$$

Where: W1 = original weight of sample W2 = weight of pre-dried sample with the filter bag W3 = weight of dried sample and filter bag after extraction.

Oil content (%) = (Weight of oil extracted/weight of the seed sample) x 100

3.4.4.2. Oil yield (kg ha^{-1})

Oil yield was calculated as a function of grain oil content and grain yield.

3.5. Data analysis

Data collected was subjected to analysis of variance (ANOVA) using linear general model (PROC GLM) procedure of Statistical Analysis System (SAS 9.4) program. Where dependent variables were not significant for year, data was pooled during analysis due to similarity (Snedecor & Cochran, 1989). Where dependent variables were significant for year, data was analysed by year. Multiple comparisons among treatment means were done using Protected Significant Difference (LSD) at P = 0.05.

CHAPTER 4 : RESULTS

4.1. Effect of planting date and genotype on days to flowering and maturity

4.1.1. Days to 50% flowering

In 2019/2020 planting season, planting date and genotype significantly ($P < 0.01$) interacted to influence days to 50% flowering (Figure 1a). Planting safflower in May (delayed planting) significantly ($P < 0.05$) increased days to 50% flowering for all genotypes (Figure 1a). On the contrary early planting (December) significantly ($P < 0.05$) reduced days to 50% flowering of all genotypes (Figure 1a). The genotype Sina took significantly ($P < 0.05$) longer days (74.0-90.7) to reach 50% flowering in all planting dates than other genotypes under study (Figure 1a). On the contrary, the genotype Gila significantly ($P < 0.05$) had shorter days (68-85) to 50% flowering than other genotypes in all planting dates (Figure 1a). The genotypes PI537636 and PI527710 did not significantly ($P > 0.05$) differ in days to 50% flowering in December, March, and May plantings, respectively, in 2019/2020 growing season (Figure 1a). In the 2019/2020 season, the genotypes Sina and PI527710 did not significantly ($P < 0.05$) differ in days to 50% flowering when planted in January (Figure 1a).

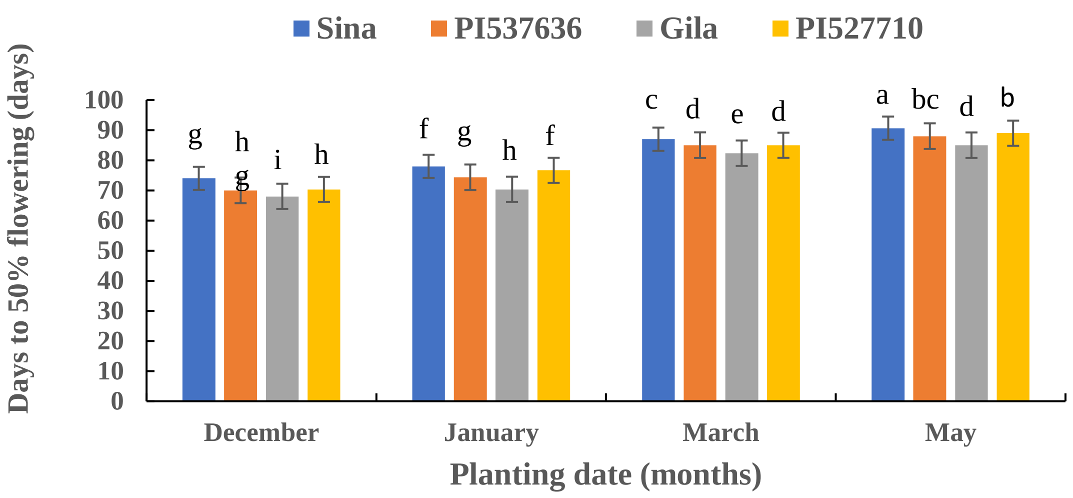

Figure 1a. Effect of planting date and genotype interaction on days to 50% flowering for the growing season 2019/2020; bars are standard error.

Planting date and genotype had no significant ($P > 0.05$) interaction in the 2020/2021 planting season, therefore main effects are reported. Planting date significantly ($P < 0.0001$) influenced days to 50% flowering in 2020/2021 season. Planting safflower in May significantly ($P < 0.05$) increased days to 50% flowering (131.58) than other planting dates in the study in 2020/2021 season (Figure 1b). On the contrary, safflower planted in December (early planting) significantly ($P < 0.05$) took the fewest days to 50% flowering (66.58) than any other planting date in the study (Figure 1b). Delayed planting significantly ($P < 0.05$) increased days to 50% flowering (Figure 1b). Safflower planted in December, January, March, and May took significantly ($P < 0.05$) 66.6, 73.8, 117.2 and 131.6 days to 50% flowering respectively, in 2020/2021 season (Figure 1b).

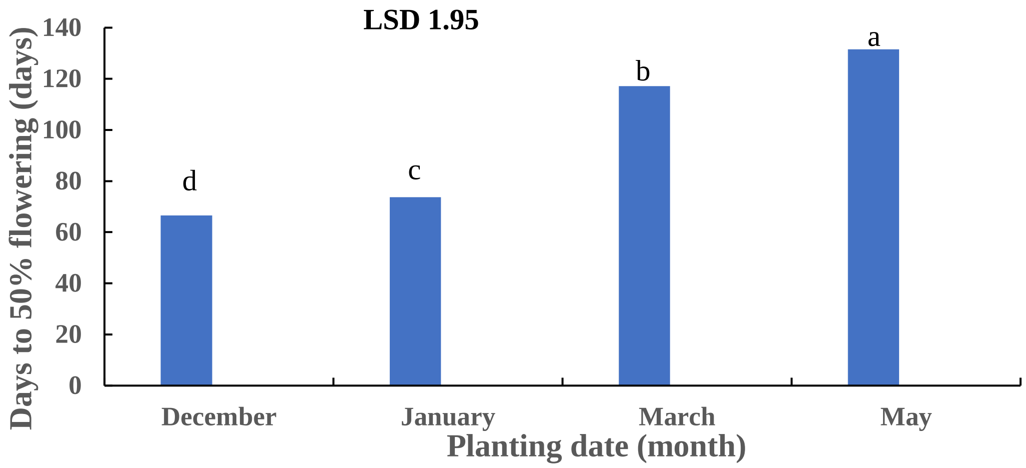

Figure 1b. Effect of planting date on the days to 50% flowering of safflower for the growing season 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

Genotype had a significant (P < 0.0001) influence on days to 50% flowering in 2020/2021 season (Figure 1c). The genotype Sina took significantly (P < 0.05) more days (101 days) to reach 50% flowering than other genotypes in the study in 2020/2021 season (Figure 1c). On the contrary, the genotypes Gila (93.8 days) and PI527710 (95.7 days) took significantly (P < 0.05) fewer days to reach 50% flowering than the genotypes Sina and PI537636 (Figure 1c). However, the genotypes Gila and PI5227710 did not significantly (P > 0.05) differ in the number of days they took to reach 50% flowering (Figure 1c).

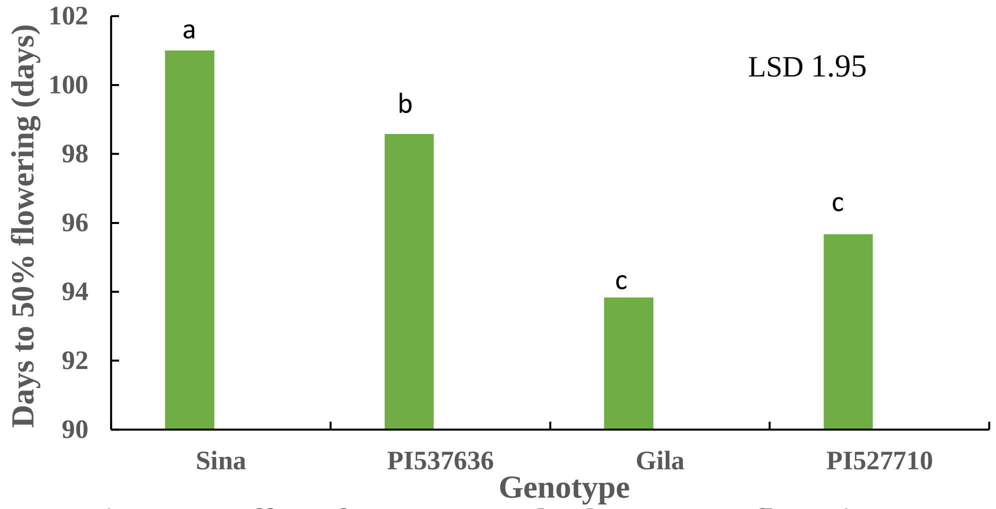

Figure 1c. Effect of genotype on the days to 50% flowering of safflower for the growing season 2020/2021

4.1.2. Days to physiological maturity

Planting date and genotype significantly ($P < 0.01$) interacted to influence days to physiological maturity in 2019/2020 growing season (Figure 2a). Days to physiological maturity was increased significantly ($P < 0.05$) when safflower planting was delayed (May) for all genotypes. (Figure 2a.). On the other hand, early planting (December) significantly ($P < 0.05$) shortened days to physiological maturity of all genotypes ($P < 0.05$) (Figure 2a.). Across all planting dates, the genotype Sina took significantly (P 0.05) more days than other genotypes under study to reach physiological maturity (100.7-130.7) (Figure 2a). On the contrary, the genotype Gila significantly ($P < 0.05$) took fewer days (96.3-119.7) to reach physiological maturity than other genotypes in all planting dates (Figure 2a). Generally, planting after December (delayed planting) significantly ($P < 0.05$) increased days to physiological maturity of all genotypes under study (Figure 2a). The genotypes PI537636, Gila and PI527710 did not significantly ($P > 0.05$) differ in days (96.3-97.7) to reach physiological maturity in December planting in 2019/2020 growing season but were significantly ($P < 0.05$) fewer than days that the genotype Sina (100.7) took to reach physiological maturity (Figure 2a). All genotypes of safflower planted in March and May of 2019/2019 planting season significantly (P < 0.05) varied in their days to reach physiological maturity (Figure 2a). However, in March and May planting, the genotypes PI527710 (120.3 days) and Gila (119.7) did not significantly (P > 0.05) vary in their days to reach physiological maturity (Figure 2a).

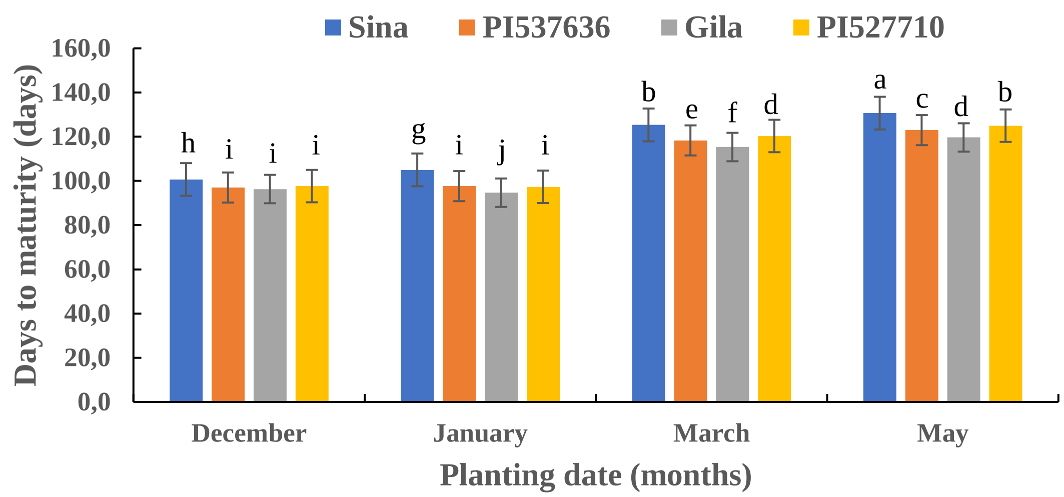

Figure 2a. Effect of planting date and genotype interaction on days to physiological maturity for the growing season 2019/2020; bars are standard error.

Planting date and genotype had no significant (P > 0.05) interaction in the 2020/2021 planting season, therefore main effects are reported. Planting date significantly (P < 0.0001) influenced days to physiological maturity in the 2020/2021 growing season (Figure 2b). Planting safflower in May significantly (P < 0.05) increased (163.3) days to physiological maturity in 2020/2021 season (Figure 2b). On the contrary, safflower planted in December significantly (P < 0.05) took fewer days (94.2) to physiological maturity than any other planting date (Figure 2b). Safflower planted in January and March took 100.6 and 146.2 days to reach physiological maturity but were significantly (P < 0.05) different (Figure 2b). Delayed planting significantly (P < 0.05) increased days to physiological maturity while early planting reduced days to maturity (Figure 2b).

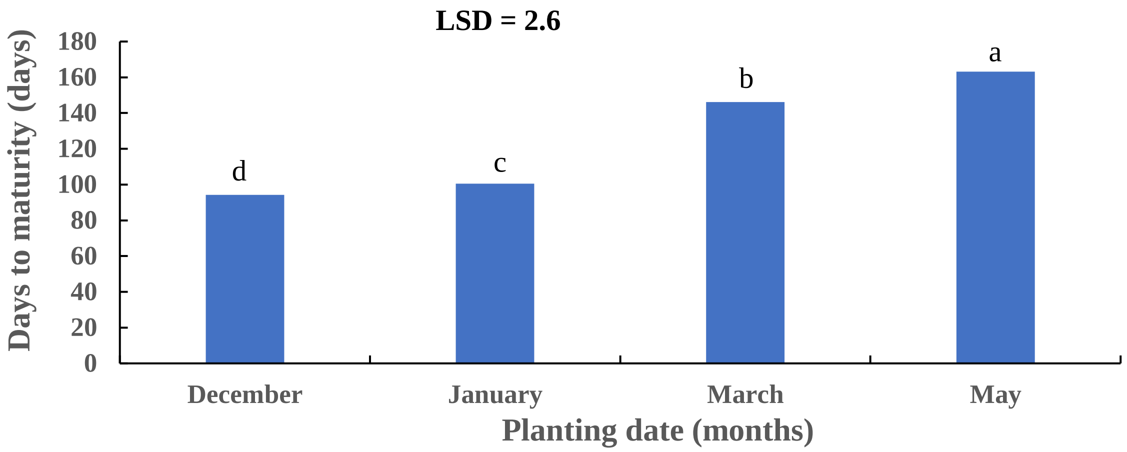

Figure 2b. Effect of planting date on the days to physiological maturity of safflower for the growing season 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

In 2020/2021 growing season, there were significant ($P < 0.0001$) genetic variations on days to physiological maturity (Figure 2c). The genotype Sina took significantly ($P < 0.05$) more days (131.1 days) to reach physiological maturity than other genotypes in 2020/2021 growing season (Figure 2c). On the contrary, the genotypes PI537636 (123.2 days) and PI527710 (122.3 days) took significantly ($P < 0.05$) fewer days than genotypes Sina and Gila (127.6 days) to reach physiological maturity but no significant ($P > 0.05$) variation was observed in days to physiological maturity between them (Figure 2c).

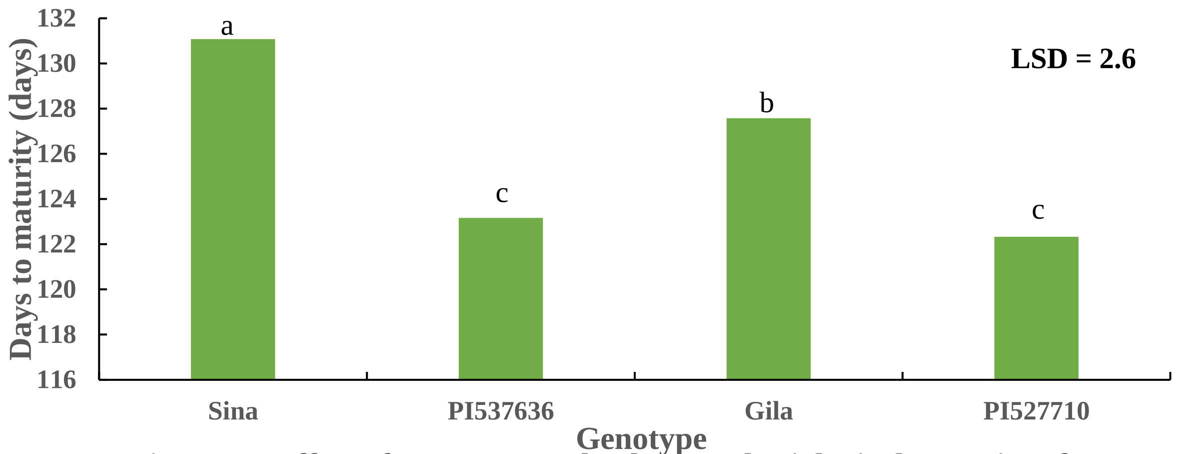

Figure 2c. Effect of genotype on the days to physiological maturity of safflower for the growing season 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

4.2. Effect of planting date and genotype on vegetative growth

4.2.1. Leaf area index (LAI)

Planting date and genotype had a significant ($P < 0.01$) interaction on leaf area index (LAI) of safflower (Figure 3). Leaf area index of safflower significantly ($P < 0.5$) increased with delayed planting in all genotypes (Figure 3). Safflower planted in May (delayed planting) had significantly ($P < 0.05$) higher LAI in all genotypes than any other planting date (Figure 3). The genotype Sina had significantly ($P < 0.05$) higher LAI in all planting dates than other genotypes irrespective of planting date (Figure 3). On the contrary, the genotype Gila had the lowest LAI in all planting dates compared to other genotypes (Figure 3). The genotype Sina planted in May had significantly ($P < 0.01$) the highest LAI 3.94 compared to all other genotypes planted in different dates (Figure 3). On the contrary, the genotype Gila planted in December had significantly ($P < 0.05$) the lowest LAI of 1.21 compared to other genotypes in all planting dates (Figure 3).

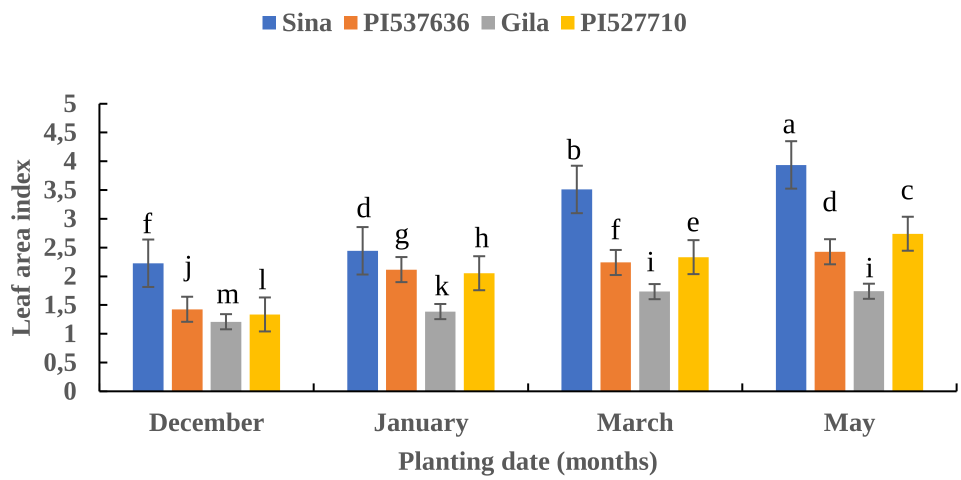

Figure 3. Effect of planting date and genotype interaction on leaf area index ; bars are standard error.

