Safflower (Carthamus tinctorius *L.)*

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1. Introduction

Safflower (*Carthamus tinctorius* L.) is a member of the Compositae or Asteraceae family (Weiss, 2000), grown to extract high-quality edible oil from seeds or for birdseed. In addition, its flowers are used as dye sources for textiles and food, medicinal purposes (Ekin, 2005; Dordas and Sioulas, 2008; Istanbulluoglu, 2009; Emongor, 2010), and have potential for the manufacture of plant-made pharmaceuticals (Lacey et al., 1998; Li et al., 2016; Liao et al., 2019). Safflower is grown in arid and semi-arid temperate regions (Weiss, 2000; McPherson et al., 2004). It is native to the Fertile Crescent, located between southern Israel and western Iraq (Ashri, 1975; Knowles and Ashri, 1995; Weiss, 2000; McPherson et al., 2004; Chapman et al., 2010; Zareie et al., 2013; Khalili et al., 2014; Pearl et al., 2014; OECD, 2020). Compared to other oilseed crops, safflower has remained a minor, underutilized, and neglected crop (Ekin, 2005; Emongor, 2010). Despite its adaptability to diverse growing conditions, high yield potential, and varied uses for different plant parts, safflower has received little research attention. On the positive side, currently interest in safflower production has increased due to low oilseed production in countries with considerable low rainfall, consumer preferences for healthy vegetable oils with lower saturated fats, medicinal uses of flowers, extraction of edible natural dyes from flowers to be used in food, pharmaceutical, and cosmetics coloring, and have become more widely known and increased demand of vegetable oil for biodiesel (Singh and Nimbkar, 2006; Mailer et al., 2008; Emongor, 2010; Emongor and Oagile, 2017; Khalid et al., 2017). Safflower oil is rich in the polyunsaturated essential fatty acid linoleic acid (70%−87%) and monounsaturated fatty acid oleic acid (11%−80%), an important trait that has increased safflower production (Murthy and Anjani, 2008; Aghamohammadreza et al., 2013; Kumar et al., 2015; Moatshe et al., 2020a). Linoleic acid offers nutritional and therapeutic benefits, such as preventing coronary heart disease, arteriosclerosis, high blood pressure, and hyper lipemia (Wang and Li, 1985; Cosge et al., 2007; Li et al., 2016;

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Liao et al., 2019). Safflower seeds are also a rich source of minerals (Zn, Cu, Mn, and Fe), vitamins (thiamine and β-carotene), and tocopherols α, β, and γ (Velasco et al., 2005) (Fig. 24.1).

2. Safflower uses

Safflower is an ancient crop (Zohary et al., 2012; FAO, 2019) with various past and present uses (Dajue and Mündel, 1996; Emongor, 2010; Emongor and Oagile, 2017). It is a multipurpose crop grown for orange-red dye, cut flowers, leafy vegetables, medicinal properties, livestock feed, and high-quality edible vegetable oil (Dajue and Mündel, 1996; Dwivedi, 2005; Emongor, 2010; Zohary et al., 2012; Li et al., 2016; Sirel and Aytac, 2016; Liao et al., 2019; Moatshe et al., 2020a). The seeds are used to extract high-quality edible and industrial oils and for bird seed (Knowles, 1989; Dajue and Mündel, 1996; Ekin, 2005; Bergman et al., 2007; Emongor, 2010; Bergman and Kandel, 2019). More recent uses of safflower include special edible oil types for human diets (Velasco and Fernández-Martínez, 2004), biofuels (Bergman and Flynn, 2009), transgenic pharmaceuticals (McPherson et al., 2004; Mündel and Bergman, 2009) due to the ease of isolating oleosin proteins from seeds (Lacey et al., 1998), and biogas production using safflower straw (Hashemi et al., 2019).

Figure 24.1
Safflower crop in a farmer's field in Botswana.

2.1 Food uses

2.1.1 Oil

Safflower oil, extracted from safflower seed, is often considered healthier than olive and canola oils (Bergman, 1997; Corleto et al., 1997) and sunflower oil (Dajue and Mündel, 1996) due to its lower percentage of saturated fatty acids. Whole safflower seed contains 16.1%–64.6% oil content depending on genotype, environmental condition, morphology, physiology, agronomic practice, growing season, and geographical region (Knowles, 1989; Dajue and Mündel, 1996; Weiss, 2000; Samanci and Ozkaynak, 2003; Elfadl et al., 2005; Camas et al., 2007; Kizil et al., 2008; Abd El-Lattief, 2012; Ahmadzadeh et al., 2014; Hamza, 2015; Killi et al., 2016; Oarabile, 2017; Emongor et al., 2017; Moatshe, 2019; Moatshe et al., 2020a). The fatty acid composition of the oil determines its quality, nutritional properties, and commercial use (food, pharmaceutical, or industrial). Safflower oil comprises the following fatty acids: linoleic (53.8%–84%), oleic (9.5%–91%), palmitic (4.9%–16.1%), stearic (1.7%–6.3%), linolenic (0%–1.5%), myristic (0%–0.2%), palmitoleic (0%–0.5%), arachidic (0%–1.9%), behenic (0%–0.7%), eicosaenoic (0%–0.2%), lignoceric (0%–0.8%), lauric (0%–0.07%), and heptadecanoic (0%–0.04%) (Knowles, 1989; Fernández-Martínez et al., 1993; Velasco and Fernández-Martínez, 2001; Cosge et al., 2007; Mailer et al., 2008; Sabzalian et al., 2008; Hamdan et al., 2009; Ensiye and Khorshid, 2010; Golkar et al., 2011; Vosoughkia et al., 2011; Ben-Moumen et al., 2013; Kostik et al., 2013; Moumen et al., 2013; Al Surmi et al., 2015; Orsavova et al., 2015; Liu et al., 2016; Emongor et al., 2017; Khalid et al., 2017; Katkade et al., 2018; Khan et al., 2018; Moatshe, 2019; Moatshe et al., 2020a).

Lipids comprise saturated (no double bonds) and unsaturated (double bonds) fatty acids. Unsaturated fatty acids can be monounsaturated or polyunsaturated. Monounsaturated fatty acids (MUFAs) have one double bond (oleic acid, C18:1; palmitoleic acid, C16:1). Polyunsaturated fatty acids (PUFAs) have two to six double bonds (linoleic acid, C18:2; arachidic acid, C20:0) (Burdge and Calder., 2005; Mišurcová et al., 2011; Orsavova et al., 2015; Piccinin et al., 2019). The human body cannot biosynthesize PUFAs with the first double bond on C3 and C6 from the methyl-end due to the absence of appropriate enzymes; therefore, these essential fatty acids must come from the diet (Burdge and Calder, 2005; Mišurcová et al., 2011; Glick and Fischer, 2013). The fundamental PUFAs are α-linolenic (ALA, 18:3, n−3) and linoleic (LA, 18:2, n-6) acids from which other PUFAs are derived (Mišurcová et al., 2011). Safflower oil contains both ALA and LA. Essential fatty acids are involved in many biochemical pathways and have cardioprotective effects due to their antiatherogenic, antithrombic, anti-inflammatory, antiarrhythmic, and hypolipidemic roles. They may also reduce the risk of cardiovascular diseases, cancer, osteoporosis, diabetes, and other health promotive activities due to their effect on lipoprotein contents, biological membrane fluidity, membraned enzyme and receptor function, eicosanoid production, blood pressure regulation, and mineral metabolism (Weiss et al., 2005; Mišurcová et al., 2011; Mobraten et al., 2013). Safflower oil is an excellent health care product (Pongracz et al., 1995; Abidi, 2001; Arslan et al., 2003), with health benefits that include prevention and treatment of hyperlipidemia, arteriosclerosis, coronary heart disease, blood pressure, osteoporosis, diabetes, cancer, and mineral metabolism (Pongracz et al., 1995; Herbel et al., 1998; Abidi, 2001; Weiss et al., 2005; Fasina et al., 2006). Herbel et al. (1998) reported that safflower oil in human diets significantly lowered plasma total cholesterol and low-density lipoprotein (LDL) cholesterol concentrations. Arslan et al. (2003) reported that safflower oil with high amounts of linoleic acid contained tocopherols, which have antioxidant effects and high vitamin E content. For this reason, safflower oil has been recommended in the diets of patients with cardiovascular diseases and for anticholesterol effects (Smith, 1996; Herbel et al., 1998; Pongracz et al., 1995; Arslan et al., 2003). Consumption of safflower oil high in oleic fatty acid has been correlated with improved liver and pancreas secretory activity and reduced risk of gastric-duodenal ulcers (Bermudez et al., 2011). The role of oleic acid in the maintenance of normal blood pressure has been confirmed by EFSA (2011) and FDA (2021).

Safflower oil high in oleic acid is highly stable on heating and does not give smoker smell during frying due to its high oxidative stability (Yodice, 1990; Smith, 1996; Sabzalian et al., 2008; Han et al., 2009; Al Surmi et al., 2015; Khalid et al., 2017). Safflower oil consistency remains the same at low temperatures (−12°C), making it suitable for frozen/chilled foods (Weiss, 2000). It is also used to prepare mayonnaise and salad dressings (Kleingarten, 1993; Nimbkar, 2002; Singh and Nimbkar, 2006). Safflower oil is also better suited to hydrogenation for margarine production than soy or canola oils (Kleingarten, 1993).

Safflower plants can be genetically modified to produce high-value proteins in seeds that can be used to develop pharmaceuticals and industrial enzymes. SemBioSys, a Calgary-based (Canada) company, has genetically transformed safflower plants to produce proteins of interest in seeds (Mündel et al., 2004; AgBiotechNet, 2006). The modification process follows the patented Stratosome Biologics system, which enhances the genetic bonding of target proteins of interest to oleosin (oil bodies of the seed). This bonding permits the purification of the target protein and the oil body fraction (Abenes et al., 1997; van Rooijen et al., 1992; Nyiforuk et al., 2006). The genetically engineered safflower plants are used to manufacture plant-produced insulin (AgBiotechNet, 2006). SemBioSys Genetics Incorporated could significantly impact the economics of insulin manufacturing, having produced the authentic insulin molecule in safflower at commercially viable levels (AgBiotechNet, 2006). The company is projected to produce over 2.5 kg insulin/ha of safflower production, enough to treat 6178 patients/year (AgBiotechNet, 2006).

2.1.2 Leaves

Safflower leaves are eaten as vegetables (Weiss, 2000; Gopalan, 2004; Sigh et al., 2017). They are rich in carotene (1.48–14.89 mg/100 g), protein (21.0%–29.7%), fat (1.1%–2.8%), riboflavin, vitamins A and C (5.92–19.0 mg/100 g), iron (3.42–55.1 mg/100 g), phosphorus (175–250 mg/100 g), calcium (185–708 mg/100 g), magnesium (142–220 mg/100 g), potassium (1510–1780 mg/100 g), sodium (469–581 mg/100 g), antioxidants, and fiber (Singh and Nimbkar, 2006; Suneel-Kumar et al., 2016a,b; Phuduhudu, 2017; Moatshe et al., 2020b). The nutritional content of safflower leaves varies with genotype, growing season, crop growth habit, environmental factors, and agronomic practice (Chope and Terry, 2009; Rouphael et al., 2012; Kunyanga et al., 2013; Suneel-Kumar et al., 2015, 2016a; Moatshe et al., 2020). Safflower leaves are consumed 30–70 days after planting (Gopalan, 2004; Suneel-Kumar et al., 2015, 2016a; Phuduhudu, 2017; Sigh et al., 2017; Moatshe et al., 2020c). Despite their high nutritional status, safflower leaf consumption as a green leafy vegetable is low to none in most countries (Fig. 24.2).

Figure 24.2
Safflower grown under drip irrigation by a farmer 30 days after germination, best stage for harvest to be used as a vegetable, Morwa Botswana.

2.1.3 Flowers

Zhaomu and Lijie (2001) reported that China produces 1800–2600 tons of safflower flowers annually used to extract dyes and manufacture pharmaceuticals. Weiss (2000) and Singh (2005) reported that safflower petals contain protein (10.4%–12.86%), total sugars (7.36%–11.81%), calcium (558–708 mg/100 g), iron (42.5–55.1 mg/100 g), magnesium (142–207 mg/100 g), potassium (3264–3992 mg/100 g), and vitamins B1, B2, B12, C, and E. Safflower flowers also contain all essential amino acids except for tryptophan (Singh, 2005). Safflower petals are used to make herbal tea (Sawant et al., 2000; Singh, 2005; Emongor, 2010; Emongor and Oagile, 2017).