4.2.2. Leaf area duration (LAD)

Leaf area duration (LAD) was significantly ($P < 0.0001$) influenced by the interaction of planting date and genotype. Leaf area duration was significantly ($P < 0.05$) increased by delayed planting in all genotypes (Figure 4). Safflower planted in May had significantly ($P < 0.05$) higher LAD in all genotypes than other planting dates (Figure 4). The genotype Sina had significantly ($P < 0.05$) higher LAD than other genotypes across all planting dates (Figure 4). On the contrary, the genotype Gila had significantly ($P < 0.05$) the lowest LAD compared to other genotypes across all planting dates (Figure 4). The genotype Sina planted in May had significantly ($P < 0.05$) the highest LAD of 183.1 days compared to other genotypes in all planting dates (Figure 4). On the contrary, the genotype Gila planted in December had significantly ($P < 0.05$) the lowest LAD of 15.6 days compared to other genotypes in all planting dates (Figure 4).

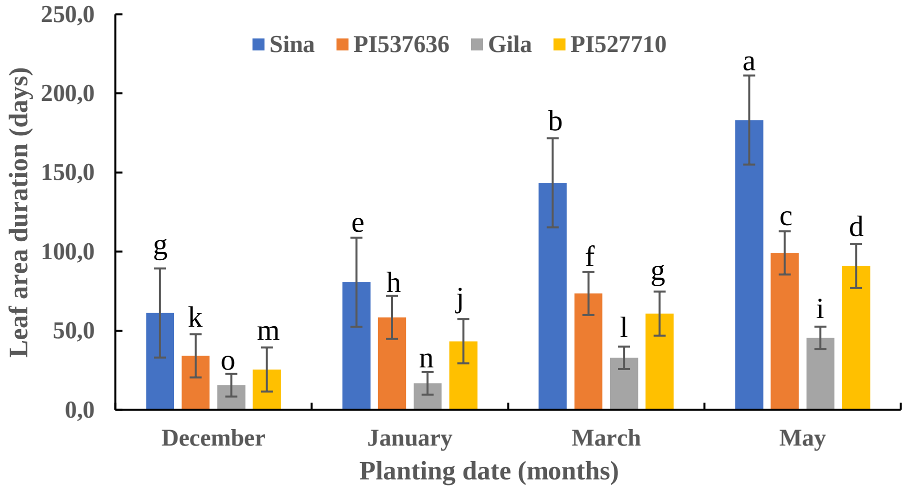

Figure 4. Effect of planting date and genotype interaction on leaf area duration ; bars are standard error.

4.2.3. Net assimilation rate (NAR)

The interaction of planting date and genotype significantly ($P < 0.0001$) influenced net assimilation rate (NAR) of safflower plants. Planting safflower in May significantly ($P < 0.05$) increased NAR of safflower plants while March planting significantly ($P < 0.05$) lowered NAR compared to other planting dates (Figure 5). The genotype Sina planted in May had significantly ($P < 0.05$) a higher NAR of 2.38 g m^{-2} day^{-1} than NARs of other genotypes in all planting dates (Figure 5). On the contrary, the genotype Gila planted in March had the lowest NAR of 0.10 g m^{-2} day^{-1} than other genotypes in all planting dates (Figure 5). Genotype PI527710 had significantly ($P < 0.05$) higher NAR than genotype PI537636 in December, January, and March, but did not significantly ($P > 0.05$) differ in NAR in March planting (Figure 5).

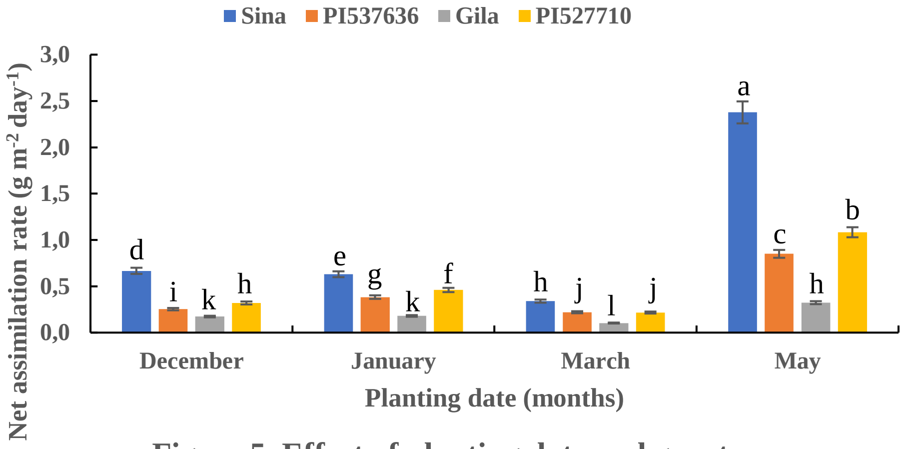

Figure 5. Effect of planting date and genotype interaction on net assimilation rate ; bars are standard error.

4.2.4. Crop growth rate (CGR)

Planting date and genotype significantly ($P < 0.0001$) interacted to influence crop growth rate (CGR) of safflower plants. All safflower genotypes planted in May had significantly ($P < 0.05$) higher CGRs than all other planting dates (Figure 6). On the contrary, all genotypes planted in March had significantly ($P < 0.05$) the lowest CGRs compared to other planting dates (Figure 6). The genotype Sina planted in May had significantly ($P < 0.05$) higher CGR of 7.35 g m^{-2} day^{-1} than that of other genotypes planted in different dates (Figure 6). The genotype Gila had significantly ($P < 0.05$) the lowest CGR than other genotypes in all planting dates (Figure 6). Genotypes PI537636 and PI527710 did not significantly ($P < 0.05$) differ in crop growth rate in December and March plantings (Figure 6).

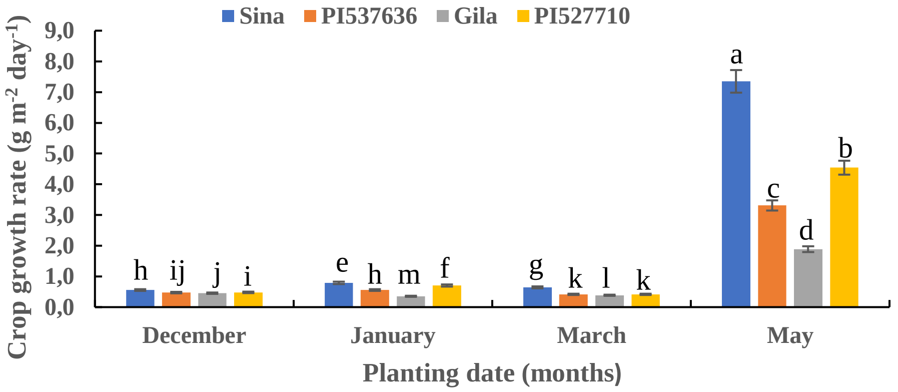

Figure 6. Effect of planting date and genotype interaction on crop growth rate ; bars are standard error

4.2.5. Leaf chlorophyll content

There was a significant ($P < 0.0001$) interaction between planting date and genotype as they influenced leaf chlorophyll content of safflower plants. The genotype Sina planted in all planting dates had significantly ($P < 0.05$) the highest chlorophyll content than other genotypes planted in different planting dates (Figure 7). On the contrary, the genotype Gila had significantly ($P < 0.05$) the lowest leaf chlorophyll content than other genotypes in all planting dates (Figure 7). The genotype Sina planted in January had significantly ($P < 0.05$) the highest leaf chlorophyll content of 69.6 µg cm^{-2} compared other genotypes in all planting dates (Figure 7). While the genotype Gila planted in May had significantly ($P < 0.05$) the lowest leaf chlorophyll content of 47.9 µg cm^{-2} compared to other genotypes in all planting dates (Figure 7). Genotype PI527710 had significantly ($P < 0.05$) higher leaf chlorophyll content than genotype PI537636 in December and January plantings (Figure 7). While in March and May plantings genotype PI537636 had significantly ($P < 0.05$) higher leaf chlorophyll content than genotype PI527710 (Figure 7).

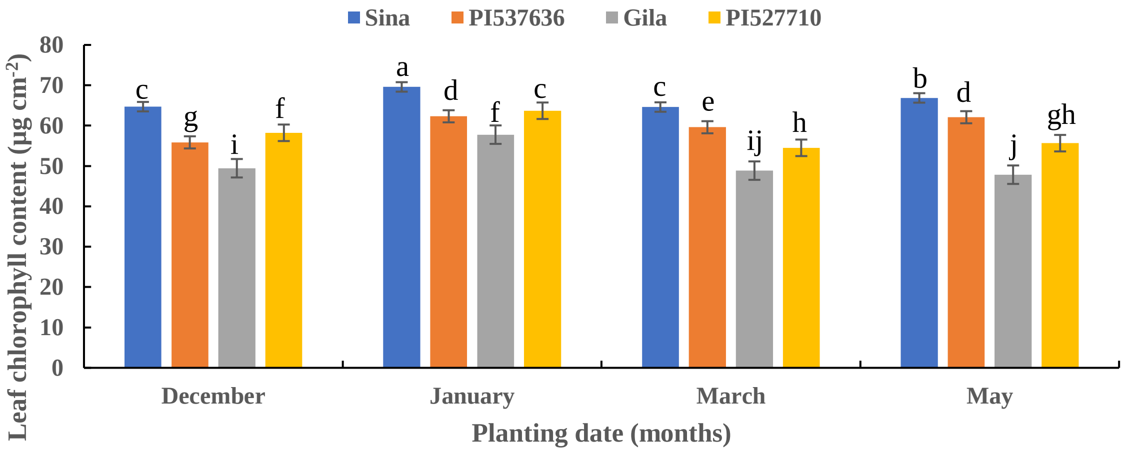

Figure 7. Effect of planting date and genotype interaction on chlorophyll content ; bars are standard error

4.2.6. Plant height

There was no significant ($P > 0.05$) interaction of planting date and genotype on safflower plant height. Planting date significantly ($P < 0.0001$) influenced plant height (Figure 8a). Delayed planting (May) significantly ($P < 0.05$) increased safflower plant height while early planting (December) significantly ($P < 0.05$) reduced plant height (Figure 8a). May and March planting significantly ($P < 0.05$) increased plant height compared to other planting dates (94 cm) and (92 cm), respectively but did not significantly ($P > 0.05$) differ in their influence on safflower plant height (Figure 8a). Planting safflower in December significantly ($P < 0.05$) produced plants that were shorter (55 cm) than other planting dates (Figure 8a). Safflower planted in January produced plants which were significantly ($P < 0.05$) taller than December planting (Figure 8a).

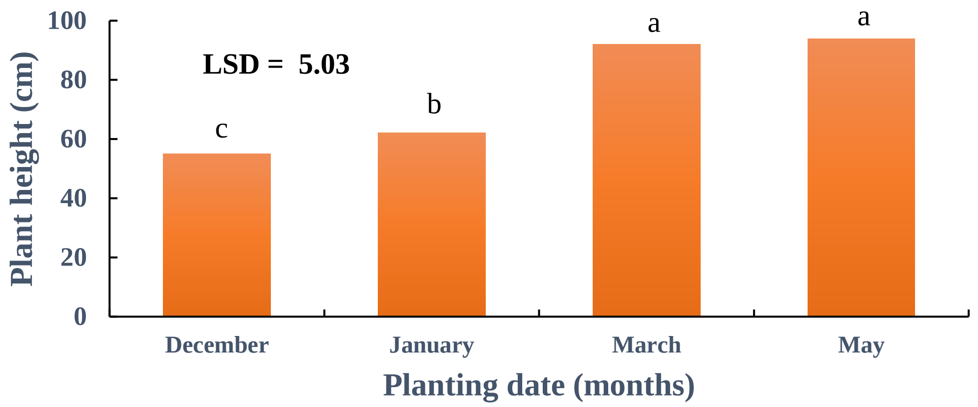

Figure 8a. Effect of planting date on safflower plant height for the combined growing seasons 2019/2020 and 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

There was significant (P < 0.05) genotypic variation in safflower plant height. The genotype Sina had significantly (P < 0.05) taller plants (80 cm) than other genotypes with exception for the genotype Gila (75cm) (Figure 8b). Genotypes PI537636 (73 cm) and PI527710 (75 cm) had significantly (P < 0.05) shorter plants than the genotype Sina, but their plant height did not statistically differ with each other and Gila (Figure 8b).

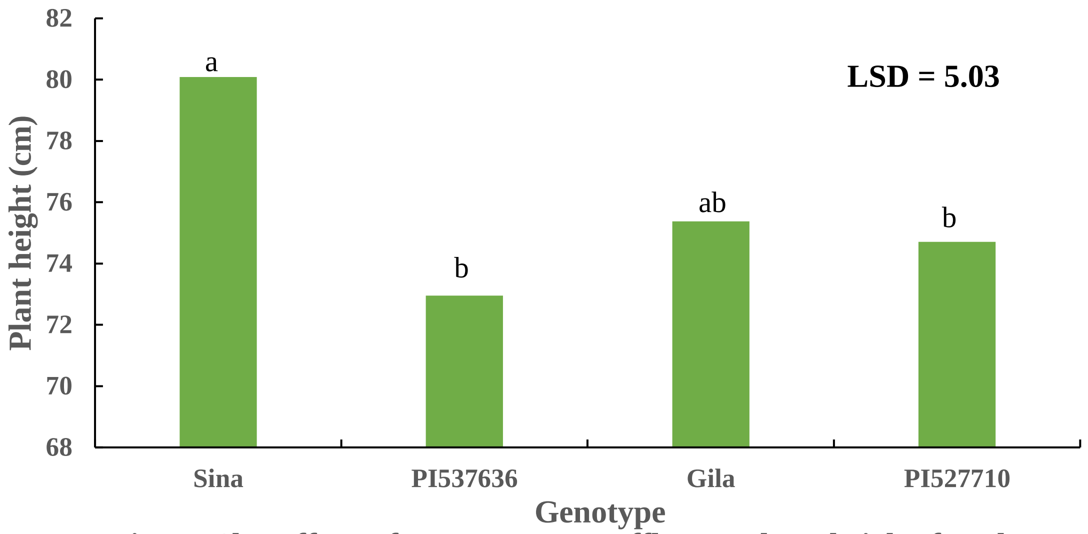

Figure 8b. Effect of genotype on safflower plant height for the combined growing seasons 2019/2020 and 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

4.2.7. Primary branch number

There was no significant (P > 0.05) interaction between planting date and genotypes on primary branch number. Planting date significantly (P < 0.0001) influenced primary branch number/plant of safflower (Figure 9a). Primary branch number/plant increased as the planting date was delayed from December to May (Figure 9a). Planting safflower in May produced plants that had significantly (P < 0.05) higher number of primary branches/plant (11.4) than any other planting dates (Figure 9a). On the contrary, planting safflower in December significantly (P < 0.05) produced plants with fewer number of primary branches/plant than any other planting dates (Figure 9a).

Genotype had a significant (P < 0.0001) influence on primary branch number/plant. The genotype Sina had significantly (P < 0.05) higher branch number/plant of 10.4 than other genotypes in the study (Figure 9b). Genotypes PI537636, Gila and PI527710 had 9.0, 9.3 and 9.3 branch number/plant, respectively which were not significantly (P > 0.05) different (Figure 9b).

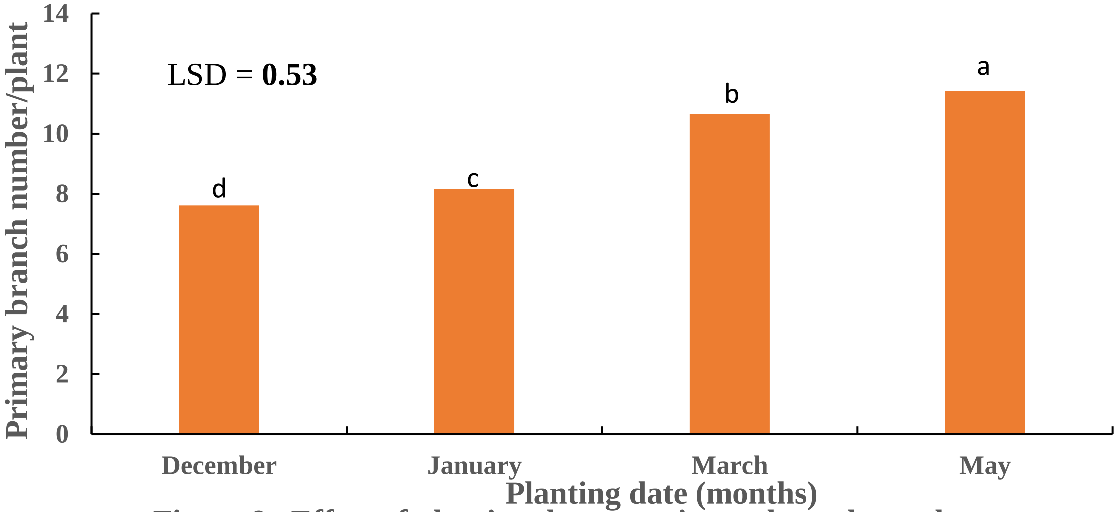

Figure 9a Effect of planting date on primary branch number per safflower plant for the combined growing seasons 2019/2020 and 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

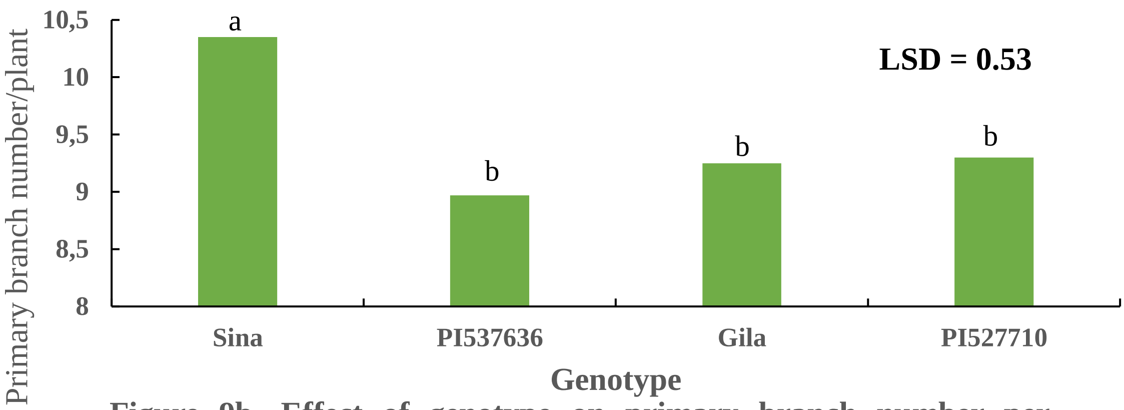

Figure 9b. Effect of genotype on primary branch number per safflower plant for the two growing seasons 2019/2020 and 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

4.3. Effect of planting date and genotype on yield components and yield

4.3.1. Stem diameter (mm)

The growing season and planting date had a significant ($P < 0.0001$) influence on the stem diameter. During the 2019/2020 planting season, safflower plants grown in May had significantly ($P < 0.05$) thicker stem diameter of 12.9 mm than other planting dates (Figure

10a). On the contrary, December planting significantly (P < 0.05) reduced stem diameter (7.6 mm) (Figure 10a). However, safflower planted in January and March in the 2019/2020 growing season had stem diameter of 8.7 and 8.6 mm which did not significantly (P > 0.05) differ (Figure 10a). Also, safflower planted in December and March 2019/2020 growing season did not significantly (P > 0.05) in their stem diameters (Figure 10a).

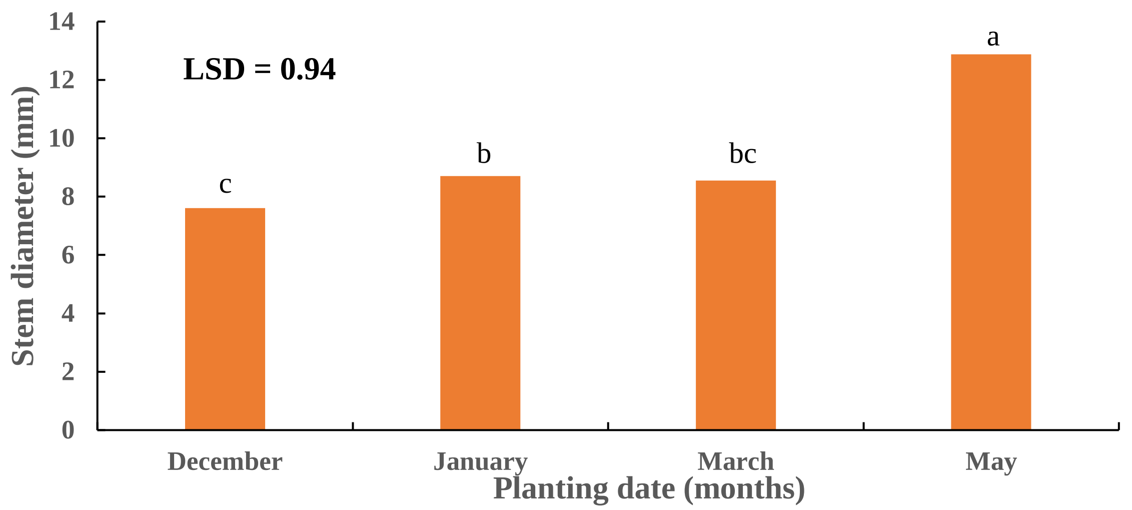

Figure 10a. Effect of planting date on the stem diameter of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

In 2020/2021 growing season, safflower planted in May significantly (P < 0.05) produced plants with thicker stem diameters of 10.6 mm than other planting dates (Figure 10b). December and January safflower plantings did not significantly (P > 0.05) differ in their stem diameters of 7.5 and 7.8 mm respectively but were significantly (P < 0.05) thinner than safflower planted in March and May 2020/2021 growing season (Figure 10b).

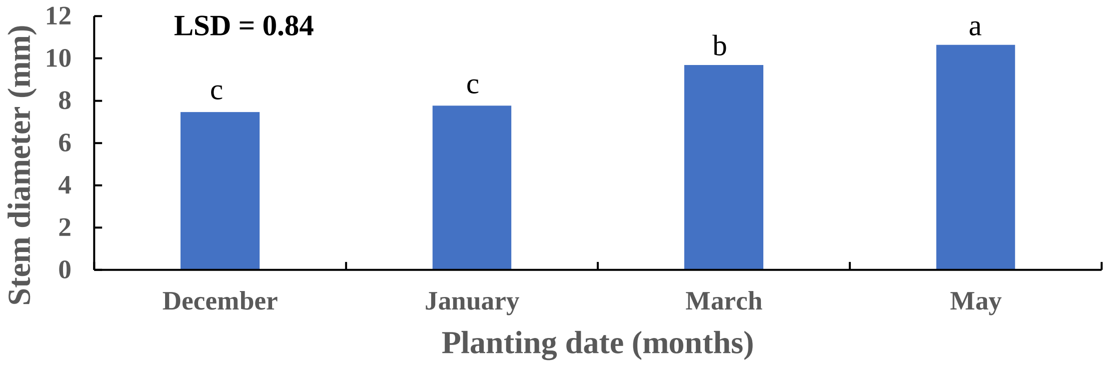

Figure 10b. Effect of planting date on the stem diameter of safflower for the growing season 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

There was significant (P < 0.05) genotypic variation with respect to safflower stem diameter in 2019/2020 growing season (Figure 10c). In the 2019/2020 planting season, the genotype Sina had plants with significantly (P < 0. 05) thicker stem diameters of 10.1 mm than plants from the genotypes PI537636 and Gila which had plants with stem diameters of 9.1 mm (Figure 10c). However, plants from the genotypes PI57636, Gila, and PI527710 did not significantly (P > 0.05) differ in their stem diameters in 2019/2020 growing season (Figure 10c). In the 2020/2021 growing season there was no significant (P > 0.05) genotypic variation with respect to safflower stem diameters among plants (Figure 10d). However, plants from the genotype Sina had non-significant (P > 0.05) thicker stem diameters of 9.4 mm than genotypes PI527710, PI57636, and Gila which had stem diameters of 8.9, 8.7, and 8.6 mm, respectively (Figure 10d).

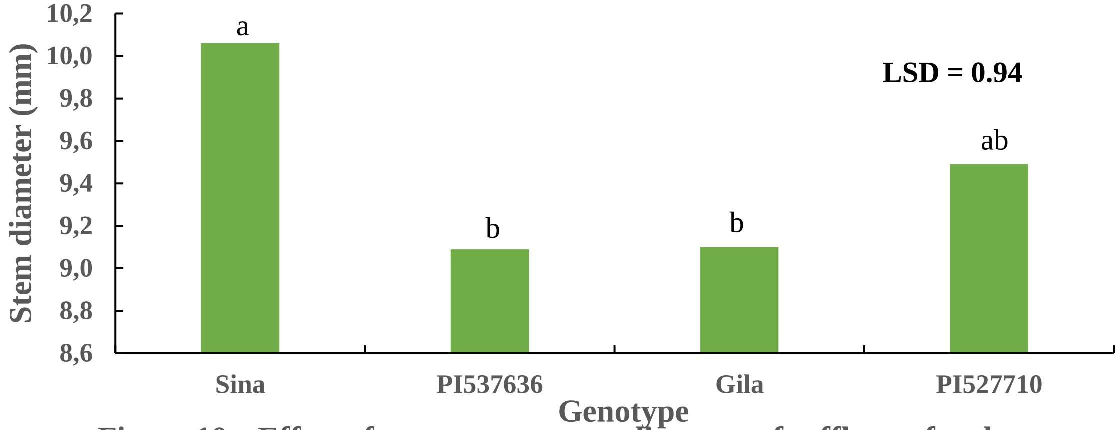

Figure 10c. Effect of genotype on stem diameter of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

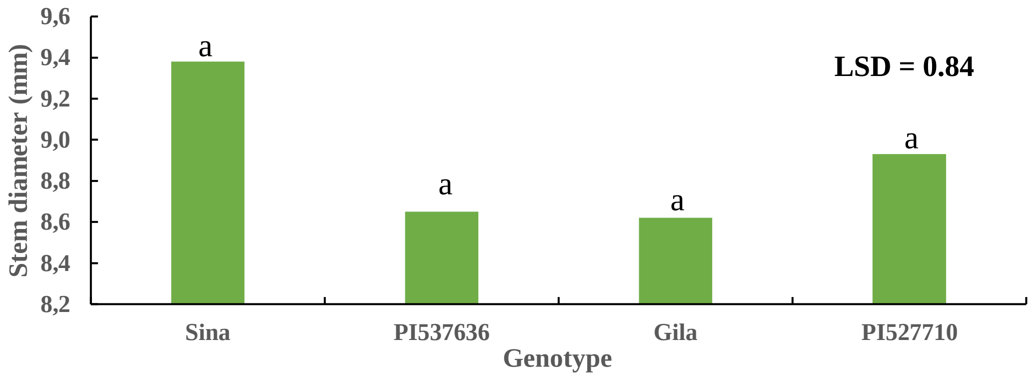

Figure 10d. Effect of genotype on the stem diameter of safflower for the growing season 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

4.3.2. Capitulum diameter (mm)

Planting date had a significant ($P < 0.0001$) influence on capitulum diameter for both seasons. Delayed planting in May in both 2019/2020 and 2020/2021 growing seasons produced safflower plants with significantly ($P < 0.05$) larger capitulum diameter of 39.9 and 42.4 mm, respectively than other planting dates (Figure 11a, b). In both planting seasons, safflower planted in March had significantly ($P < 0.05$) smaller capitula diameter of 29.8 and 29.6 mm, respectively than other planting dates (Figure 11a, b). In 2019/2020 growing season, safflower planted in December and January did not differ in their capitula diameters (Figure 11a). However, in the 2020/2021 growing season, safflower planted in January resulted with plants which had significantly (P < 0.05) larger capitula diameter of 39.6 mm than December planting which produced plants with capitula diameter of 36.1 mm (Figure 11b).

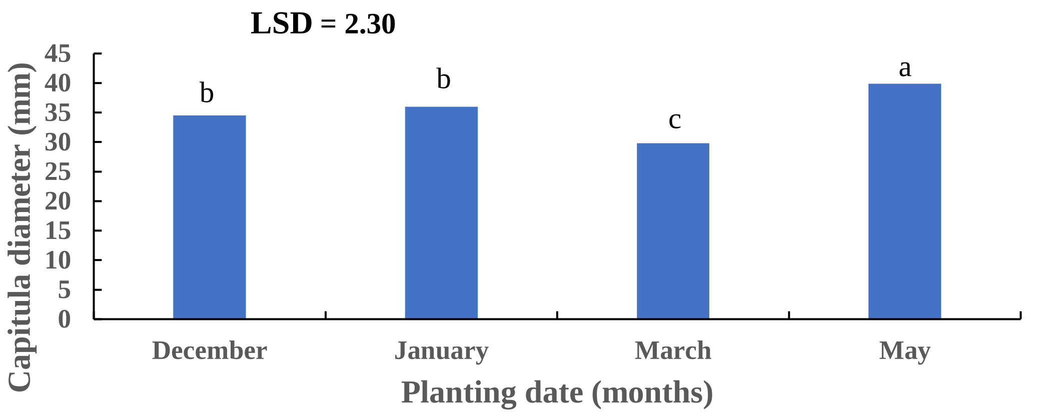

Figure 11a. Effect of planting date on capitula diameter of safflower for the growing seasons 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

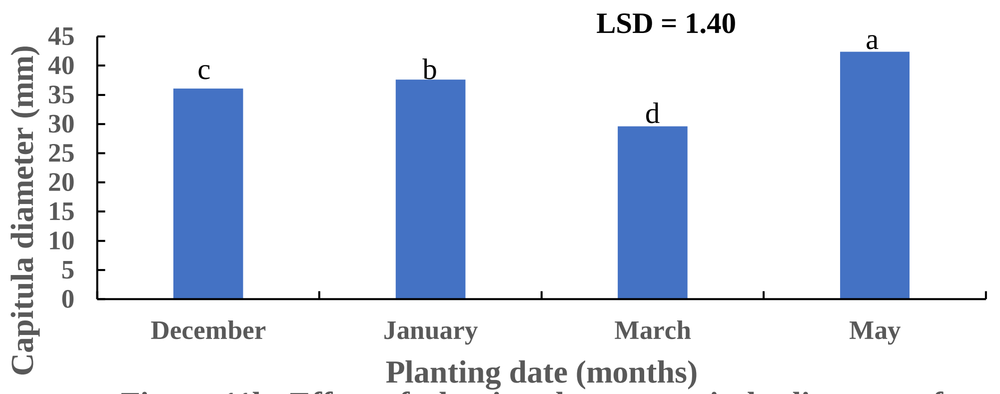

Figure 11b. Effect of planting date on capitula diameter of safflower for the growing seasons 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

In 2019/2020 planting season, there was no genotypic variation of safflower capitula diameter (Figure 11c). However, in the 2020/2021 growing season, there was significant ($P < 0.05$) genotypic variation with respect to capitula diameter (Figure 11d). In 2019/2020 growing season, the genotype Sina had plants with significantly ($P < 0.05$) larger capitula diameter of 38.8 mm than the genotypes PI537636, Gila, and PI527710 which had capitula diameters of 35.5, 35.2, and 36.2 mm, respectively (Figure 11d). The capitula diameter of the genotypes PI537636, Gila and PI527710 did not significantly ($P > 0.05$) vary in 2020/2021 growing season (Figure 11d).

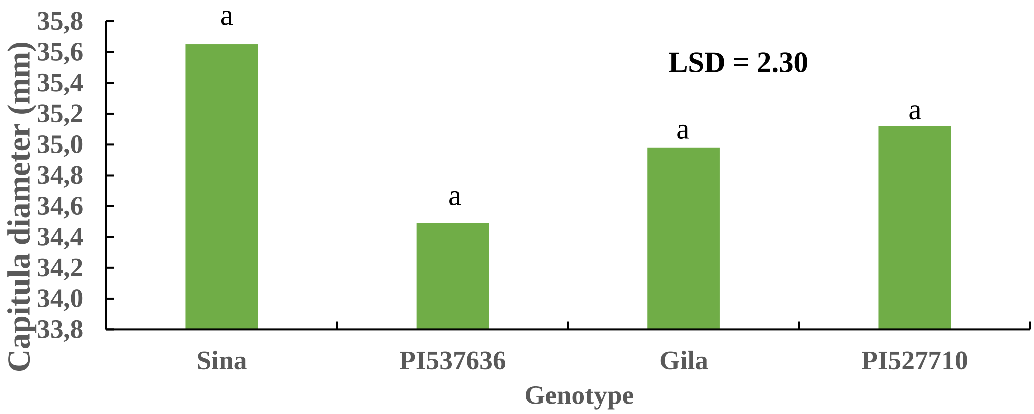

Figure 11c. Effect of genotype on capitula diameter of safflower for the growing season 2019/2020. Means separated by the LSD at $P < 0.05$; means followed by the same letter(s) are not significantly different.

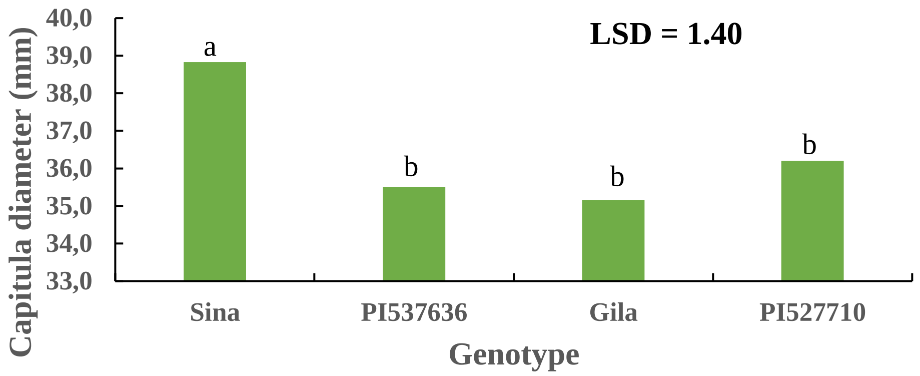

Figure 11d. Effect of genotype on capitula diameter of safflower for the growing season 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

4.3.3. Capitula number per plant

Planting date had a significant (P < 0.0001) influence on capitula number per plant. Safflower capitula number per plant increased and reduced with delayed and early planting, respectively (Figure 12a). Planting safflower in May produced plants that significantly (P < 0.05) had higher number of capitula per plant of 51 than planting in December, January, and March which produced plants with capitula number per plant of 39, 45, and 30, respectively (Figure 12a).

Genotype had a significant (P < 0.0001) influence on capitula number per plant. The genotype Sina had plants with significantly (P < 0.05) higher capitula number per plant of 48 than other genotypes (Figure 12b). The genotypes PI537636 and PI527710 had 40 and 42 number of capitula per plant, respectively and were not significantly (P > 0.05) different from each other but were significantly (P < 0.05) higher than the capitula number per plant (36) of the genotype Gila (Figure 12b).

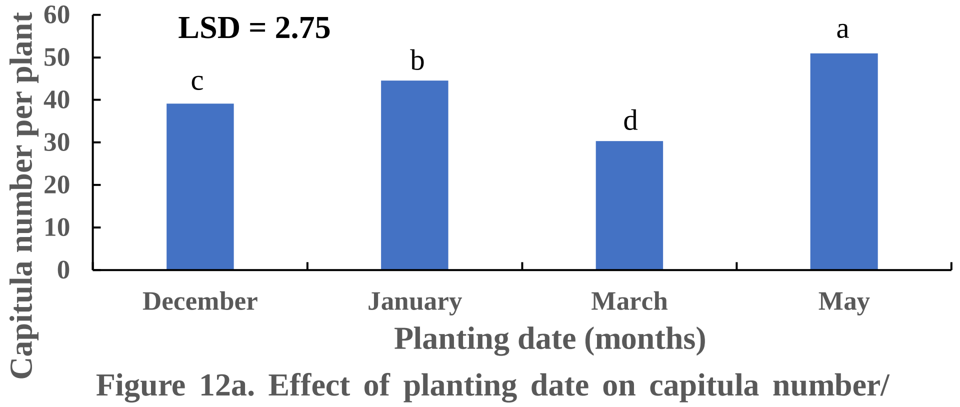

Figure 12a. Effect of planting date on capitula number/ plant of safflower for the growing seasons 2019/2020 and 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

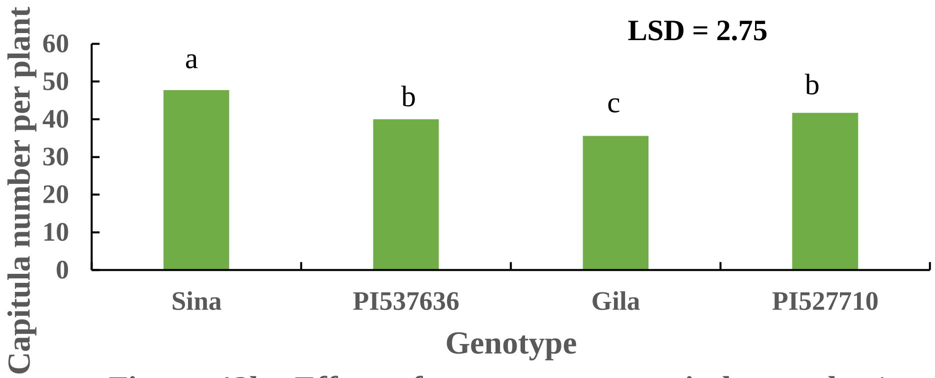

Figure 12b. Effect of genotype on capitula number/ plant of safflower for the growing seasons 2019/2020 and 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

4.3.4. Seed number per capitulum

Planting date and genotype significantly ($P < 0.0001$) interacted to influence seed number per capitulum in 2019/2020 and 2020/2021 growing seasons. Seed number per capitulum significantly ($P < 0.05$) increased with delayed planting in May depending on genotype in 2019/2020 and 2020/2021 growing seasons, with exception of March planting (Figure 13a, b). Irrespective of growing season and planting date, the genotype Sina had plants with significantly ($P < 0.05$) higher seed number per capitulum than genotypes PI537636, PI527710, and Gila (Figure 13a, b). On the contrary, in both seasons, the genotype Gila had plants with significantly (P < 0.05) lower seed number per capitulum than other genotypes under study in all planting dates (Figure 13a, b). The genotype PI527710 had plants with significantly (P < 0.05) higher seed number per capitulum than the genotypes Gila and PI537636, irrespective of planting date and growing season (Figure 13a, b).