Safflower flowers can be used for medicinal purposes (Wang and Li, 1985; Zhou, 1986, 1992; Yu, 1987; Qin, 1990; Qu, 1990; Li et al., 2016; Mani et al., 2020; Adamaska and Biernacka, 2021); they have purgative, analgesic, and antipyretic characteristics, and can be used to treat patients with poisoning (Asgarpanah and Kazemivash, 2013). Safflower petals are used to treat menstrual cramps, postpartum hemorrhage, whooping cough, chronic bronchitis, rheumatism, and sciatica (Wang and Li, 1985; Zhou, 1986; 2005; Luo et al., 2019; Adamska and Biernacka, 2021) and cardiovascular, cerebrovascular, and gynecological complications (Han et al., 2016; Li et al., 2016; Ao et al., 2018; Hu et al., 2020; Ma et al., 2019; Zhang et al., 2019; Chen et al., 2020; Mani et al., 2020; Ye et al., 2020). Safflower petal extracts contains anticoagulant, vasodilating, antihypertensive, antioxidative, neuroprotective, immunoprotective (Bie et al., 2010; Xu et al., 2017; Li et al., 2018; Sun et al., 2018; Lee et al., 2020; Tan et al., 2020), and anticancer agents (Jin et al., 2019; Ma et al., 2019; Qu et al., 2019), with promotive impacts on melanin synthesis (Yin et al., 2015; Adamska and Biernacka, 2021). Safflower is also effective for ailments involving the neurotropic, cardiotropic, hemopoietic, and diaphoretic systems (Punjanon et al., 2004). The phytochemistry of safflower petals indicates several active compounds, including flavonoids, hydroxysafflor yellow A, phenylethanoid glycosides, coumarins, fatty acids, and steroids, in various plant parts (Zhou et al., 2009; Li et al., 2016; Zhang et al., 2017).

Severe sepsis and septic shock are common in critical care medicine and correlated with high mortality (Angus et al., 2001; Russel et al., 2008; Perner and Haase, 2012; Asfar et al., 2014; Van Zanten et al., 2014; Li et al., 2016). Li et al. (2016) showed that safflower yellow A significantly reduced mortality and increased survival in severe sepsis and septic shock patients. Failure of multiple organs and deterioration of cardiorespiratory function systems cause high mortality from severe sepsis and septic shock (Angus et al., 2001; Van Zanten et al., 2014; Li et al., 2015, 2016). Safflower yellow improved the hemodynamic index of patients with severe sepsis and septic shock by increasing blood pressure and decreasing heart rate, thus improving the tissue and organ perfusion indices

(Li et al., 2016). The decreased heart rate conferred benefits such as lengthening coronary diastolic perfusion time, improving coronary perfusion, and alleviating myocardial ischemia and hypoxia (Li et al., 2016).

Stroke is a leading cause of death and disability worldwide (Mathers and Loncar, 2006; Li et al., 2015). Despite improvements in stroke care, most patients only make partial or poor recovery after stroke, with chronic disability the major burden of stroke (Wolfe, 2000; Li et al., 2015). Based on traditional Chinese medicine, clinical trials in China showed beneficial effects of Safflower Yellow Injection in treating cerebral infarction (Li et al., 2015). Safflower Yellow Injection contains hydroxysafflor yellow A (Yang et al., 2001; Ma et al., 2012; Ye et al., 2012) and was certified by the State Pharmaceutical Administration of China in 2002 after evaluation in clinical trials (Li et al., 2015). Hydroxysafflor yellow A's protective effect in ischemic stroke have been related to antithrombosis (Zhu et al., 2005; Fan et al., 2014; Li et al., 2015), anticoagulation (Sun et al., 2010; Li et al., 2015), antioxidation (Sun et al., 2012), anti-inflammation (Ye and Gao, 2008), and anticalcium dysregulation (Tian et al., 2004).

The main components of safflower petals are carthamidin and carthamin (Tang and Eisenbrand, 1992; Asparpanah and Kazemivash, 2013; Li et al., 2015; Zhang et al., 2017), nontoxic food colorants (yellow and red, respectively) for coloring and flavoring foods such as cakes, sweets, biscuits, butter, ice cream, rice, soups, sauces, and breads, and as additives in pharmaceuticals and beverages (Watanabe and Terabe, 2000; Zohary and Hopf, 2000; Ekin, 2005; Emongor, 2010). With the advent of cheaper synthetic dyes such as aniline, the use of safflower flowers as a source of edible color declined to zero in the 20th century. However, interest in safflower petal extracts as a source of natural food colorant has recently increased due to a ban on the use of synthetic colors in foods in European countries and elsewhere and health-conscious consumers moving away from synthetic food colorants and demanding naturally derived food colorants (Dajue and Mündel, 1996; Singh and Nimbkar, 2006; Emongor, 2010; Hughes et al., 2010; Katz and Williams, 2011; Jadhav and Joshi, 2015; Bagley, 2017; Vogel, 2018). Dried safflower petals also contain quinochaloness, flavonoids, alkaloids, polyacetylene, aromatic glucosides, and organic acids (Tu et al., 2015) (Figs. 24.3 and 24.4).

2.2 Livestock feed

Safflower can be grown in regions with relatively low temperatures (Koutroubas and Papadoska, 2005), saline land (Kaya et al., 2003), and water deficit (Leshem et al., 2000; Quiroga et al., 2001; Bassil and Kaffka, 2002; Yau, 2007; Bar-Tal et al., 2008; Emongor, 2010; Emongor and Oagile, 2017) where most fodder crops cannot grow. Safflower can be used as fodder of high nutritive value when harvested at the onset of flowering (French et al., 1988; Smith, 1996; Weiss, 2000; Standford et al., 2001; Berglund et al., 2007;

Figure 24.3
Safflower petal harvesting in Lethakeng Botswana.

Figure 24.4
Safflower flowering at the end of winter in a farmer's field, Morwa Botswana.