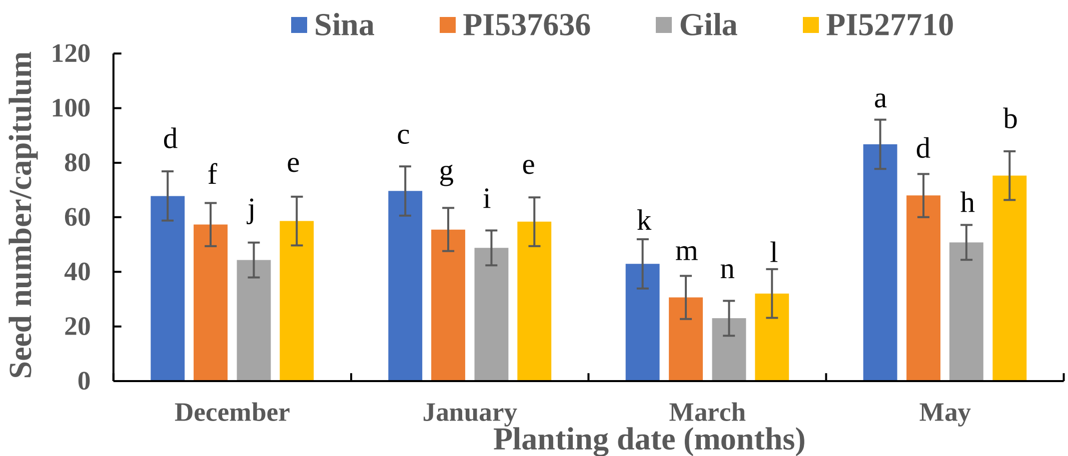

Figure 13a. Effect of planting date and genotype interaction on seed number/capitulum for the 2019/2020 season ; bars are standard error

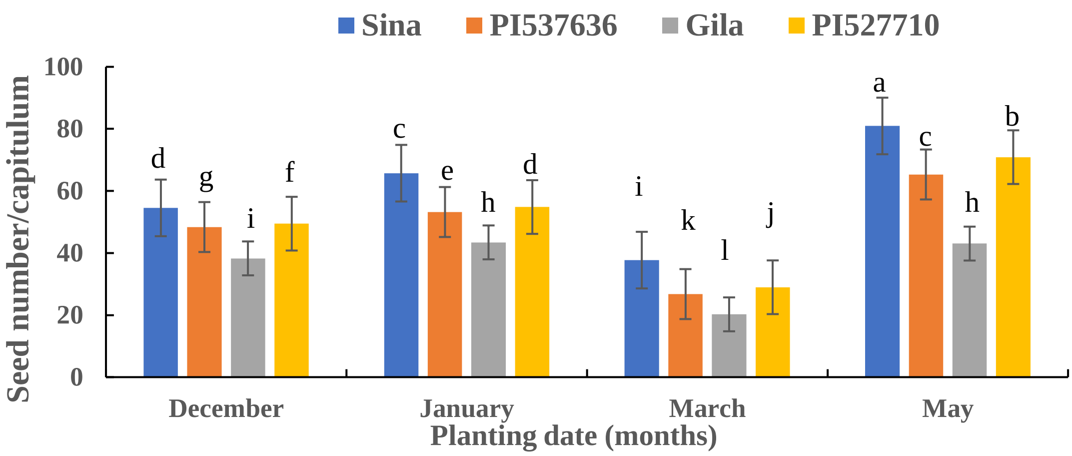

Figure 13b. Effect of planting date and genotype interaction on seed number/capitula for the 2020/2021 season; bars are standard error.

4.3.5. Thousand (1000-seed) weight

Planting date and genotype had no significant (P > 0.05) interaction in the 2019/2020 planting season, therefore main effects are reported. Planting date significantly (P < 0.0001) influenced 1000-seed weight in 2019/2020 season. Planting safflower in May significantly (P < 0.05) produced plants with higher 1000-seed weight of 34.3 g than safflower planted in December, January, or March of 2019/2020 growing season (Figure 14a). On the contrary, safflower planted early in December had significantly (P < 0.05) lower 1000-seed weight of 28.2 g) than safflower planted in March and May but did not significantly (P > 0.05) with 1000-seed weight (30 g) of safflower planted in January of 2019/2020 growing season (Figure 14a).

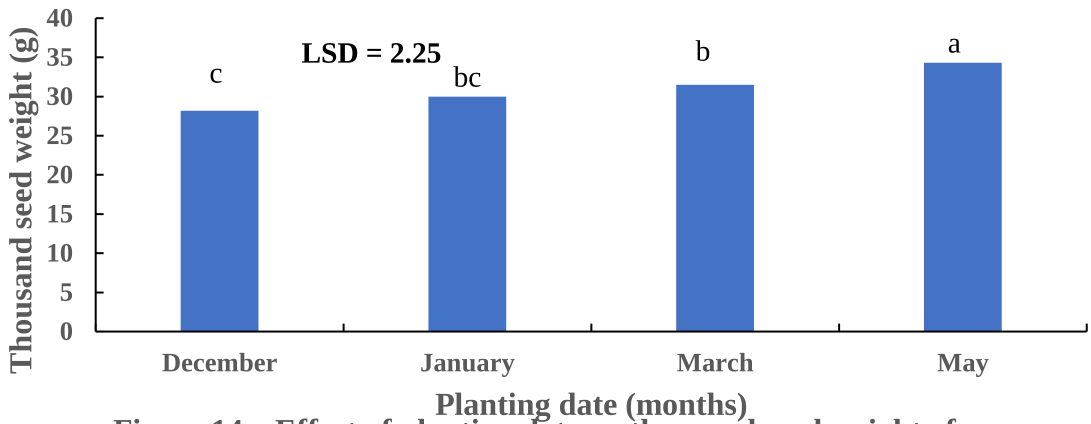

Figure 14a. Effect of planting date on thousand seed weight of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

Genotype had a significant (P < 0.0001) influence on 1000-seed weight in 2019/2020 growing season. The genotype Sina had plants that produced significantly (P < 0.05) plants with higher 1000-seed weight of 35.1 g than other genotypes in the study in 2019/2020 season (Figure 14b). On the contrary, the genotype Gila produced plants that had significantly (P < 0.05) lower 1000-seed weight of 25.5 g than other genotypes used in the current study in 2019/2020 growing season (Figure 14b). Genotypes PI537636 and PI527710 had 1000-seed weight of

31.69 and 31.8 g, respectively which did not differ significantly (P > 0.05) from each other, but significantly (P < 0.05) higher than the 1000-seed weight of the genotype Gila in 2019/2020 growing season (Figure 14b).

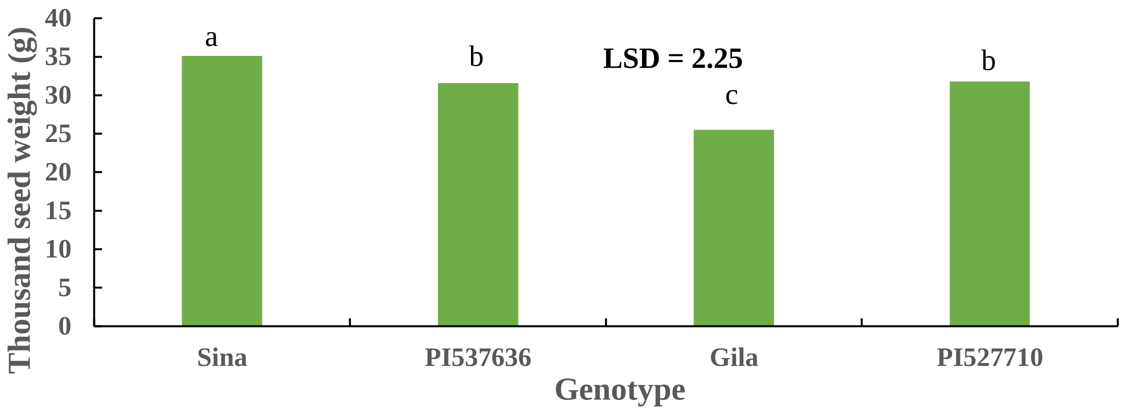

Figure 14b. Effect of genotype on thousand seed weight of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

There was a significant (P < 0.0001) influence of planting date and genotype interaction on thousand seed (1000-seed) weight of safflower grown in 2020/2021 season. The genotype Sina interacted with all planting dates in the 2020/2021 growing season to produce plants with significantly (P < 0.05) the highest 1000-seed weight than other genotypes irrespective of planting date (Figure 14c). The genotype Sina planted in May of 2020/2021 growing season produced plants with significantly (P < 0.05) higher 1000-seed weight of 41.7 g than other genotypes planted in different planting dates, with exception of the genotypes PI527710 and Sina planted in May and March, respectively (Figure 14c). The genotype Gila in all planting dates had the lowest 1000-seed weight (Figure 14c). The least 1000-seed weight of 25.8 g was produced by plants of the genotype Gila planted in December of 2020/2021 growing season (Figure 14c). The 1000-seed weight of plants from the genotype Gila did not significantly (P > 0.05) with planting date in 2020/2021 growing season (Figure 14c). generally, 1000-seed weight increased significantly (P < 0.05) with delayed planting from December to May (Figure 14c). However, early planting in December significantly (P < 0.05) reduced thousand seed weight of safflower plants across all genotypes (Figure 14c).

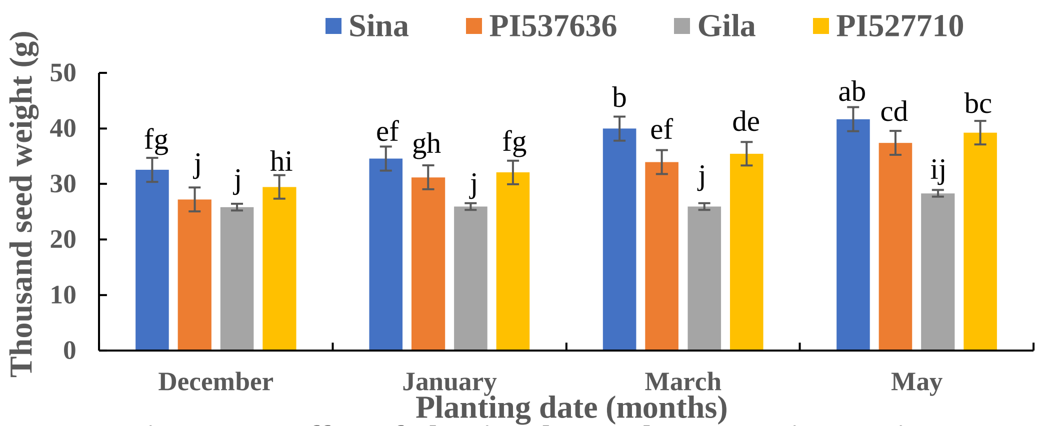

Figure 14c. Effect of planting date and genotype interaction on thousand weight for the 2020/2021 season; bars are standard error

4.3.6. Seed yield (kg/ha)

Season and planting date had a significant (P < 0.0001) influence on safflower seed yield in both 2019/2020 and 2020/2021 growing seasons. Delayed planting in May significantly (P < 0.05) increased seed yield of safflower by 3954 and 3161 kg/ha in 2019/2020 and 2020/2021 planting seasons, respectively compared to other planting dates (Figure 15a, b). Planting safflower in March significantly (P < 0.05) produced lower seed yield of 1152 and 985 kg/ha in 2019/2020 and 2020/2021 growing seasons, respectively than other planting dates (Figure 15a, b). In the 2019/2020 growing season, January planting produced significantly (P < 0.05) higher seed yield of 3331 kg/ha than December (3072 kg/ha) and March (1152 kg/ha) planting dates (Figure 15a). However, in 2020/2021 growing season, safflower planted in December and January did not significantly (P > 0.05) vary in their seed yields (Figure 15b).

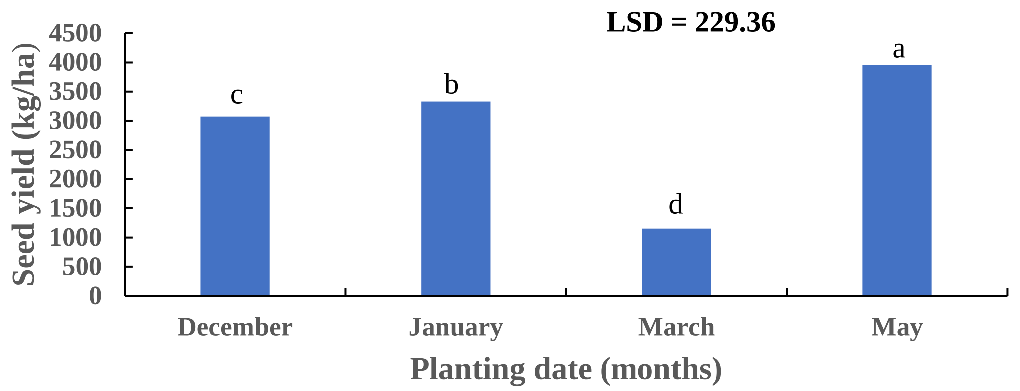

Figure 15a. Effect of planting date on seed yield of safflower for the growing season 2019/2020. Means separated by the LSD at $P < 0.05$; means followed by the same letter(s) are not significantly different

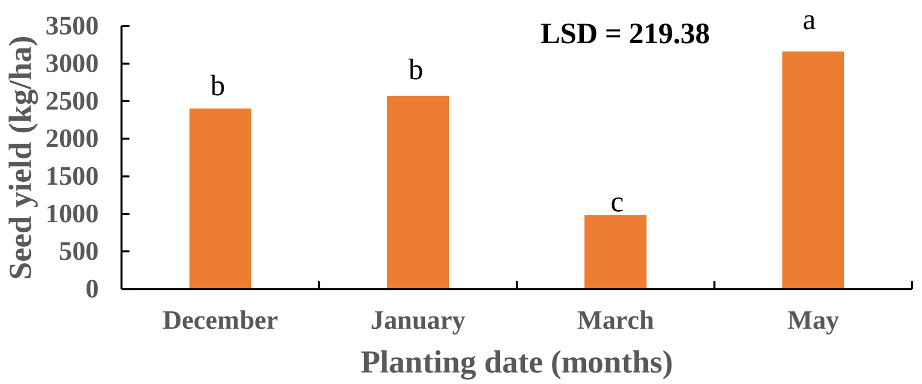

Figure 15b. Effect of planting date on seed yield of safflower for the growing season 2020/2021. Means separated by the LSD at $P < 0.05$; means followed by the same letter(s) are not significantly different

There was a significant ($P < 0.0001$) variation of safflower seed yield in both 2019/2020 and 2020/2021 growing seasons. In both seasons genotype Sina had significantly ($P < 0.05$) higher yield of 3505 and 2862 kg/ha than other genotypes, respectively (Figure 15c, d). On the contrary, the genotype Gila produced significantly ($P < 0.05$) lower seed yield of 2151 and 1619 kg/ha in 2019/20 and 2020/2021 growing seasons, respectively, than other genotypes used in the study (Figure 15c, d). The genotypes PI537636 and PI527710 had seed yield of 2816 and 3036 kg/ha in 2019/2020 growing season, respectively, but were not significantly (P

> 0.05) different, but significantly (P < 0.05) higher than the seed yield (2151 kg/ha) of Gila (Figure 15c). In the 2020/2021 growing season, the genotype PI527710 had significantly (P < 0.05) higher seed yield of 2700 kg/ha than genotypes PI537636 and Gila (Figure 15d).

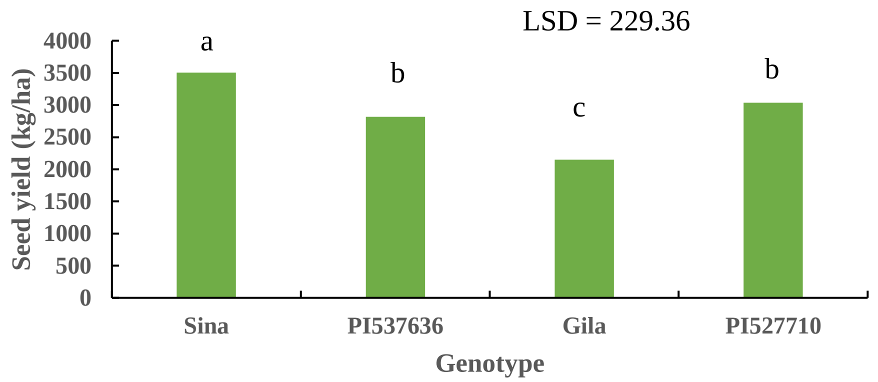

Figure 15c. Effect of genotype on seed yield of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

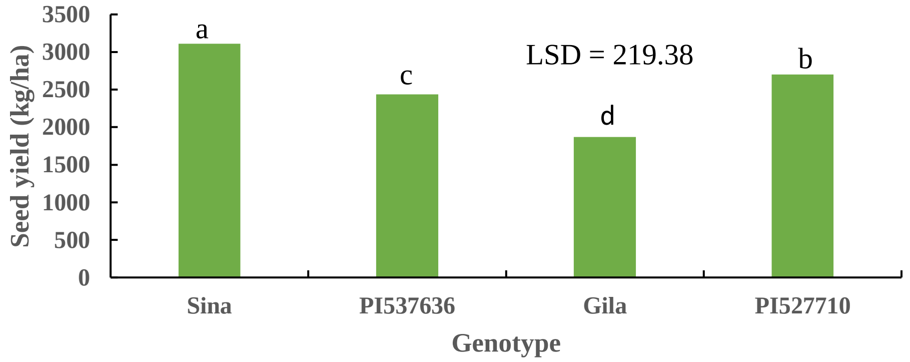

Figure 15d. Effect of genotype on seed yield of safflower for the growing season 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

4.3.7. Total dry matter (Biological yield)

Planting date and genotype had no significant (P > 0.05) interaction in the 2019/2020 planting season, therefore main effects are reported. Planting safflower in May planting in the 2019/2020 growing season significantly (P < 0.05) produced plants with higher biological yield of 5281 kg/ha than other planting dates in the study (Figure 16a). On the contrary, safflower planted in March with exception of December planting, significantly (P < 0.05) produced plants with lower biological yield of 3651 kg/ha than January and May planting dates (Figure 16a).

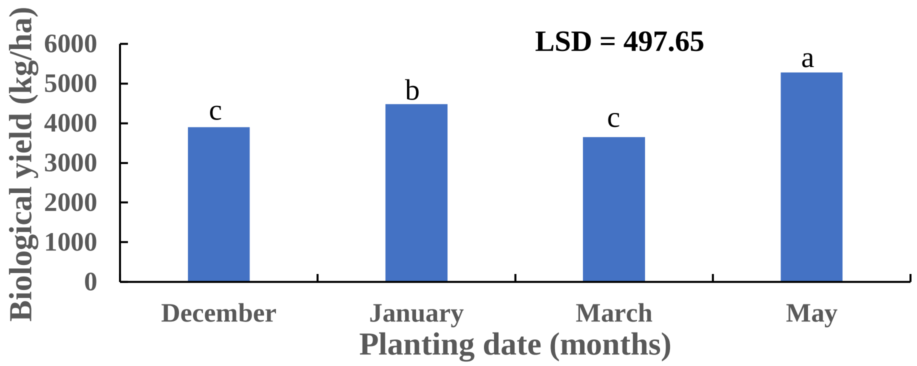

Figure 16a. Effect of planting date on biological yield of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

In 2019/2020 growing season, there was significant (P < 0.001) genetic variation on safflower biological yield (Figure 16b). The genotype Sina had significantly (P < 0.05) higher biological yield of 4875 kg/ha than other genotypes except for genotype PI527710 (4459 kg/ha) (Figure 16b). On the other hand, the genotype Gila had significantly (P < 0.05) lower biological yield of 3805 kg/ha than other genotypes excluding the genotype PI537636 which had a biological yield of 4174 kg/ha (Figure 16b). In 2019/2020 growing season, the biological yield of genotypes Sina and PI527710, and PI537636 and PI527710 did not significantly (P > 0.05) vary (Figure 16b).

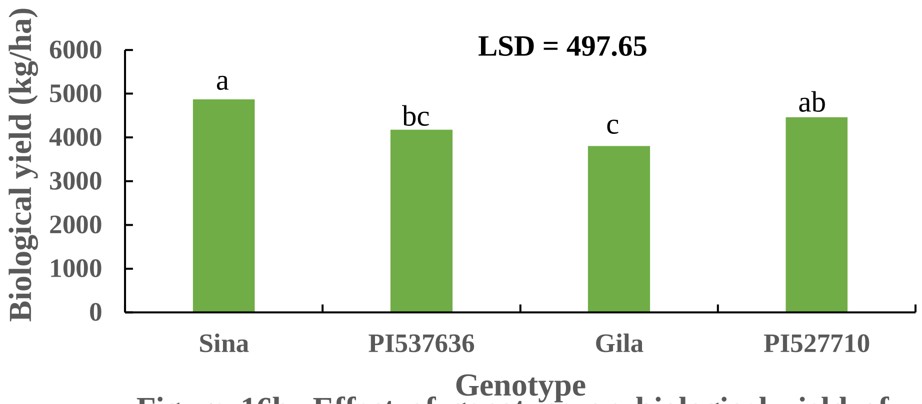

Figure 16b. Effect of genotype on biological yield of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

There was a significant (P < 0.0001) interaction between planting dates and genotypes on biological yield of safflower in the 2020/2021 growing season. The genotype Sina planted in May of 2020/2021 growing season significantly (P < 0.05) produced the highest biological yield of 5156 kg/ha compared to any genotypes and planting dates (Figure 16c). On the contrary, the genotype Gila planted in December of 2020/2021 growing season, produced significantly (P < 0.05) the lowest biological yield of 3275 kg/ha compared to other genotypes and planting dates (Figure 16c). The genotype Sina had significantly (P < 0.05) the highest biological yield ranging from 4149 to 5156 kg/ha depending on planting dates compared to other genotypes in all planting dates (Figure 16c). However, in the 2020/2021 growing season, genotypes PI527710, PI537636 and Gila, PI537636, Gila and PI527719, and Gila planted in December, January, March, and May, respectively, did not significantly (P > 0.05) differ in their biological yields (Figure 16c). Also, the biological yield of the genotypes Sina and PI527710, and PI537636 and PI527710 planted January and May respectively, did not significantly (P > 0.05) differ in the 2020/2021 growing season (Figure 16c).

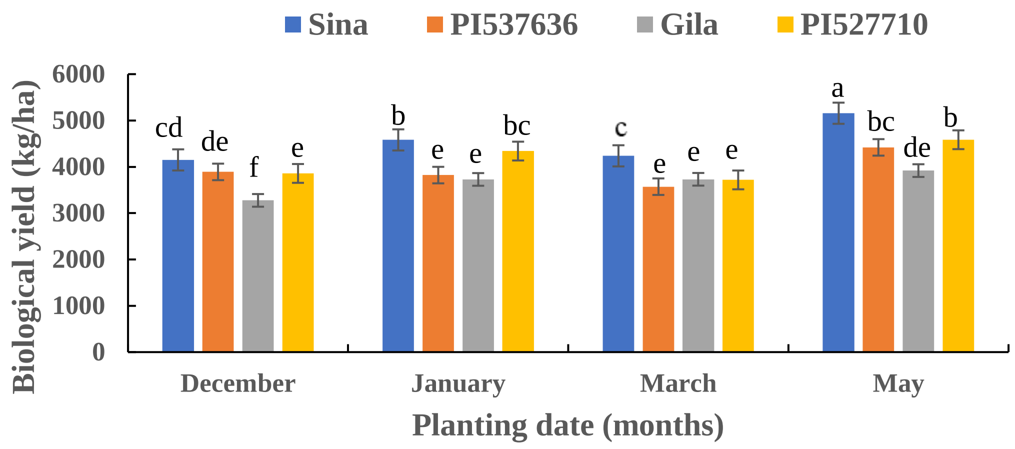

Figure 16c. Effect of planting date and genotype interaction on biological yield of safflower for the 2020/2021 season; bars are standard error

4.3.8. Harvest index

Season and planting date had a significant (P < 0.0001) influence on safflower harvest index. During the 2019/2020 growing season, safflower plants grown in December, January, and May had significantly (P < 0.05) higher harvest indices of 0.79, 0.75, and 0.75, respectively than safflower planted in March which had a harvest index (HI) of 0.32 (Figure 17a). The HIs of safflower planted in December, January, and May of 2019/2020 growing season did not significantly (P > 0.05) differ (Figure 17a).

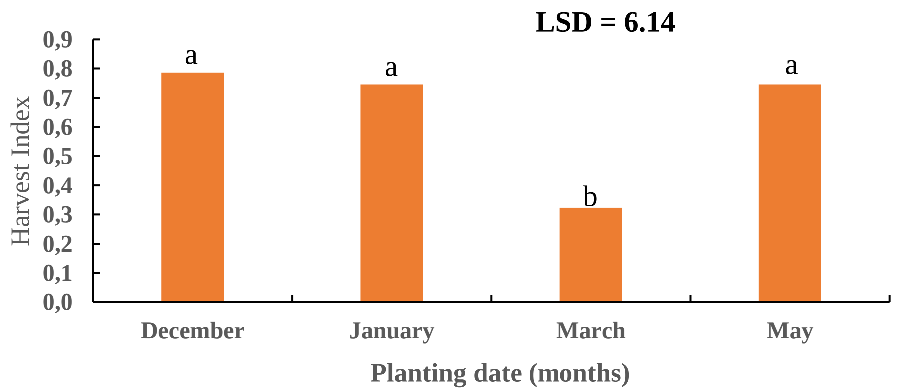

Figure 17a. Effect of planting date on harvest index of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

In the 2019/2020 growing season, there was significant (P < 0.01) genotypic variation on HI. Genotypes Sina, PI537636, and PI527710 had significantly (P < 0.05) higher HI of 0.70, 0.66, and 0.67, respectively than the genotype Gila which had HI of 0.57 (Figure 17b). There was no significant (P > 0.05) HI variation of the genotypes Sina, PI537636, and PI527710 (Figure 17b).

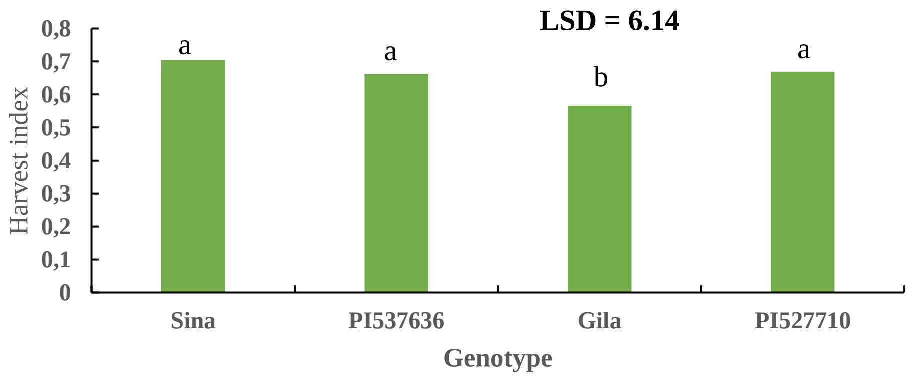

Figure 17b. Effect of genotype on harvest index of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

In the 2020/2021 growing season, planting date and genotype interacted to influence HI. The genotype Sina planted in May significantly (P < 0.05) produced plants with higher HI of 0.73 than other genotypes planted in different dates with exception of Sina planted in January of 2020/2021 growing season (Figure 17c). In the 2020/2021 growing season, the genotype Gila had significantly (P < 0.05) lower HI than other genotypes in all planting dates (Figure 17c). In all planting dates, the genotype Sina had significantly (P < 0.05) the higher HI within and across planting date(s) in the 2020/2021 growing season (Figure 17c). In the May planting of 2020/2021 growing season, the genotypes PI537636 and PI527710 did not significantly (P > 0.05) vary in their HIs (Figure 17c).

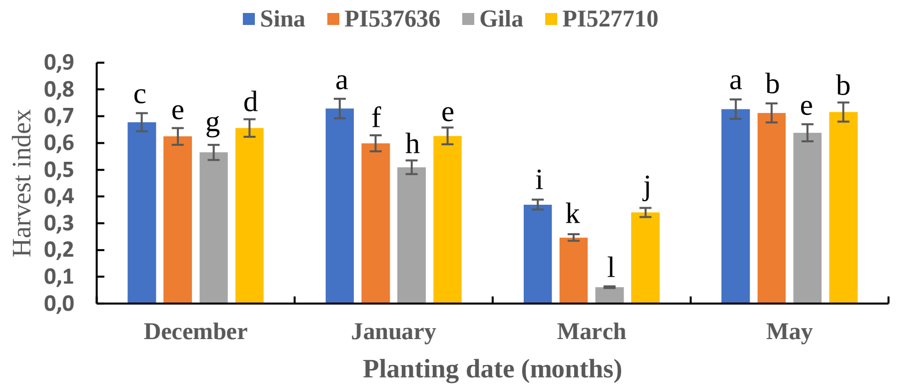

Figure 17c. Effect of planting date and genotype interaction on harvest index for the 2020/2021 season; bars are standard error

4.4. Effect of planting date and genotype on oil content and oil yield

4.4.1. Oil content (%)

In both 2019/2020 and 2020/2021 planting seasons, planting date and genotype significantly ($P < 0.01$) interacted to influence seed oil content of safflower (Figure 18a, b). Planting safflower in May significantly ($P < 0.05$) increased oil content for all genotypes (31.07-35.81) and (29.29-34.81) in season 1 and 2 respectively (Figure 18a, b). On the contrary planting in March significantly ($P < 0.05$) reduced oil content of all genotypes (27.79-25.42) and (19-24.43) in season 1 and 2 respectively (Figure 18a, b). The genotypes Sina and Gila had significantly ($P < 0.05$) higher oil content in all planting dates than other genotypes under study in 2019/2020 season (Figure 18a). On the contrary, the genotypes PI537636 and PI527710 did not significantly ($P > 0.05$) differ in oil content across all planting dates (Figure 18a). In 2019/2020 growing season, the genotype Sina planted in May had the highest seed content of 35.8% compared to other genotypes in all planting dates (Figure 18a). In 2020/2021 season, the genotype Sina had significantly ($P < 0.05$) higher oil content of 24.4% than other genotypes planted in March (Figure 18b). While genotype Gila had significantly ($P < 0.05$) higher oil content of 34.8% than other genotypes planted in May (Figure 18b). All genotypes under study did not significantly (P > 0.05) differ in January planting, while genotypes PI537636, Gila and PI527710 did not differ significantly (P > 0.05) in December planting in the second season (Figure 18b).

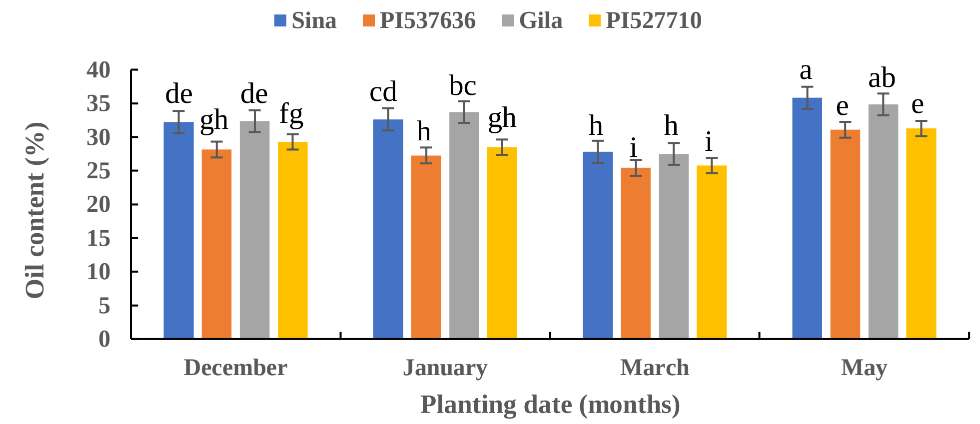

Figure 18a. Effect of planting date and genotype interaction on oil content for the 2019/2020 season; bars are standard error

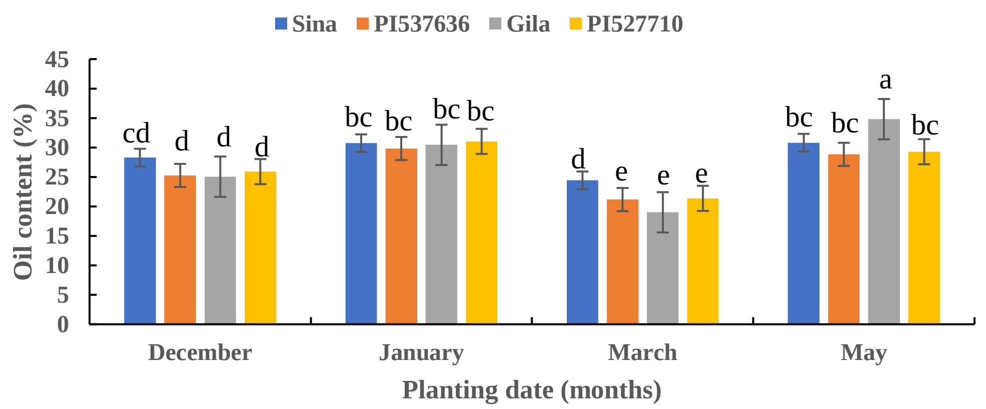

Figure 18b. Effect of planting date and genotype interaction on oil content for the 2020/2021 growing season; bars are standard error

4.4.2. Oil yield

Oil yield was significantly (P < 0.0001) influenced by season and planting date in 2019/2020 and 2020/2021 growing season seasons. Planting date significantly (P < 0.05) influenced safflower seed oil yield in both 2019/2020 and 2020/2021 growing seasons (Figure 19a, b). Planting safflower in May had significantly (P < 0.05) higher seed oil yield of 1317 and 973 kg/ha produced in 2019/2020 and 2020/2021 growing seasons, respectively than other planting dates (Figure 19a, b). On the contrary safflower planted in March of both seasons significantly (P < 0.05) produced lower seed oil yield of 306 and 221 kg/ha than any planting dates in the study (Figure 19a, b). Planting safflower in January significantly (P < 0.05) produced higher seed oil yield of 1014 and 784 kg/ha in 2019/2020 and 2020/2021 growing seasons, respectively than December or March planted safflower (Figure 19a, b).

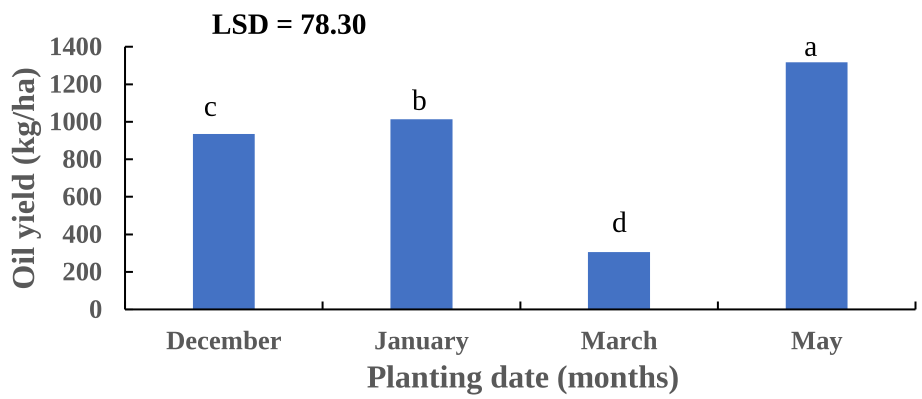

Figure 19a. Effect of planting date on oil yield of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

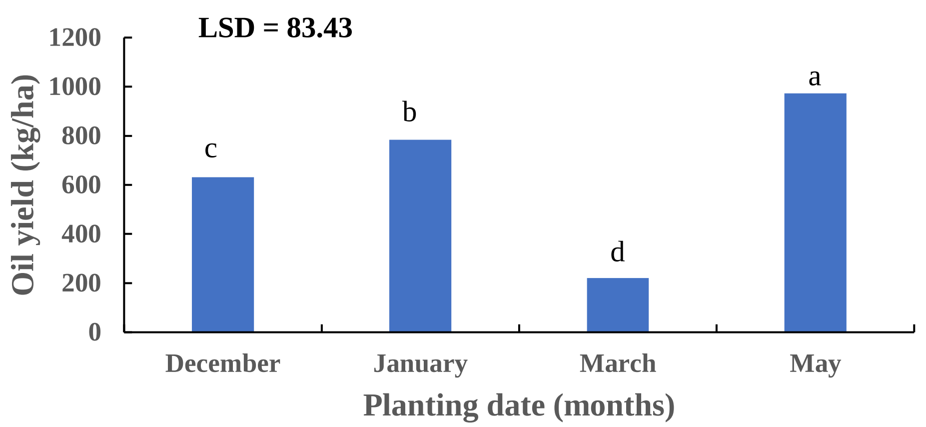

Figure 19b. Effect of planting date on oil yield of safflower for the growing season 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

Genotype significantly ($P < 0.0001$) influenced safflower seed oil yield in 2019/2020 and 2020/2021 growing seasons. In both seasons, the genotype Sina significantly ($P < 0.05$) produced higher seed oil yield of 1014 and 784 kg/ha than other genotypes in the study (Figure 19c, d). On the contrary, the genotype Gila significantly ($P < 0.05$) produced the lowest seed oil yield of 721 and 490 kg/ha compared to other genotypes (Figure 19c, d). The genotype PI527710 had significantly ($P < 0.05$) higher seed oil yield of 890 and 683 kg/ka in 2019/20 and 2020/2021 growing seasons, respectively than the genotype PI537636, but lower than seed oil yield of Sina (Figure 19c, d).