Peiretti, 2009, 2017). Safflower is a cheap source of natural PUFAs and MUFAs for livestock (Moatshe et al., 2020a). Safflower can be grazed directly or preserved as silage or hay (Weinberg et al., 2002; Corleto et al., 2005; Landau et al., 2005). Safflower seed, meal, and cake can be used as protein and energy supplements for animal nutrition (Chidoh, 2012; Phuduhudu, 2017; Peiretti, 2017; Kereilwe et al., 2020). Whole safflower seeds are good sources of fat for lactating dairy cows (Stegeman et al., 1992; Alizadeh et al., 2010). Safflower cake or meal is high in protein (40%–55%) (Gohl, 1982; Lardy and Anderson, 2009; Voicu et al., 2009; Jacob, 2015; Phuduhudu, 2017; Phuduhudu et al., 2018) and thus can be used as a protein supplement for low protein forages in ruminant diets (Bolte et al., 2002; Bottger et al., 2002; Dixon et al., 2003; Kott et al., 2003; Scholljegerdes et al., 2004) or poultry backgrounding diets (Yadav and Mathur, 2009; Ehsani et al., 2014).

2.2.1 Forage

Safflower plants can be grazed by animals or stored as hay or silage when plants are still succulent (Bar-Tal et al., 2008). Safflower forage is palatable with feed value and yields similar to or better than oats or lucerne (Smith, 1996; Wichman, 1996). Safflower pasture is adequate for growing ruminants with medium nutrient requirements for pasture quality (Landau et al., 2005). Safflower pasture quality and yield depend on the stage of plant development and biomass accumulation (Tanaka et al., 1997; Uslu, 1997; Landau et al., 2005; Berglund et al., 2007; Peiretti, 2009; Phuduhudu, 2017; Kereilwe et al., 2020). Safflower plants cut at an early stage of growth yield less forage but have high nutritional content. The best time to harvest safflower for livestock fodder is at the bud initiation stage or seed filling stage (Mündel et al., 2004; Corleto et al., 2005; Landau et al., 2005; Peiretti, 2009; Phuduhudu, 2017). Sheep and cattle can graze succulent safflower plants at the end of the elongation or bolling stages, regrowth, or stubble fields after harvest (Landau et al., 2004; Chidoh, 2012; Phuduhudu, 2017). Vonghia et al. (1992) reported that safflower green fodder had similar digestibility as a vetch–oat mixture when fed to rams. Cattle fed safflower forage in flowers was more susceptible to mouth ulceration due to spines because it was not selective of the various plant parts, unlike sheep and goats (Stanford et al., 2001; Mündel et al., 2004). However, spineless safflower cultivars have been bred as fodder for cattle (Leshem et al., 2001; Landau et al., 2004) (Fig. 24.5).

2.2.2 Silage

The quality of silage depends on the quality of the vegetation and the fermentation process. It is also important to know the dry matter (DM), pH, buffering capacity, and soluble solids content of safflower at harvest and during the fermentation process. Cutting safflower plants before the flowering stage lengthens the wilting period due to the low DM, impacting the drying velocity during wilting for ensiling (Weinberg et al., 2002; Peiretti, 2009). When safflower plants are harvested at the flowering stage for silage,

Figure 24.5
Safflower plants in the elongation stage, suitable for grazing, and making silage or hay for livestock, Morwa Botswana, August 2021.

wilting is not needed (Corleto et al., 2008). Safflower silage could be used as fodder in arid and semi-arid regions due to its drought tolerance (Weinberg et al., 2002, 2006). Landau et al. (2004) and Cazzato et al. (2011) demonstrated that safflower silage can be substituted for cereal silages in the diets of high-yielding dairy cows.

2.2.3 Seed and meal

Safflower cake is produced from the meal remaining after extracting the oil from seeds. It is high in proteins and can be used as a protein supplement for low protein forages in ruminant (Bolte et al., 2002; Bottger et al., 2002; Dixon et al., 2003; Kott et al., 2003; Scholljegerdes et al., 2004) or poultry diets (Yadav and Mathur, 2009; Ehsani et al., 2014), but it is not adequate for other monogastric animals due to its deficiency in lysine, methionine, and isoleucine (Scholljegerdes et al., 2004). Supplementing kid goats in Pakistan with safflower cake at 200 g kg^{-1} of feed was more economical and sustainable than the control diet due to the low cost (Ragni et al., 2015). The fatty acids in whole safflower seeds can affect the adipose tissue composition of conjugated linoleic acid (CLA) and transvaccenic acid (Bottger et al., 2000) and intestines (Scholljegerdes et al., 2001) in beef cattle. Bolte et al. (2002) studied the effect of dietary supplementation of cracked high-linoleate safflower seeds (16.6%) and high-oleate safflower seeds (14.7%) on the FA content of the adipose tissue and muscle in lambs. Lambs fed high-linoleate safflower seeds had 3–5 times higher CLA and transvaccenic acid than those fed the control diet. Similarly, lambs fed 6% safflower oil as dietary supplementation had higher FA and CLA composition in muscles (pars costalis diaphragmatis, leg, rib), subcutaneous adipose, and liver than the control diet (Mir et al., 2000).