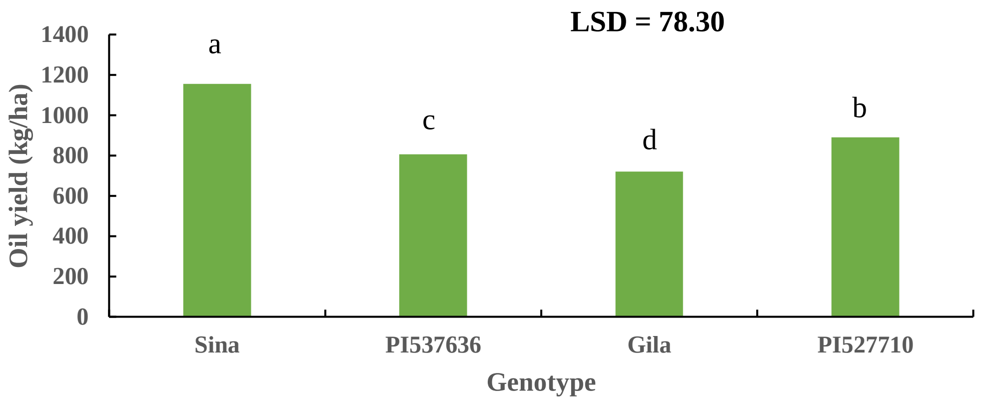

Figure 19c. Effect of genotype on oil yield of safflower for the growing season 2019/2020. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different

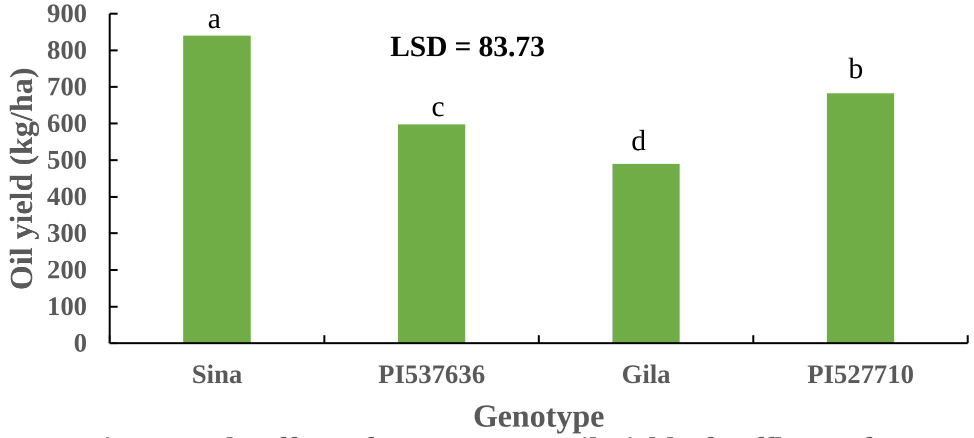

Figure 19d. Effect of genotype on oil yield of safflower for the growing season 2020/2021. Means separated by the LSD at P < 0.05; means followed by the same letter(s) are not significantly different.

CHAPTER 5 : DISCUSSION

5.1. Effect of planting date and genotype on days to flowering and physiological maturity

Understanding crop phenology and adaptation is related to its inherent maturation features, which influence patterns of crop development and are key factors in determining crop yield in a specific locality with a particular climate (Shimono, 2009; Mo et al., 2017). In the current study, planting safflower in May (delayed planting) significantly increased days to 50% flowering (85-132 days) and physiological maturity (122-163 days) depending on genotype. On the contrary early planting (December) significantly ($P < 0.05$) reduced days to 50% flowering (67-74 days) and physiological maturity (94-101 days) depending on genotype. The differences in days to 50% flowering and physiological maturity due to planting dates was attributed to air temperature during summer and winter. Planting safflower in December and January occurred in summer when the average monthly minimum and maximum air temperature was 18.8 and 30.7°C, respectively. While the average monthly minimum and maximum temperature in winter was 7.0 and 24.9°C. Temperature affects growth and developmental stages of all plants from emergence to anthesis (Erwin, 1991; Slafer & Rawson, 1994, Hatfield et al., 2011). The rate of crop development is temperature dependent if water is available. Within an ideal range, the rate of crop development is positively associated with temperature, with growth accelerated as the temperature rises (Ritche & Ne Smith, 1991; Goudriaan & Laar, 1994; Rasul, 2012; Hatfield, 2008; 2011; Hatfield & Prueger, 2015). In the current study, safflower's physiological maturity and flowering were delayed by low air temperatures reaching down to 2.09^{0}C in the winter because reactions to temperature vary across crop species throughout their life cycles and are mostly phenological responses. Moatshe (2019) and Moatshe et al. (2020) reported that winter-grown safflower in Botswana showed significantly longer phenological stages than summer-grown safflower in terms of rosette, elongation, branching, flowering, and physiological maturity. For example, depending on genotype, safflower required between 89 and 114 and 106 and 142 days after planting to reach physiological maturity in the summer and the winter, respectively (Moatshe, 2019; Moatshe et al., 2020). The average minimum and maximum temperatures for the research period were 4-16°C and 22-29°C, respectively, and 17-23°C and 28-36ºC in winter and summer, respectively (Moatshe, 2019; Moatshe et al., 2002). Bergman and Kandel (2019) reported that safflower took 110-120 days from emergence to maturity in North Dakota, USA. While Al-Doori (2017) reported that late planting of safflower delayed physiological maturity because of reduced average air temperature during growth which resulted in delayed flowering time induced by short photoperiod. Shabana et al. (2013) reported that safflower planted on 1st of November and 1st of December in Egypt flowered and reached physiological maturity after 133 and 112 days, and 169 and 146 days, respectively, depending on genotype. Unfavourable photoperiod and high temperatures were responsible for the reduction in days to flowering and maturity because of late planting because they caused the crop cycle to advance quickly to the development stage at the expense of yield and yield components (Shabana et al., 2013). Although safflower is a day-neutral plant, long days are necessary to initiate flowering since day length has a significant influence on flowering time (Gilbert, 2008). Short days cause plants to go through a longer rosette stage and mature physiologically late (Dajue & Mündel, 1996; Emongor, 2010; Emongor et al., 2017; Moatshe, 2019). Also, Wachsmann et al. (2001) reported that in Southern Australia, depending on the safflower genotype, the initiation of the elongation and flowering stages took 31–43 and 103–130 DAS, respectively. Similarly, Sarkees and Tahir (2016), found a significant interaction between safflower planting dates and genotypes on the number of days to flowering and physiological maturity stage in spring season. The effect of growing season on safflower phenological stages has been reported elsewhere in literature (Emongor et al., 2015; Kedikanetswe, 2012; Ahadi et al., 2011; Golkar et al., 2011; Koutroubas et al., 2004; Alizadeh, 2005; Esendal, 1997). Temperature has also been reported to positively interact with photoperiod and vernalisation at the earlier phases of crop phenology (Porter & Decolle, 1988; Kirby & Appleyard, 19844). Also in rose production, days to flowering are shortened by high temperatures (Moe & Kristoffersen, 1969; Hak et al. 2001). In wheat and oats, Slafer and Rawson (1994) reported that the primary factor influencing the length of time from sowing to emergence, anthesis, and maturity was temperature. They also reported that in oats (*Avena sativa* L.), time of panicle development on shoot apex, panicle emergence, anthesis and grain filling are significantly dependant on temperature and day length (Slafer & Rawson, 1994).

There was significant genotypic variation in the current study with respect to days to 50% flowering and physiological maturity. For example, the genotypes Sina and Gila took significantly longer and shorter days of 74.0-90.7 and 68-85, respectively, to reach 50% flowering in all planting dates than other genotypes under study. Similarly, in all planting dates, the genotypes Sina and Gila took significantly more and lesser days 101-131 and 96-120, respectively, to reach physiological maturity. This was attributable to variations in the genetic makeup of the safflower genotypes used. The two most significant phenological traits of safflower that influence yield are days to flowering and physiological maturity (Emongor et al., 2017; Oarabile, 2017; Golkar, 2014; Omidi et al., 2012; Weiss, 2000). Days to emergence and physiological maturity are important in breeding for early or late maturing varieties. Additive and dominant gene effects have been reported to control earliness in safflower (Golkar, 2011; Singh et al., 2008). Additive (Shahbazi & Seaidi, 2007; Kotecha, 1979) and dominant gene action (Gupta & Singh, 1988) have been reported in safflower to regulate number of days to physiological maturity. Golkar (2011) reported that days to flowering in safflower are genetically controlled by dominant gene effects. While Gupta and Singh (1988) found effects of partial dominance on the number of days to safflower flowering. Golkar (2014), on the other hand, explained inconsistent genetic expression in safflower as the result of genetic and environmental interaction. The observed genetic variation in days to 50% flowering and physiological maturity in the current study is valuable information that would be used in future for selection and breeding safflower cultivars that would be adaptable to various Districts of Botswana due to varying low and high temperatures in winter and summer, respectively. Genetic variation in days to flowering and physiological maturity in safflower is reported in literature (Dajue & Mündel, 1996; Oarabile, 2017; Emongor et al., 2017; Bella et al., 2019; Moatshe, 2019; Moatshe et al., 2020). The significant interaction between planting dates and genotypes pertaining to days to 50% flowering and physiological maturity in the current study indicated genotype and environment interaction. Safflower genotypes performance has been reported to vary with climatic conditions, locality or region, planting time, and cultural practices (Shabana et al., 2013; GRDC, 2017; Emongor & Oagile, 2017; OECD, 2020).

5.2. Effect of planting date and genotype on vegetative growth

5.2.1. Leaf growth (Leaf area index, leaf area duration, and chlorophyll content)

Planting date and genotype had a significant influence on the leaf growth parameters of safflower both in winter and summer in the current study. Planting date significantly interacted with genotype to influence the leaf area index (LAI), leaf area duration (LAD), and chlorophyll content. Delayed planting (planting after December) significantly increased safflower LAI and LAD in all genotypes in the current study. The increase in LAI and LAD in all genotypes due to late planting was attributed to lower temperatures and longer maturation period in winter than summer. During the study period, the maximum and minimum temperatures in winter and summer were 24.9 and 7°C, and 30.7 and 18.8°C, respectively. The lower temperatures experienced in winter prolonged leaf growth and LAD leading to large leaves with delayed senescence and high accumulation of photoassimilates in all genotypes necessary for leaf growth resulting in high LAI and prolonged LAD. Increase in leaf growth, LAI and LAD are essential for photosynthetic activities and crop yield (Nagaraj., 2010; Dar et al., 2009; Emongor, 2007). The amount of leaf area in safflower crop canopy affects growth, physiology, photosynthetic active radiation (PAR), and yield (Omidi & Sharifmogadas, 2010; Sharifi et al., 2012). Crops planted at the ideal date develop larger leaf area, absorb maximum solar radiation, and perform more effectively than crops that are planted not in an ideal date (Mohankumar & Chimmad, 2005; Tayebi et al., 2012; Khadtare et al., 2018). Moatshe (2019) reported that safflower leaf growth was higher when planted in winter compared to summer due to low winter temperatures (4-16 and 22-29ºC) which caused slow growth rate and led to accumulation of photoassimilates for leaf growth. In summer, short LAD was promoted by high summer temperatures (7-23 and 28-36ºC) which accelerated leaf growth as required heat units were met immediately (Rasul et al., 2016, Moatshe, 2019), resulting in genotypes having small LAI and LAD (Moatshe, 2019, Koutroubas et al., 2004; Robertson et al., 2004; Wang et al., 2012). Emongor et al. (2017) reported that winter-planted safflower had a higher LAD than safflower grown in summer in Botswana due to a long growth period.

The significant interaction of planting date and genotype on safflower LAI, LAD and leaf chlorophyll content observed in the current study was attributed to genetic and environment interaction. In the current study, the genotypes Sina and Gila had significantly ($P < 0.05$) higher and lower LAI, LAD, and leaf chlorophyll content, respectively, in all planting dates than other genotypes irrespective of planting date. Leaf area index, LAD and leaf chlorophyll content play a significant role in crop photosynthesis and yield. High leaf area, LAI, LAD, and chlorophyll content increases light absorption, resulting in high net canopy photosynthesis (Monteith, 1977; Evans, 1993; Mohankumar et al., 2005; Omidi & Sharifmogadas, 2010; Sharifi et al., 2012; Bagheri & Hasanvandi, 2013). Leaf length which affects LAI is said to be impacted by both additive and non-additive gene action in safflower (Kotecha, 1979; Golkar, 2014; Golkar et al., 2017). Golkar et al. (2017) reported that there was significant genetic and environment interaction of agronomic traits of safflower grown in different locations of Iran. Moatshe (2019) reported significant genetic variation of LAI, LAD, and leaf chlorophyll content of five safflower genotypes grown in Botswana. Emongor et al. (2017) also reported that winter-planted safflower in Botswana had higher LAD than safflower grown in summer due to its longer growing cycle induced by low air temperature in winter. Golkar et al. (2009) reported high significant genetic variation in safflower leaf chlorophyll a+b, chlorophyll a, chlorophyll b, carotenoids, and antioxidants as influenced by stress (environment). While Mokhtassi-Bidgoli et al. (2007) reported significant genetic variation of leaf chlorophyll a, chlorophyll b, total carotenoids, LAI, and LAD among six safflower genotypes grown in Iran. Furthermore, 20 safflower genotypes and F_1 hybrids were found to differ significantly in total leaf chlorophyll content, and the variation was associated with the different genes among the genotypes used in the study (Golkar et al. 2009). As leaves grow, exposure to sunlight induces the expression of genes that code for components of the photosynthetic apparatus in plants (Foyer & Paul, 2001; Addo-Quaye et al., 2011). Significant genetic variation for chlorophyll a, chlorophyll b and carotenoid content in other crop species has also been reported (Johnson et al., 1993; Kurilich et al., 1999).

5.2.2. Crop growth and net assimilation rates (CGR & NAR)

The results of the current study showed that there was a significant interaction of planting date and genotype as they influenced CGR and NAR. Planting safflower in May had significantly higher NAR and CGR than plants planted in March. The genotype Sina planted in May had significantly higher NAR of 2.38 and CGR of 7.35 g m^{-2} day^{-1}, respectively than that of other genotypes planted in different dates. On the contrary, the genotype Gila planted in all planting dates had the lowest NAR and CGR compared to other genotypes. The high NAR and CGR in safflower planted in May irrespective of genotype compared to other planting dates observed in the current study was partly attributed to high LAI, LAD and leaf chlorophyll content in the same planting date which resulted in high light interception and absorption of PAR. According to studies, safflower with high leaf area, LAI, LAD, and chlorophyll content intercepts more light resulting in high net canopy photosynthesis and high dry matter accumulation (Mohankumar et al., 2005; Omidi & Sharifmogadas, 2010; Sharifi et al., 2012; Bagheri & Hasanvandi, 2013). Other studies have shown that LAD and canopy extinction coefficient (k) are important factors influencing radiation absorption during the growth season of crops (Watiki et al., 1993; Orange & Ebad 2011).

The high NAR and CGR in safflower planted in May (late planting) irrespective of genotype compared to other planting dates observed in the current study was also attributed to low cooler temperatures (maximum and minimum 24.9 and 7°C) in winter which are suitable for safflower growth and development. Depending on the phenological stage, the optimum temperature for safflower growth and development is between 15 and 30°C (Mündel, 1969; Dajue & Mündel, 1996; Emongor, 2010; Emongor & Oagile, 2017; GRDC, 2017). Moatshe (2019) reported that growing season had a significant effect on the NAR and CGR of safflower plants in all phenological stages in Botswana. Winter grown safflower had significantly higher NAR, but lower CGR than summer grown plants at the same days after sowing (Vaghar et al., 2014; Moatshe, 2019). The high NAR during winter than summer was attributed to high LAI and long LAD during winter which was influenced by air temperature (4-16°C). Similar results have been reported in other safflower growing areas of the world (Wang et al., 2012; Robertson et al., 2004; Koutroubas et al., 2004). Temperature significantly affects the NAR and CGR of safflower (Shahsavari et al., 2014; Dadashi & Kajehpour, 2003) and wheat (Jame & Cutforth, 2004; Kajehpour & Seidi, 2001). While Omidi and Sharifmogadas (2010) reported low LAI, NAR and CGR among safflower genotypes in late planted (October planting) safflower in Iran due to unfavourable high air temperatures. More recently, Al-Zubaidy and Al-Mohammad (2021) in Babylon, Iran reported that safflower planted on 1st of December had significantly higher leaf area and chlorophyll content than safflower planted either 1st or 15th of November. This was attributed to conductive air temperature and high relative humidity which encouraged the efficient emergence of seedlings and performance in the development of useful vegetative parts (Al-Zubaidy & Al-Mohammad, 2021). LAI, NAR, and CGR were related to air temperature in soybeans (Isoda et al., 2011).

There was a significant genetic variation of NAR, CGR and leaf chlorophyll content among safflower genotypes in the current study. The genotype Sina and Gila had significantly the highest and lowest NAR, CGR and leaf chlorophyll content in all planting dates. This was attributed to genetic differences among genotypes as influenced by the environment. Additive gene action affects safflower morphological traits including LAI, LAD, NAR, CGR, and leaf chlorophyll content (Kotecha, 1979; Shahbazi & Saeidi, 2007; Golkar et al., 2012; Golkar, 2014; Hassan et al., 2015). Moatshe (2019) reported that the genotypes Sina and Gila grown in Botswana had significantly higher and lower NAR, CGR and leaf chlorophyll content respectively, than other genotypes planted in various plant densities. Yadav (2014) and Naghavi (2011) attributed to the significance of the interaction of safflower genotype and plant density on variability in the genetic inheritance among the varieties and differences in the supply of plant nutrients in different plant densities ranging from 55,556 to 166,667 plants/ha. While Golkar et al. (2009) reported that significant variations in leaf chlorophyll a, b, and total chlorophyll content were found among 20 safflower genotypes and FI hybrids. In all genotypes, chlorophyll b level was lower than chlorophyll a content (Golkar et al., 2009). Similar variations in leaf chlorophyll contents of safflower genotypes had been reported earlier by Gadallah (2000). Mokhtassi-Bidgoli et al. (2007) reported the genotypic differences in leaf chlorophyll content, NAR, and CGR across six safflower genotypes. The genotypes 'Varamin-295', 'IL-111' and 'Zarghan-279' had significantly the highest leaf chlorophyll content, NAR, and CGR respectively, between end of rosette and branching stage compared to all genotypes studied (Mokhtassi-Bidgoli et al., 2007). However, Oarabile (2017) reported that safflower genotype had no significant effect on leaf chlorophyll content.