Feeding oilseeds to lactating dairy cows can change the fatty acid composition and milk quality. Feeding lactating dairy animals with oilseeds changed the percentage of unsaturated fatty acids in milk fat by up to 40% (Casper et al., 1990; Stegeman et al., 1992; Kim et al., 1993; Dschaak, 2008); however, high biohydrogenation (BH) occurs in the rumen (Palmquist and Jenkins, 1980). Godfrey (2006) reported that feeding unprocessed safflower seed (SS) led to 50% of the seeds being excreted in the manure. However, feeding coarsely ground SS at 2% of diet DM to dairy cows improved feed efficiency by 11%. Milk fat content was not affected when cows were fed rolled SS at 10% of dietary DM in diets containing at least 50% of the forage as alfalfa (Stegeman et al., 1992). Dschaak (2008) reported that dairy cows fed a basal diet containing 56% forage (69% alfalfa hay and 31% maize silage) and 44% concentrate mix supplemented with 1, 2, 3, or 4% safflower seed (47% oil content and 26% NDF) of dietary DM resulted in a milk yield and energy corrected milk of 33.7 and 31.6 kg day^{-1}. Milk fat content decreased with increasing SS inclusion, while the rations did not affect milk protein and lactose contents (Dschaak, 2008). Milk fat content decreased by 11% with 4% SS in the dietary DM, but feeding 1, 2, or 3% SS resulted in a similar milk fat content (Dschaak, 2008). The content of milk urea N decreased with SS, irrespective of the proportion included, suggesting that SS supplementation improved dietary N use for milk production (Dschaak, 2008). Dry matter digestibility increased with SS supplementation at 1, 2, or 3% (Dschaak, 2008). Cis-9, trans-11 CLA in milk significantly increased as SS supplementation level increased (Dschaak, 2008). The total n-3 and n-6 FA contents in milk increased with SS supplementation (Dshaak, 2008). Dschaak (2008) showed that SS high in fat (47%) and low in fiber (26% NDF) can be used as a feed supplement for lactating dairy cows at less than 3% of dietary DM without causing deleterious effects on lactational performance. The enhanced milk quality with increased cis-9, trans-11 CLA content due to the addition of SS could improve human health. Safflower seeds have beneficial effects for consumers as they are rich in PUFAs (76% of total FAs-linoleic and linolenic FAs). Bell et al. (2006) reported that supplementing safflower oil at 6% of dietary DM increased cis-9, trans-11 CLA in cow milk, the best natural source of CLA in the human diet due to its anticarcinogenic properties (Pariza and Hargraves, 1985). Diet-induced changes in ruminal BH with enhanced levels of CLA in milk fat are also associated with decreased milk fat percentage. The BH theory of milk fat depression, proposed by Bauman and Griinari (2001), was based on the hypothesis that the pathways of ruminal BH change under certain dietary conditions to produce unique FA intermediates, some of which are potent inhibitors of milk fat biosynthesis, such as trans-10, cis-12 CLA (Baumgard et al., 2000). Feeding safflower oil to lactating dairy cows increased the contents of trans-10, cis-12 CLA in milk fat (Bell et al., 2006). Similar results of decreasing diet-induced milk fat are reported in the literature (Piperova et al., 2000; Peterson et al., 2003; Dschaak, 2008; Dschaak et al., 2010).

2.3 Textile industry

Dried flower petals are used to extract natural dyes used in food coloring and dyeing clothes (Oelke et al., 1992; Coronado, 2010; Emongor, 2010). Natural dyes from plants are becoming important because they are natural. The colorful matter in safflower is carthamin (red-water insoluble) and carthamidin (yellow-water souble) (Shin et al., 2008; Garcia, 2009). Mainly, the red colorant has been used for cosmetics and textiles (Shin et al., 2008; Badiger et al., 2009). The yellow carthamidin has not been used as a natural dye for textiles but is used as a natural food colorant (Yoon et al., 2003; Saito et al., 2005; Jadhav and Joshi, 2015; Bagley, 2017; Vogel, 2018). Carthamidin is present in a higher proportion than carthamin in safflower petals and is more stable than carthamin under UV light (Kanehira and Saito, 2001; Shin et al., 2008). Hydrophilic fibers such as cotton, wool, and others can pick up safflower dye because it is a direct or substantive (water-soluble compounds that have an affinity for fiber) dye (Badiger et al., 2009). The water-soluble yellow dye (carthamidin) and insoluble red dye (carthamine) are used in the carpet-weaving industry in Eastern Europe and the Indian subcontinent (Weiss, 2000).

2.4 Cut flower industry

In Western Europe, Japan, Latin America, the USA, and Kenya, spineless varieties of safflower are grown as cut flowers for domestic and export markets (Kiptum, 1998; Bradley et al., 1999; Kizil et al., 2008; Uher, 2008; Emongor, 2010). Safflower exploitation in European floriculture rapidly increased from 1980 to 2000 (Hegele, 1985; Hartrath, 1986; Ekin, 2005; Uher, 2008). In 2000, 35.2 million flowering stems of safflower were supplied to Dutch cooperative flower auctions for total sales of €5.3 million, with safflower ranked 39th among all cut flowers of commercial significance (Uher, 2008). In the same year, safflower was ranked 19th among imported cut flowers, with a sales value of about €2.6 million. However, from 2001 onward, flowering stem production and imports of safflower decreased; in 2008, safflower was ranked 59th with a total sales value of only €3.4 million (Uher, 2008). Safflower cut flowers are harvested when petals are visible on most of the flowers, and flowers are one-quarter to one-half open, as buds do not open well after harvest; freshly cut flowers usually last up to 10 days (Dole and Wilkins, 2005; Emongor and Oagile, 2017).

2.5 Other uses of safflower

Safflower high in linoleic fatty acid is used to manufacture high-quality paint and varnishes (Liebert, 1985; Dajue and Mündel, 1996; Smith, 1996; Singh and Nimbkar, 2006; Berglund et al., 2007). Research is underway investigating safflower oil as a biodiesel or blended with petroleum diesel (Oelke et al., 1992; Ogut and Oguz, 2006; Ilkilic et al., 2011; Nosheen et al., 2018; Yesilyurt et al., 2020). Safflower oil is also used in the cosmetics industry to produce hair creams, shampoos, face creams, perfumes, and body lotions due to its oily emollient and moisturizing properties (Liebert, 1985; Shouchun et al., 1993; Weiss, 2000; Nishimura et al., 2008; Domagalska, 2010).

3. Global distribution

Safflower originated in an area bound by the eastern Mediterranean, the Persian Gulf, Eastern Europe, Central Asia, and Abyssinia [Ethiopia and Eritrea] (Vavilov, 1951; Dajue and Mündel, 1996; McPherson et al., 2004; El-Bassam, 2010; Zohary et al., 2012; Zareie et al., 2013; Khalili et al., 2014; GRDC, 2017). Safflower seeds were reportedly used in Egyptian tombs over 4000 years ago and in China over 2200 years ago (Dajue and Mündel, 1996; Gyulai, 1996; Weiss, 2000). Compared to other oilseed crops, safflower is minor and underutilized despite its significant benefits (Dajue and Mündel, 1996; Ekin, 2005; Sehgal et al., 2009; Emongor, 2010; FAO, 2020a). Currently, safflower is commercially grown in more than 60 countries, occupying over one million hectares of agricultural land and producing over 850,000 tons of seed (FAO, 2020a). The top 10 leading countries for safflower seed production are Kazakhstan, the USA, Russia, Mexico, China, India, Argentina, Turkey, Tanzania, and Australia (FAO, 2020a; Tridge, 2021). Europe produces the most cut safflowers (Hegele, 1985; Hartrath, 1986; Ekin, 2005; Uher, 2008). Currently, safflower cultivation is increasing in arid and semi-arid regions due to the crop's drought, heat, cold, and salt tolerance properties (Bassil and Kaffka, 2002; Khalili et al., 2014; Emongor et al., 2015; Emongor and Oagile, 2017). Fig. 24.6 shows the global distribution of safflower cultivation georeferenced in 2017 (GBIF Backbone Taxonomy, 2017), not including safflower cultivation in East Africa (Tanzania, Kenya, and Sudan). Safflower cultivation recently commenced in Botswana.