5.2.3. Plant height (cm)

In the current study there was a significant influence of planting date on plant height of safflower. Safflower planted in May and December had the tallest and shortest plants, respectively. These differences in plant height were partly explained by the differences in photoperiod and temperatures during winter and summer. Safflower planted in May when temperatures (maximum and minimum 24.9 and 7°C) are generally cooler with longer nights (13.5 hours) were taller than those planted in summer (maximum and minimum temperatures 30.7 and 18.8°C; shorter nights 10.5 hours). Safflower's growth and development in Botswana are influenced by the cool (<20°C) and short (10-hour) days (Dajue & Mündel, 1996; Emongor et al., 2015; 2017; Moatshe, 2019). The greater variation between night and day temperatures (DIF) in winter promotes safflower plant height (Kedikanetswe, 2012; Emongor et al., 2015; 2017; Moatshe, 2019). Large variation in day and night temperatures (maximum and minimum) have significant morphological effects on stem elongation of some plants (Went, 1944). For a variety of species, it has been shown that the variation in temperatures between day and night (DIF), can be used to regulate plant height (Myster & Moe, 1995). The stem elongation increases in response to the difference between the daytime and nighttime temperatures (DIF) (Berghage & Heins, 1991; Erwin et al., 1989; Karlsson et al., 1989; Emongor et al., 2015; 2017; Moatshe, 2019). For many plant species, internode elongation is promoted by high day temperatures in comparison to night temperatures (Berghage & Heins, 1991; Myster & Moe, 1995; Dole & Wilkins, 2005). Safflower plants were taller when grown in winter as opposed to summer due to greater stem elongation caused by the higher positive DIF and cool morning temperatures (4–10ºC). The rise in safflower plant height was likely caused by the positive DIF throughout the winter, and that stimulated the production of gibberellins, which are known to enhance cell and internode elongation (Taiz & Zeiger, 2002; Emongor et al., 2015). Bey et al. (2021) reported in Turkey that sowing date, year, and environmental factors (precipitation) significantly influenced safflower plant height. Similar findings have been reported in literature concerning safflower (Alinaghizadeh et al., 2008; Omidi & Sharifmogadas, 2010; Tayebi, 2012; Hatiopoglu et al., 2012; Ghanbari-Odivi et al., 2013).

The differences in safflower plant height due to planting date observed in the current study was also partly attributed to longer maturation period and higher LAI, LAD, NAR, CGR and leaf chlorophyll content of plants planted in May (winter) than summer (December-January). The long maturation period and high LAI, LAD, NAR, CGR and leaf chlorophyll content promoted high light interception, absorption of PAR, net canopy photosynthesis and high dry matter accumulation. The variables LAI, LAD, NAR, CGR and leaf chlorophyll content indicate canopy development and effectiveness for absorbing solar radiation, determining the effectiveness of photosynthetic processes, the accumulation of dry matter, and the potential crop yield (Monteith, 1977; Evans, 1993; Muchow et al., 1986; Foyer & Paul, 2001; Mohankumar et al., 2005; Omidi & Sharifmogadas, 2010; Sharifi et al., 2012; Bagheri & Hasanvandi, 2013). Esendal et al. (2008) reported that winter sown safflower had taller plants than spring sown safflower showing that climatic conditions and agronomic practices influence plant height. Moatshe (2019) reported that safflower planted in winter in Botswana had higher LAI, LAD, NAR, CGR, RGR, leaf chlorophyll content, and taller plants than summer planted safflower.

There was a significant genetic variation among safflower genotypes in the current study. Safflower genotypes ranged in height from 72.95 to 80.08 cm, with genotype Sina having the tallest plants and genotype PI537636 having the shortest plants. To assess gene action for morphological traits in safflower, biometrical evaluation has been conducted (Golkar, 2014). Height of safflower plants is a significant morphological trait that is influenced by additive gene action (Kotecha, 1979; Shahbazi & Saeidi, 2007; Chapman et al., 2010; Golkar et al., 2012; 2017). Extra-nuclear genes have not been shown to alter the height of safflower plants (Mandal & Banerjee, 1997). Safflower plant height has also been reported to have moderate to high heritability of 50.7-77.0% (Ramachandram & Goud, 1981; Reddy et al., 2004; Parameshwar, 2009; Erbas et al., 2016). Bey et al. (2021) and Ozturk et al. (2008) reported that safflower plant height had low heritability and it was greatly influenced by environmental factors. Important genotypic variation for safflower plant height has been reported in literature (Moatshe, 2019; Emongor et al., 2017; Oarabile, 2017; Zareie et al., 2013; Hamza, 2015; Killi et al., 2016). El-Lattief (2012) reported that there was significant genetic variation among 25 safflower genotypes in the trait plant height. While Carapetian (2001) reported that there was significant variation for plant height between winter- and spring-type safflower genotypes in Iran. After evaluating 400 accessions of safflower in Romania, Bratuleanu (1997) reported that plant height was largely determined by genotype, though it can be influenced by the environment and cultural practices (Dajue, 1993; Dajue & Mündel, 1996; Weiss, 2000; Camas et al., 2007).

5.2.4. Primary branch number per plant and branch diameter

In the current study, the genotype and planting date both independently significantly affected the number of primary branches per plant and branch diameter of safflower. The results demonstrated delayed planting increased primary branch number/plant and branch thickness. Primary branch number/plant and thickness increased as the planting date was delayed from December to May. Planting safflower in May produced plants that had 11.4 primary branches/plant and on the contrary, planting safflower in December, January, and March produced plants with 7.6, 8.2 and 10.7 primary branches/plant, respectively. The high branching and branch thickness of safflower plants with delayed planting was attributed to long maturation period and good vegetative growth (LAI, LAD, NAR, CGR, RGR, leaf chlorophyll content, and plant height) induced by cool air temperatures, low evapotranspiration rate (more moisture available for plant growth), and dry matter accumulation in winter (Heggenstaller et al., 2009; Emongor et al., 2013; 2015; 2017; Moatshe et al., 2020a). Long days have been reported to inhibit branching of safflower this partly explained the few primary branches of safflower planted in summer (December and January) (Salisbury & Ross, 1992; Liangjin & Xiaojin. 1999; Sarkees & Tahir, 2016; Moatshe et al., 2016; Emongor et al., 2017; Oarabile, 2017).

The significant genotypic variation on the number of primary branches/plant and branch diameter observed in the current study was attributed to genetic differences among genotypes. Primary branch number/plant and branch diameter in safflower are under additive gene effects (Kotecha, 1979; Gupta & Singh 1988; Dajue & Mündel 1996; Kotecha, 1979; Shahbazi & Saeidi, 2007; Golkar et al., 2012; Golkar, 2014). The genetic variation in vegetative growth of safflower observed in the current study agrees with that reported in literature (Dajue & Mündel, 1996; Arslan, 2007; Zareie et al., 2013; Hamza, 2015; Killi et al., 2016; Moatshe et al., 2016; Sarkees & Tahir, 2016; Emongor et al., 2017; Moatshe et al., 2020a)

5.3. Effect of planting date and genotype on yield and yield components

5.3.1. Yield components

Plant height, first branch height, number of branches, capitula diameter, number of seeds (achene) per capitulum, number of capitula per plant, and seed weight are the variables utilised as yield components for safflower (Chaundry, 1990; Gonzalez et al., 1994; Omidi & Tabrizi, 2000; Bagheri et al., 2001; Camas & Esendal, 2006; Ahmadzadeh et al., 2012; Emongor et al., 2013; 2015; Moatshe et al., 2016; Emongor & Oagile, 2017; Emongor et al., 2017; Oarabile, 2017; Moatshe et al., 2020b).

The findings of the current study showed that genotype and planting date significantly increased yield components of safflower (capitula diameter, capitula number/plant, seed number/capitulum, 1000-seed weight, and total dry matter). Safflower planted in May and March had the highest and lowest yield components observed in the current study. In general, late planting with exception of March planting increased safflower yield components. The increase in yield components with delayed planting was partially explained by long maturation period and high LAI, LAD, NAR, CGR, RGR, and leaf chlorophyll content induced by cool air temperatures, low evapotranspiration rate (more moisture available for plant growth), and dry matter accumulation in winter (Heggenstaller et al., 2009; Emongor et al., 2013; 2015; 2017; Moatshe et al., 2020a). Long maturation period and high LAI, LAD, NAR, CGR, RGR and leaf chlorophyll content promoted absorption of PAR leading to high photoassimilation and accumulation of dry matter which was observed in the current study. These physiological variables (long maturation, high LAI, LAD, NAR, CGR, RGR, and leaf chlorophyll content) have a significant impact on the development and maturation of seeds due to the photosynthetic surface (LAI), which accounts for the duration and extent of the photosynthetic tissue (LAD) and reflects the photosynthetic efficiency (NAR), affects the accumulation of assimilates (CGR), which serve as the seed's source for growth, development, and maturation. Assimilate sink demand is usually high during the seed filling stage and majority of photoassimilates needed come from photosynthesis (Dosio et al., 2000; Aguirrezabal et al., 2003). Therefore, optimising growth conditions for photosynthetic activity is important and was achieved in May planting in the current study. Maintaining a greater photosynthetic rate throughout anthesis and grain filling stage was essential for developing more seeds, which in turn affects grain yield, based on the positive relation between photosynthetic rate and grain yield per plant (Djanaguiraman et al., 2020). Aguirrezabal et al. (2003) reported that environmental changes during the seed filling stage had an effect on yield components of safflower. Low temperatures and delayed sowing were reported to enhance pollination and yield components of safflower (Alinaghizadeh et al., 2008; Mohamadzadeh et al., 2011). Also in the current study, planting safflower in March significantly reduced yield components because the bolling stage coincided with very low temperatures during winter. The low temperatures (-6.3- -4.2°C plants exposed for about three days) caused chilling injury which reduced the yield components especially capitula number/plant, capitula diameter, seed number/capitulum and 1000-seed weight. Kolanyane (2022) in Botswana reported that safflower yield components were significantly impacted by extremely low temperatures of -6.3 and -4.2°C that occurred on two separate occasions in July and August 2021.While Mohammadzadeh et al. (2011) reported reduced 1000-seed weight of safflower was low due to less dry matter accumulation in the seeds caused by unfavourable temperatures. Though safflower can withstand harsh conditions, flowering stage is most susceptible to environmental stress (Chehade et al., 2022). Low temperatures and poor levels of photosynthetic activity resulted in extremely low plant dry weight (Naserzadeh et al., 2018). Abiotic stresses, such drought and low temperatures, cause plants to utilise less water, use their water more inefficiently, have fewer leaves, have less chlorophyll in their leaves, have fewer photosynthetically active cells, and produce fewer seeds (Hajihashemi et al., 2018; Wassan et al., 2021; Mosupiemang et al., 2022; Zhang et al., 2022). Increased temperature (40°C) lowered the rate of assimilate export by 80% from enlarged leaves on the flowering shoot, suggesting that assimilate export and partitioning are influenced by temperature (Jiao & Grodzinski 1998). The effect of high temperature and shortening of the growth cycle of safflower planted in December and January partially explains the low yield components observed in the current study. Bey et al. (2021) reported that years x cultivars x sowing dates, year x cultivar and year x sowing date significantly influenced safflower capitula number/plant, seed weight/capitulum, and 1000-seed weight in Turkey. They attributed the variation in yield components to genetic and environment interaction especially precipitation. Yield components of safflower as affected by cultivar x sowing date has been documented in literature (Kizil, 2002; Badri et al., 2012; Emami et al., 2011; Hatipoglu et al., 2012; Seadh et al., 2012). However, Aslantas and Akinerdem (2019) and Barla et al. (2020) reported that the delayed sowing date significantly reduced the capitula number/plant.

The results of the current study showed that safflower genotypes significantly influenced the yield components (capitula diameter, capitula number/plant, seed number/capitulum, 1000-seed weight, and total dry matter). The genotypes Sina and Gila had consistently the highest and lowest yield components respectively, irrespective of planting date in the current study. While the genotype PI527710 was consistently second to Sina in all the yield components in the current study. In the current investigation, the genotypic variance on yield components was attributable to genetic variations between the genotypes. Significant genetic variation of safflower genotypes has been observed in previous literature for capitula number/plant, seed number/capitulum, 1000-seed weight, and biological (dry matter) yield (Singh & Nimbkar, 2006; Camas et al., 2007; Kizil et al., 2008; Nikabadi et al., 2008; Abd El-Lattief, 2012; Zareie et al., 2013; Asghar & Younes; 2015; Hamza; 2015; Killi et al.,2016; Emongor et al., 2017; Oarabile, 2017; Moatshe et al., 2016; 2020a). Golkar et al. (2012a, b) reported that capitula diameter of safflower was under the control of dominant gene effects. Emongor et al. (2017), Oarabile (2017), Moatshe (2019), and Moatshe et al. (2020a) reported that safflower genotypes significantly varied in yield components (capitula number per plant, capitula diameter, seed (achene) number per/capitulum and 1000-seed weight. The genotype Sina is said to be more adaptable to different ecological conditions (Ahadi et al., 2011; Singh et al., 2016; Kose et al., 2018; Bey et al., 2021). While Camas and Esendel (2006) revealed that capitula diameter had a low broad-sense heritability. These findings reveal the importance of environmental effects on capitula diameter and explaining the interaction of genotype and planting date on capitula diameter observed in the current study which is also an excellent index for ornamental application of safflower. For the genetic control of node number on the main stem with generation mean analysis, the additive-dominance model has also been reported (Abel, 1976). According to Abel, (1976), some epistatic effects have also been reported for internode length.

Capitula number/plant is an important agronomic trait of yield whose genetic control has been reported under dominance gene effects (Pahlavani et al., 2007). Deshmakh et al. (1991) reported a high heterosis for capitula number/plant. While Shahbazi and Saeidi (2007) and Golkar et al. (2017) reported that additive×additive and dominance×dominance epistases had important roles in the genetic control of capitula number/plant. Sahu and Tewari (1993) reported on the importance of additive-dominance model for the genetic control of capitula number/plant. While Singh and Pawar (2005) reported that capitula number/plant was the control of epistatic gene action. Ramachandram and Goud (1981) showed that maternal effects played a significant role in the inheritance of capitula number/plant and 1000-seed weight. Number of seeds/capitulum has been reported under the control of additive gene effects (Mandal & Banerjee, 1997; Singh & Pawar, 2005; Singh et al., 2008; Nakhaei et al., 2014; Golkar et al., 2017). This suggests that the selection breeding strategy can be utilised for increasing seed number/capitulum. According to literature, the genetic regulation of 1000-seed weight is strongly influenced by additive gene effects (Nakhaei et al., 2014; Golkar et al., 2012b; 2017). Additionally, it has been discovered that the digenic model (additive-dominance) affects the regulation of 1000-seed weight (Shahbazi & Saeidi, 2007; Golkar et al., 2014; 2017).

5.3.2. Seed yield and harvest index

Seed yield and harvest index (HI) were significantly influenced by genotype and planting date. Safflower planted in May and March had the highest (3161 to 3954 kg/ha) and lowest (985 to 1152 kg/ha) seed yield and HI (0.73 to 0.75 May; 0.06 to 0.32 March), respectively, observed in the current study depending on genotype and growing season. In general, late planted safflower with exception of March planting increased safflower seed yield and HI. The increase in seed yield and HI from late planted safflower with exception of March planting was explained by the high vegetative growth (long maturation, high LAI, LAD, NAR, CGR, RGR, and leaf chlorophyll content) and yield components (capitula diameter, capitula number/plant, seed number/capitulum, 1000-seed weight, and total dry matter) which occurred in the same planting dates. The long maturation, high LAI, LAD, NAR, CGR, RGR, and leaf chlorophyll content increased photoassimilate biosynthesis and accumulation which resulted in high dry matter production, seed yield and HI. Heggenstaller et al. (2009), Emongor et al. (2013, 2015, 2017), and Moatshe et al. (2020a) reported that winter grown safflower had long maturation period and high LAI, LAD, NAR, CGR, RGR and leaf chlorophyll content induced by cool air temperatures, low evapotranspiration rate and dry matter accumulation which resulted in high safflower yield components and yield of safflower. Seed filling is an important phenological stage that involves translocation of assimilates necessary for several components needed for protein, carbohydrate, and lipid biosynthesis in the developing seeds (Pravallika et al., 2020). The movement and retention of pre-anthesis assimilates are essential physiological processes during seed filling stage for maximum safflower seed yield (Koutroubas et al., 2004; Chehade et al., 2022). High yield components of safflower and a longer growth season lead to a higher accumulation of dry matter, better translocation of photosynthetic products to flowers, increased pollination and development of capitula (Sarkees & Tahir, 2016). Large and high number of capitula/plant plus high plant dry matter (yield components) lead to high safflower seed yield (Chehade et al., 2022; Sarkees & Tahir, 2016; Koutroubas et al., 2004). Significant positive interactions between seed yield and leaf area duration have been reported thus longer leaf duration resulted in high interception of photosynthetically active radiation (Kumidini et al., 2001; Schittenhelm et al., 2004; Liu et al., 2005; Mokhtassi-Bidgoli et al., 2007). This was in agreement with Morrison et al. (1999) and Khalil and Manan (1992) who reported positive correlations between seed yield, photosynthesis and leaf chlorophyll content in soybean. The relationship between leaf chlorophyll concentration and seed yield in safflower may be due to changes in sink capacity, carbon/light utilization efficiency, the length of time that green leaf area remains present, and/or the timing of seed filling (Mokhtassi-Bidgoli et al., 2007). Safflower cultivars that produce high yields typically exhibit traits including high seed filling, robust leaf development, and postponed plant senescence (longer LAD) (Mokhtassi-Bidgoli et al. 2007). Positive and significant correlations between safflower morphological, phenological, agronomical traits with seed yield have been reported (Gonzalez et al., 1994; Omidi, 2002; Mozafarri & Azari, 2006; Moghaddasi & Omidi, 2010; Kedikanetswe, 2012; Karimi et al., 2013; Moatshe et al., 2016; Oarabile, 2017; Emongor et al., 2017, La Bella et al., 2019; Moatshe, 2019). Additionally, the final seed yield of safflower may be between 65 to 72% comprised of the translocation of dry matter and nitrogen accumulation during the vegetative phase (Chehade et al., 2022). In sunflower, Miklic (2001) reported that lower temperatures and more precipitation lengthened the grain-filling time and increased sunflower seed size.

The significant low seed yield and HI observed for safflower planted in March was attributed to exposure of plants to low chilling temperatures of -4.2 to -6.3°C in winter which coincided with the reproductive phase of safflower plants which is highly sensitive to cold conditions. The safflower plants suffered from chilling injury (Appendices 3-5). Frost soon after flowering significantly reduced safflower seed yield (Li & Mündel, 1996; Kolanyane, 2022). According to Emongor & Oagile, (2017), if there is no frost during the elongation and flowering stages of growth and development, safflower can tolerate a wide range of temperatures from -15 to 40°C. For the growth of their roots and rosette, safflower seedlings require cool temperatures (15–20°C) following emergence. However, high temperatures (20 to 30°C) during stem elongation and reproduction limit seed weight and oil content, which ultimately lowers the overall yield (Li, 1989; Mündel et al., 1992; Li et al., 1997; Carapetian, 2001; El-Bassam, 2010, Emongor, 2010; Emongor & Oagile, 2017). When mature safflower plants are exposed cold temperatures of -2°C or less for longer than 24 hours, they experience chilling injury (Emongor & Oagile, 2017; GRDC, 2017; OGTR, 2019; OECD, 2020; Emongor & Emongor, 2022). Low air temperatures alter plant respiration rates at night, disturb pollination process and lowers biomass accumulation and crop yield due to exposure to low extreme temperatures which hinders plants to produce more fruit (Hatfield et al., 2011; Hatfield & Prueger 2015; GRDC, 2017; OGTR, 2019; OECD, 2020; Emongor & Emongor, 2022). Early senescence of safflower plants occurred in the current study as a result of chilling injury (Appendices 3-5) interrupted the development of leaves, capitula and seed resulting in significant reduction in seed yield and yield components. Reduction in seed yield of safflower due to reduction in several yield components are reported in literature (Ozel et al., 2004; Omidi & Sharifmogadas 2010; Khalil et al., 2013; Sahu & Thakur 2016). The lower seed yield in safflower planted in December than January compared to May planting was attributed to high average air temperatures of 35.2°C exposed to plants during the growing period (summer). Samanci and Ozkaynak (2003) reported decreased safflower seed yield due to higher air temperatures during the flowering stage resulting in reduced pollination and fertilization processes. Temperature and humidity are some of the variables which influence pollen viability (Samanci & Ozkaynak, 2003).

Safflower genotypes under study had significant genotypic variation with respect to seed yield and HI. This was due to genetic variations between the study genotypes. Genotypic variation of safflower seed yield has been reported to be under additive gene action (Nakhaei, 2014; Golkar et al., 2012; 2017). However, Rajab and Fried (1992), Mandal and Banerjee (1997), Singh et al. (2008), and Deedawat et al. (2015) reported predominant role of gene dominance in safflower seed yield. Genetic variation among safflower genotypes is reported in literature (Ashri et al., 1974; Rahmatalam et al., 2001; Jochinke et al., 2002; Mahasi et al., 2006; Singh & Nimbkar, 2006; Camas et al., 2007; Kizil et al., 2008; Elfadl et al., 2010; Ali & Mahmoud, 2012; Hamza, 2015; Killi et al., 2016; Oarabile, 2017; Emongor et al., 2017; Moatshe, 2019; Moatshe et al., 2020). The genotype Sina had significantly higher seed yield (2862 to 3505 kg/ha) and HI (0.63 to 0.70) depending on the growing season than other genotypes. The significant high seed yield and HI of the genotype Sina compared to other genotypes was attributed to longer growth period, taller plants, thicker stem diameter, higher LAI, LAD, NAR, CGR, dry matter, seed number/capitulum, and capitula number/plant than other genotypes The opposite was true for the genotype Gila in the current study. Studies carried out across different locations on 20 different safflower genotypes recommended genotype ‘Sina’ (PI537598) as the best performing and highly adaptable genotype in different environments producing the highest yields compared to other genotypes (Alizadeh, 2001; Poordad, 2003; Amoughin et al., 2012). Moatshe et al. (2016) in Botswana reported safflower seed yields in the range of 2000 to 5500 kg/ha depending on genotype, plant density and growing season. Kizil et al. (2008) in Turkey reported safflower seed yield of 1706 to 3111 kg/ha depending on genotype and growing season. Camas et al. (2007) and Killi et al. (2016) from Turkey reported a safflower seed yield of 913-2482 and 827-992 kg/ha, respectively, depending on genotype. While Abd El-lattief (2012) and Hamza (2016) in Egypt reported a safflower seed yield of 512 to 2846 and 1978 to 2510 kg/ha, respectively, depending on genotype. There are literature reports citing safflower seed yield ranging from 800 to 3325kg/ha depending on genotype (Inan & Kirici, 2001; Dadashi & Khajehpour, 2004, Eslam, 2004; Azari & Khajehpour et al., 2005, Bayraktar et al., 2005; More et al., 2005; Cosge & Kaya, 2008; Tonguc & Erbas, 2009; Okcu et al., 2010; Beyyava et al., 2011; Sirel & Aytac, 2016). Safflower cultivars may generate large volumes of yield because of their increased plant height, biological yield, crop yields per head, and favourable environmental conditions (Alinaghizadeh et al., 2008).

5.4. Effect of planting date and genotype on oil content and yield

5.4.1. Oil content

In the current study, the interaction of planting date and genotype significantly influenced safflower seed oil content. The current findings demonstrated that the lowest and highest oil content was produced from safflower genotypes planted in March and May, respectively. The differences in oil content among safflower genotypes was attributed to varied weather conditions mainly temperature, which were favourable for oil production in May than March planting. During May planting, safflower plants reached and developed vegetatively (emergence, rossete, elongation, branching) under cool winter conditions (May-July) and reached reproductive stage (from anthesis to physiological maturity) during warm summer conditions (August-September) which favoured oil content production due to high vegetative growth, yield components, and seed yield. According to Emongor and Oagile, (2017), warm weather resulted in high safflower seed oil content. Genetic and environmental factors and their strong interaction affected safflower oil content among genotypes (Knowles & Ashri, 1995; Yeilaghi et al., 2012; Loghmani et al., 2019). This implied that the diversity in genes and environment affected seed development and maturation process of grain formation which ultimately influenced oil content (Bhardwaj et al., 2003; Yeilaghi et al., 2012). Oil content and seed yield were shown to be positively correlated in the current study, thus high seed yield in May correlated with high oil content while low yields in March correlated with low oil content. This agrees with the findings of Shabana et al. (2013) who established a positive association between seed yield and oil content. Furthermore, in the current study, both safflower seed yield and oil content declined due to the short growing season which might have decreased the availability of carbohydrates during the time for oil synthesis. The low seed yield and oil content recorded in March were caused by crucial stages of flowering and seed filling converging with cold conditions which affected the plants' production due to chilling injury. Due to its detrimental effects on the enzymes responsible for converting carbohydrates to lipids, cold stress may have led to an accumulation of seed oil (Sehgal et al., 2018; Chehade et al., 2022). Sampaio et al. (2017) in Brazil reported that cold winter conditions negatively influenced safflower seed yield and oil content. All stages of plant growth and development are impacted by temperature stresses on both annual and perennial crops (Hatfield & Prueger 2015). For the first and second planting seasons, oil content ranged between 25.42-35.81% and 19-34.81%, respectively in the current study depending on the genotype. In different parts of the world, genotype-related differences have been observed in safflower oil content ranging from 20 to 47.5% (Smith, 1996; Weiss, 2000; Arslan & Kucuk 2005; Gawand et al., 2005;

Koutroubas & Papadoska 2005; Camas et al., 2007; Kizil et al., 2008; Vorpsi et al 2010; El-Lattief, 2012; Bergman & Kandel, 2013; Hamza, 2015; Killi et al., 2016).

Gene differences were responsible for the genetic variance in safflower genotypes' seed oil content that was identified in the current study. Variation of oil content and yield of oil seed crops including safflower has been reported to be influenced by morphological and physiological traits of seeds which are controlled by genetic expression (Ensiye & Khorshid. 2010; Cosge et al., 2007; Fernandez-Martinez, 2002; Baydar, 2000). Caliskan and Caliskan (2018) and Kose and Blir (2017) reported that for safflower, the genetic structure of a cultivar was an important determinant of the oil content compared to the environment. Different authors studying safflower have reported additive gene action (Golkar et al., 2011; 2017; Golkar, 2014), dominance alleles (Gupta & Singh, 1988; Ramachandran & Goud, 1981) or epistatic effects (Pahlavani et al., 2007) significantly controlled seed oil content.

In the current study, the genotype Sina had the highest oil content of 24.4-35.8% which was except for the genotype Gila, higher than the seed oil content of all other genotypes. The genotype PI537636 had the lowest seed oil content of 21.2-31.1% which was lower than the seed oil content of all the other genotypes depending on planting date and season of growing. Significant genetic variation in safflower seed oil content due to genotype has been reported in different regions of the world (Dajue & Mündel, 1996; Weiss, 2000; Samanci & Ozkaynak, 2003; Elfadl et al., 2005; Camas et al., 2007; Kizil et al., 2008; Abd El-Lattief, 2012; Hamza, 2015; Killi et al., 2016; Moatshe, 2019; Moatshe et al. 2020a). Samanci and Ozkaynak (2003) in Turkey reported that safflower seed oil content varied between 34.27 to 40.5% depending on genotype. Killi et al. (2016) also from Turkey reported that safflower seed oil content ranged between 29.53-33.89% depending on genotype. Abd El-Lattief (2012) evaluating 25 genotypes of safflower in Egypt reported that the seed oil content ranged between 26.36 to 36.50% depending on genotype. Hamza (2015) reported that safflower genotypes (six) grown under reclaimed soils in Egypt and irrigated with saline water (4.2 dS/m) varied in seed oil content between 28.5 to 34.3% depending on genotype. While Yeilaghi et al. (2012) evaluated 64 genotypes of safflower from different countries (seed sources from Iran, Syria, Turkey, USA, Cyprus, Mexico Egypt, Palestine, Portugal, Pakistan, China and France) in Iran found that seed oil content ranged between 23.39 to 35.49% depending on genotype and origin of seed (country).

5.4.2. Oil yield (kg/ha)

The oil yield of a crop is positively related to grain dry mass than oil content (Sharifmoghaddasi & Omidi, 2009; Moghaddasi & Omidi, 2010; Amoghein et al., 2012; Dosio et al., 2013; Shabana et al., 2013; Moatshe et al., 2016, 2020a). Planting date significantly influenced safflower oil yield in the current study. In both 2019/2020 and 2020/2021 seasons, safflower planted in May produced significantly high oil yield of 1317 and 973 kg/ha, respectively than other planting dates. On the contrary, safflower planted in March produced significantly lower oil yield of 306 and 221kg/ha, for 2019/2020 and 2020/2021 seasons respectively than other planting dates. The high safflower oil yield with May planting was explained by the high vegetative growth (long maturation, high LAI, LAD, NAR, CGR, RGR, and leaf chlorophyll content), yield components (capitula diameter, capitula number/plant, seed number/capitulum, 1000-seed weight, and total dry matter), seed yield, and seed oil content. The opposite was true with safflower planted in March. Increase in safflower seed yield, yield components, and seed oil content are reported to be significantly positively correlated with increase in safflower oil yield (Sharifmoghaddasi & Omidi, 2009; Moghaddasi & Omidi, 2010; Amoghein et al., 2012; Dosio et al., 2013; Shabana et al., 2013; Moatshe et al., 2016, 2020a; Chehade et al., 2022).

According to Abd El-Laffief (2012), the relationship between seed yield and oil yield is significantly positive (r = 0.99). Sharifmoghaddasi and Omidi (2009) confirmed a source-sink relationship by reporting a significantly positive correlation between safflower grain yield and oil yield (0.84), biomass coefficient (0.71) and number of capitulum per plant (0.97). Safflower seed yield and oil yield have been shown to be positively correlated in literature (Johnson et al., 2001; Omidi, 2006; Eslam et al., 2010; Bagavan & Ravikumar, 2011; Dosio et al., 2013; Shabana et al., 2013; Moatshe et al., 2016, 2020a). Begna and Angandi (2016) also reported that during seed filling period, high assimilate supply is positively associated with high oil content and yield. The correlation between oil yield and yield related traits implies that an increase in the above agrophysiological variables contributed to an efficient and effective seed filling process and nutrient reserve accumulation which are the key contributors to seed yield, oil content and oil yield.

A significant genotype variation in safflower seed oil yield was observed in the current study. The results showed that the genotype Sina produced significantly higher oil yield of 840 to 1156 kg/ha than other genotypes, while the genotype Gila produced the lowest seed yield of 490 to 721 kg/ha, depending on season. In the current study, genotypes such as Sina that had high vegetative growth (long maturation, high LAI, LAD, NAR, CGR, RGR, and leaf chlorophyll content), yield components (capitula diameter, capitula number/plant, seed number/capitulum, 1000-seed weight, and total dry matter), seed yield, and seed oil content also had high seed oil yield. The variation of safflower oil content and yield are influenced by morphological and physiological traits of seeds as controlled by genetic expression (Baydar, 2000; Fernandez-Martinez, 2002; Cosge et al., 2007; Ensiye & Khorshid, 2010; Kose & Blir, 2017; Oarabile, 2017; Emongor et al., 2017; Caliskan & Caliskan, 2018; Moatshe, 2019; Moatshe et al. 2020a). Oarabile (2017) in Botswana reported that the genotype Sina produced much more oil than the other genotypes under study, with a yield of 1313 kg/ha. Oil yields from the genotypes PI 314650-Milutin-114-Kazakistan and PI 306830-BJ-1632-India were not statistically different, despite the genotype PI 537632-1038-USA's yield of 692 kg/ha being second only to Sina's (Oarabile, 2017). The lowest oil yield was 226 kg/ha for the genotype PI 30441-BJ-2621-Iran (Oarabile, 2017). In Oarabiles' study, the oil yield ranged between 226 and 1,313 kg/ha depending on the safflower genotype. Camas et al. (2007) and Omidi et al. (2012) reported safflower oil yield of 193-821 and 412-522 kg/ha depending on genotype, respectively. According to Gawand et al. (2005), four safflower cultivars produced oil with yields ranging from 322 to 460 kg/ha. While Koutroubas and Papadoska (2005) evaluating 21 genotypes of safflower reported oil yield ranged from 416 to 701 kg/ha. Abd El-Lattief (2012) in Egypt evaluated 25 safflower genotypes and reported an oil yield of 141 to 1,039 kg/ha depending on genotype. While Hamza (2016) also from Egypt evaluating six safflower genotypes reported oil yield of 580 to 860 kg/ha. Omidi (2006) in a four-year study evaluating 10 safflower genotypes reported oil yield of 238 to 967 kg/ha depending on genotype and year. Omidi (2006) also noted that the interactions between year x location, and year x location x genotype were significantly different, suggesting that the responses of various safflower genotypes to various climatic conditions varied. While Shabana et al. (2013) and Jalilian et al. (2012) reported that interaction of environmental factors during seed development and crop physiological maturity influenced genotype differences in oil yield of safflower. Therefore, the safflower oil yield of the current study was within the range reported in literature cited above.

CHAPTER 6 CONCLUSION

6.1. Conclusion

From the results, the best time to plant safflower in Botswana is in the month of May during the onset of winter season. Thus, late planting in May significantly ($P < 0.05$) increased phenological traits, vegetative growth, yield components, oil content, seed yield and oil yield of safflower. On the other hand, although March planting had a longer growth cycle, high LAI, LAD, plant height, more branch numbers and heavier 1000-seed weight, the safflower seed yield was significantly low than any other planting date. This was because the parameters that influenced yield such as NAR, CGR, capitula number and seed number were significantly ($P < 0.05$) lower than other planting dates caused by low chilling temperatures of 0°C or below. The slow growth of agro-physiological (NAR, CGR, capitula number and seed number/capitulum) parameters were experienced during anthesis when flowering converged with low winter air temperatures of -4.2-- -6.3°C in winter which lasted for 2-3 days led to chilling injury which reduced safflower seed yield in safflower planted in March. Planting in March was highly discouraged as plant performance was drastically reduced due to unfavourable climatic conditions converging at a sensitive phenological stage (onset of flowering). The best performing genotypes were Sina, followed by PI527710 and PI57636 which did not differ significantly, and Gila was the least performing genotype in most traits.

6.2. Recommendations

It was recommended that the same study be repeated in other locations of Botswana with different climatic conditions and more genotypes be evaluated. Studies on the difference in night and day temperatures (DIF) be undertaken because DIF is an important attribute that influences morphological and physiological attributes of safflower.

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APPENDIX

Appendix 1. Average monthly precipitation, temperature, and relative humidity in South-East Botswana for 2019/2020 and 2020/2021 growing seasons.

2019/2020 season							
Temperature (^{0}C)				Rainfall (mm)	Relative humidity (%)		
Month	Max	Min	Monthly mean		0800hrs	1400hrs	Monthly mean
December	35.15	21.33	28.24	108	65.42	44.65	55.03
January	31.06	19.15	25.11	136.7	73.00	44.68	58.84
February	31.37	18.99	25.18	28.5	67.83	37.34	52.59
March	30.30	17.04	23.67	53.6	69.39	36.29	52.84
April	27.68	13.91	20.80	52.6	69.70	36.17	52.93
May	25.11	7.07	16.09	0	69.77	24.81	47.29
June	21.64	3.25	12.45	0	65.63	26.93	46.28
July	22.01	2.09	12.05	0	57.00	22.58	39.79
August	25.46	6.67	16.07	0	47.38	19.81	33.59
September	28.87	13.64	21.25	0	43.15	22.48	32.82
October	31.13	18.20	24.67	47.4	53.87	31.67	42.77
November	29.94	17.86	23.90	124.7	70.77	41.87	56.32
Annual mean			20.79				47.59
Total				551.5			
2020/2021 season							
December	29.67	19.53	24.60	128.2	72.40	49.52	60.96
January	30.32	20.17	25.24	46.4	71.51	48.28	59.90
February	28.35	18.88	23.62	24.8	72.37	54.17	63.27
March	29.51	15.35	22.43	1.1	77.18	35.28	56.23
April	29.38	12.13	20.76	4.4	62.38	24.82	43.60
May	25.29	8.31	16.80	0	67.83	25.73	46.78
June	23.18	4.66	13.92	0	67.35	20.56	43.96
July	21.48	2.26	11.87	0	60.86	21.48	41.17
August	26.18	8.47	17.32	0	56.19	19.30	37.75
September	30.01	13.22	21.61	0	44.18	22.16	33.17
October	29.76	15.10	22.43	43.5	51.46	20.81	36.14
November				35.2	51.52	17.67	34.60
Annual mean			20.05				
Total				283.6			

Appendix 2. Safflower at pre-anthesis before chilling injury

Appendix 3**.** Safflower showing severe signs of chilling injury at flowering initiation

Appendix 4**. Safflower plant leaves showing signs of senescence during flowering.**

Appendix 5. Flower heads showing sign of senescence due to chilling injury.