4. Tolerance to abiotic and biotic stresses

Crop production is threatened by several stress factors, often correlated with global warming (Schlenker and Roberts, 2009; Challinor et al., 2014; Zhao et al., 2017). Crop adaptation to changing environmental conditions often reduces yields. Multiple abiotic and/or biotic stresses can result in crops adapting to one stress but becoming susceptible to other stresses. Global warming is predicted to increase the frequency of droughts, floods,

Figure 24.6
Recorded global distribution of cultivated safflower (*Carthamus tinctorius* L.) from 1795 to 2019. NB: *Yellow (or light gray) dots* indicate georeferenced occurrences.

and heatwaves (IPCC, 2007; Mittler and Blumwald, 2010). Climate change may also affect the habitat range of pests and pathogens, with high temperatures increasing pathogen spread (Bale et al., 2002; Luck et al., 2011; Madgwick et al., 2011; Nicol et al., 2011). Climate change could also further enhance the migration of pathogens and pests, resulting in locally adapted crop cultivars becoming susceptible to new biotic stresses. This has been exemplified by the migration of fall armyworm (*Spodoptera frugiperda*) from its native tropical and subtropical Americas (Meagher et al., 2004; FAO, 2020b) to Africa and other parts of the world. Fall armyworm devastated crops in sub-Saharan Africa from 2016 to 2018. Due to climate change, the fall armyworm was first detected in west and central Africa in 2016. Within 2 years, it had spread to all sub-Saharan Africa (FAO, 2020b) and is now an established pest in Botswana and the rest of southern Africa. The other example is the desert locust (*Schistocerca gregaria* forsk.), a commonly solitary insect in desert and scrub regions of northern Africa, the Sahel, Arabian Peninsula, and parts of Asia to western India (Steedman, 1990). However, the increase in prolonged heavy rain and rare cyclones in eastern Africa and the Arabian Peninsula from 2018 to 2020 caused a plague of desert locusts to descend to East Africa, West Africa, and South Africa (National Geographic, 2020), decimating food and fodder crops and green vegetation and threatening the already fragile food security in the region.

The rise in global temperatures could cause climate anomalies, leading to crops encountering increasing abiotic and biotic stress combinations, which will severely affect their growth, development, and yield (Mittler, 2006; Prasad et al., 2011; Atkinson et al., 2013; Suzuki et al., 2014; Mahalingam, 2015; Ramegowda and Senthil-Kumar, 2015). The presence of combined abiotic stresses can be more destructive to crop productivity than individual stresses at different stages of crop growth and development (Mittler, 2006; Prasad et al., 2011, 2021). Drought, high and low temperatures, and salinity stress can affect the presence and spread of pathogens, insect pests, and weeds (Coakley et al., 1999; Scherm and Coakley, 2003; McDonald et al., 2009; Peters et al., 2014). Combined stresses further affect plant—pest interactions by altering plant physiology and defense responses (Scherm and Coakley, 2003). Combined stress factors on crops are not always additive because the results depend on the nature of interactions between the stress factors (Atkinson et al., 2013; Prasch and Sonnewald, 2013; Choudhary et al., 2016; Hussain et al., 2016). Understanding the nature of these interactions is important for determining the impact of combined abiotic and biotic stresses on plants. Sustainable safflower production requires understanding the physiological strategies and molecular and genetic basis of tolerance to combined biotic and abiotic stresses to breed safflower genotypes and develop agronomic practices profitable in safflower production (Hussain et al., 2016).

Abiotic and biotic stresses affect crop growth, development, and yield. Abiotic stresses commonly affecting crop productivity are extreme temperatures (heat and cold), drought, flooding, salinity, nutrient deficiencies, and heavy metal toxicities, which are estimated to reduce crop yields by more than 50% (Wang et al., 2003). Safflower production generally occurs in arid and semi-arid without irrigation and fertilizer application (Hojati et al., 2011). While safflower has a relatively low water requirement compared with other oilseed crops, it does not tolerate waterlogging. Waterlogging for more than 2 days deprives roots of oxygen, leading to plant death (GRDC, 2017). Waterlogging further promotes the development of root diseases such as Phytophthora root rot (Emongor and Oagile, 2017; GRDC, 2017; OECD, 2020). Heavy rain or irrigation combined with high humidity and temperatures greater than 20°C during flowering and physiological maturity inhibit pollination, promote diseases, especially leaf blight caused by *Alternaria carthami* and *A. alternate*, discolor seeds, and cause seeds to germinate in the capitula (Mortensen et al., 1983; Li and Mündel, 1996; Mündel et al., 1997; Mirshekari et al., 2013; Emongor and Oagile, 2017; GRDC, 2017). Santos et al. (2018) reported that safflower plant height, yield components, and seed and oil yields depend on the interaction of watering regime and nitrogen (N) fertilizer application rate. Other studies have also demonstrated the importance of water and nutrient availability in safflower production (Siddiqui and Oad, 2006; Dordas and Sioulas, 2008; Elfadl et al., 2009; Bagheri and Sam-Dailiri, 2011; Omidi et al., 2012; Aghamohammadreza et al., 2013; Miri and Bagheri, 2013; Hasanvandi et al., 2014; Sampaio et al., 2016). Salinity and drought stress negatively affect safflower growth, development, seed and oil yields, and fatty acid composition (Irving et al., 1988; Bassil and Kaffka, 2002; Koutroubas et al., 2004; Farooq et al., 2009; Koutroubas and Papakosta, 2010; Hojati et al., 2011; Harrathi et al., 2012; Hussain et al., 2016). Omidi et al. (2012) reported that water stress reduced photosynthesis, cell expansion, plant height, leaf number and leaf area, yield, and economic efficiency. Omidi et al. (2012) confirmed the findings of Omidi and Sharifmogadas (2010), who concluded that the amount of available water was important for determining safflower yield. Safflower genotype and plant density significantly interacted to influence phenological characteristics (Mokhtassi-Bidgoli et al., 2007; Sharifi et al., 2012; Vaghar et al., 2014; Emongor et al., 2015; Moatshe, 2019) and oil content and fatty acid composition (Murthy and Anjani, 2008; Aghamohammadreza et al., 2013; Liu et al., 2016; Golkar et al., 2017; Moatshe et al., 2020a). Variation in safflower oil content and fatty acid composition can be caused by various factors, such as genotype, geographic location, cultural practice (agronomic management), soil type, climatic condition, and growing season (Fernández-Martínez et al., 1993; Cosge et al., 2007; Guan et al., 2008; Mailer et al., 2008; Vosoughkia et al., 2011; Aghamohammadreza et al., 2013; Khalid et al., 2017; Moatshe et al., 2020a). Safflower grown under high temperatures (>25°C in summer in Botswana) accelerates safflower growth and development, reducing yield and oil content (Emongor et al., 2015, 2017; Moatshe et al., 2020a). The reduced seed yield and oil content of summer-grown safflower compared to winter-grown was attributed to contracted phenological stages, including physiological maturity (Kedikanetswe, 2012; Emongor et al., 2015, 2017; Moatshe et al., 2020a). Contracted phenological stages of safflower in warmer climates have been reported in literature (Craufurd and Wheeler, 2009; Walthall et al., 2012; Elias et al., 2018).

Biotic factors that significantly influence crop productivity are insect pests, weeds, and pathogens (fungi, bacteria, viruses, and nematodes). Safflower evolved from desert or arid environments and is thus susceptible to foliar and root rot diseases when grown in regions with high rainfall or irrigated under conditions accompanied by high relative humidity and temperatures >25°C (Dajue and Mündel, 1996; Nimbkar, 2008; Mirshekari et al., 2013; Emongor and Oagile, 2017; OECD, 2020). The most common foliar disease in areas with high rainfall is leaf blight caused by *Alternaria carthami* (Morrall and Dueck, 1982; Mündel et al., 1985; Dajue and Mündel, 1996; Singh and Nimbkar, 2006; Emongor and Oagile, 2017). Other foliar diseases include those caused by *Botrytis cinerea*, *Cercospora* *carthami*, *Pseudomonas syringae*, *Puccinia carthami,* and *Ramularia carthami* (Dajue and Mündel, 1996; Emongor and Oagile, 2017; GDRC, 2017). Safflower is also susceptible to root rot diseases caused by *Phytophthora* spp. *(P. cryptogea, P. dreschsleri), Sclerotinia sclerotiorum, Pythium ultimum, Fusarium oxysporum* f.sp. *carthami*, and *Verticillium dahlia* (Dajue and Mündel, 1996; Nasehi et al., 2013; Emongor and Oagile, 2017; Esfahani et al., 2018). In Iran, charcoal rot, caused by *Macrophomina phaseolina*, has become a significant disease infecting safflower (Esfahani et al., 2018) and has also been identified in Australia (GDRC, 2010).

The most serious insect pest to constrain safflower distribution is the safflower fly (*Acanthiophilus helianthi*), currently confined to Africa, Asia, and Europe (Dajue and Mündel, 1996; Emongor and Oagile, 2017). However, in Botswana and other African countries, India, Spain, the Middle East, Asia, Russia, Australia, and the USA, aphids are the dominant insect pests of safflower (Dajue and Mündel, 1996; Hanumantharaya et al., 2008; Nimbkar, 2008; Vaani et al., 2016; Esfahani et al., 2012; Emongor and Oagile, 2017; GDRC, 2017; OECD, 2020). In Iran, the most important insect pests of safflower are capsule fly (*Acanthiophilus helianthi*), aphids (*Uroleucon carthami*), capsule borer (*Helicoverpa peltigera*), spider mites (*Tetranychus urtica*), and caterpillars (*Perigaea capensis*) (Esfahani et al., 2012).

Safflower is a poor weed competitor during the rosette stage and before stem elongation (Blackshaw et al., 1990; Tanaka et al., 1997; Uslu, 1997; Carapetian, 2001; Emongor, 2010; Emongor and Oagile, 2017; GRDC, 2017; Bergman and Kandel, 2019). The rosette stage lasts for three to 6 weeks depending on the air temperature or growing season, longer when the air temperature is below 20°C, allowing weeds to become established before safflower plants can cover the soil surface (Emongor and Oagile, 2017; GRDC, 2017; Moatshe, 2019). Therefore, prompt weed control is important in safflower production. Weeds can reduce safflower yield by up to 75%, depending on the weed species (Blackshaw et al., 1990; Armah-Agyeman et al., 2002).

5. Environmental adaptation

Safflower is grown in many parts of the world due to its adaptability to environmental conditions such as drought, extreme temperatures, salinity, and low nutrients (Weiss, 2000; Bassil and Kaffka, 2002; Koutroubas et al., 2004; Tuncturk and Yildirim, 2004; Farooq et al., 2009; Koutroubas and Papakosta, 2010; Hojati et al., 2011; Harrathi et al., 2012; Omidi et al., 2012; Hussain et al., 2016; Emongor and Oagile, 2017). Safflower can be cultivated as an oil crop under the poor environmental conditions that prevail in semi-arid and arid regions (Camas et al., 2005; Yadzi-Samadi and Bagheri, 2005; Kizil et al., 2008; OGTR, 2019; OECD, 2020). Safflower can also be grown year-round in countries that do not experience winter or have mild winters in reference to temperature. In countries with severe winters (north temperate), safflower can be grown in winter/spring and summer, with a growing season of 127–140 days (Armah-Agyeman et al., 2002; Mündel et al., 2004; GRDC, 2017; Bergman and Kandel, 2019; OECD, 2020; AgMRC, 2021).

5.1 Altitude

Safflower can grow from sea level up to 2000 m above sea level (Dajue and Mündel, 1996; Emongor, 2010; Emongor and Oagile, 2017).

5.2 Temperature

The response of crop species to temperature differs, with mostly phenological responses (Hatfield and Prueger, 2015; Moatshe et al., 2020a). Most crops have higher optimum temperatures for vegetative development than reproductive development (Torabi et al., 2013; Hatfield and Prueger, 2015). The optimum temperature for growth and development of safflower is 20–32°C (Torabi et al., 2015; Emongor and Oagile, 2017).

Safflower seeds have no dormancy (Bérvillé et al., 2005; McPherson et al., 2009; Emongor and Oagile, 2017)). Safflower seeds take 3–14 days to germinate depending on temperature (Mündel, 1969; Emongor, 2010; Torabi et al., 2013; Emongor and Oagile, 2017; GRDC, 2017; OGTR, 2019; OECD, 2020). Germination occurs at minimum temperatures of 2–5°C, but the optimum temperature for germination is 15.6°C (Mündel, 1969; Kaffka and Kearney, 1998; Emongor, 2010; Torabi et al., 2013; Emongor and Oagile, 2017). Torabi et al. (2013) reported excellent safflower seed germination at 5–30°C and 8–12 h day length. After emergence, safflower seedlings require cool temperatures (15–20°C) for root growth and rosette development but high temperatures (20–30°C) during stem elongation and reproduction (Li, 1989; Mündel et al., 1992; Li et al., 1997; Carapetian, 2001; El-Bassam, 2010; Emongor, 2010; Emongor and Oagile, 2017). Safflower seedlings at the rosette stage can tolerate temperatures from −7 to 15°C, depending on the genotype or variety (Li, 1989; Mündel et al., 1992; Li et al., 1997; Carapetian, 2001; El-Bassam, 2010; Emongor, 2010; Emongor and Oagile, 2017; GRDC, 2017; OECD, 2020). Mature safflower plants suffer from chilling injury when exposed to frosts of −2°C for more than 24 h. Temperature significantly affects safflower plant height (Emongor et al., 2015; Moatshe, 2019). Positive DIF of 16.4–20.7°C (difference between night and day temperatures) at the elongation stage significantly increases safflower plant height and primary branches (Emongor et al., 2013, 2015, 2017; Moatshe, 2019; Moatshe et al., 2020c). A positive DIF increases internode elongation for many plant species (Berghage and Heins, 1991; Myster and Moe, 1995; Dole and Wilkins, 2005) and can enhance gibberellin synthesis, promoting cell and internode elongation (Taiz and Zeiger, 2002; Emongor, 2002, 2007; Emongor et al., 2017). Average daily temperatures >26°C during flowering and achene filling reduces seed yield and oil content (Camas et al., 2007; Cosge et al., 2007; Shabana et al., 2013; Emongor et al., 2017; GRDC, 2017; Moatshe, 2019; Moatshe et al., 2020b). Safflower can tolerate up to 46°C, but high seed yields occur when daytime temperatures are <32°C during flowering (GRDC, 2017; Bergman and Kandel, 2019).

5.3 Photoperiod

Safflower is a day-neutral plant; however, summer cultivars from temperate countries, planted as a winter crop in subtropical and tropical regions with short days, have a long rosette stage with delayed physiological maturity (Dajue and Mündel, 1996; Emongor, 2010; Emongor et al., 2017; Moatshe, 2019). Increased temperature and day length increases safflower stem elongation and branching (Dajue and Mündel, 1996; Singh and Nimbkar, 2006; OECD, 2020). Safflower flowering time is primarily influenced by day length, requiring long days to initiate flowering (Gilbert, 2008). In Botswana, cool temperatures (<20°C) and short days (<10 h) delayed rosette, elongation, flowering, and physiological maturity stages of safflower by 5.2, 10, 24.4, and 35.3 days, respectively, irrespective of genotype or plant density (Emongor et al., 2017; Moatshe, 2019). Dadashi and Khajehpour (2004) reported that flowering duration and time to physiological maturity significantly decreased as day length increased. Dadashi and Khajehpour (2004) further reported that the interaction of temperature and day length explained the large variation in the duration of phenological stages in safflower, irrespective of genotype.

5.4 Soils

Safflower can be cultivated on a wide range of soils at soil pH 5–8 (Tuncturk and Yildirim, 2004; Oyen and Umali, 2007; Emongor, 2010; Emongor and Oagile, 2017; OGTR, 2019; OECD, 2020). The best soils are fertile, deep, well-drained with high water holding capacity, such as sandy loams (Emongor and Oagile, 2017; Bergman and Kandel, 2019; OGTR, 2019; OECD, 2020). Safflower can also be grown in coarse-textured soils (sandy soils) with low water holding capacity provided precipitation and moisture distribution are adequate, or irrigation is available, especially in semi-arid and arid regions (Emongor and Oagile, 2017; Bergman and Kandel, 2019). Fertile, deep black or gray, self-mulching or black cotton soils (vertisols), which enhance root development, can also be used for safflower cultivation (OGTR, 2019; OECD, 2020). Loamy and alluvial soils are also satisfactory but should be deep and free from hardpans or plinthite that prevents deep root penetration for water extraction (OGTR, 2019; OECD, 2020). Safflower plants do not tolerate waterlogging; therefore, soils prone to waterlogging must be avoided because they predispose the crop to root diseases. Safflower can tolerate salinity (Bassil and Kaffka, 2002; Omidi et al., 2012; Hussain et al., 2016; Emongor and Oagile, 2017; OGTR, 2019; OECD, 2020), more so when caused by sodium salts than calcium and magnesium salts (Oyen and Umali, 2007; Kizil et al., 2008; Omidi et al., 2012; OGTR, 2019; OECD, 2020). High salinity above 14 dS m^{-1} reduces safflower growth and seed yield (Oyen and Umali, 2007; FAO, 2010; OGTR, 2019; OECD, 2020).

5.5 Rainfall

Safflower requires annual rainfall of 600–1000 mm that is well distributed throughout the crop growth cycle (Marchione and Corleto, 1993; Corleto et al., 1997). Little to no rainfall or irrigation is needed at physiological maturity to ripen the capitula (FAO, 2010; Emongor and Oagile, 2017). Peak water use of 8–12 mm day^{-1} is required during flowering (Zaman and Das, 1990; Moatshe, 2019; Kiran, 2021). In semi-arid and arid regions, supplementary irrigation at the start of flowering increases safflower seed yield (Emongor et al., 2015, 2017; GRDC, 2017; Moatshe, 2019). However, excess rainfall during flowering causes leaf and capitula diseases, reducing yield by up to 100% (Kolte, 1985; Dajue and Mündel, 1996). Prolonged rainfall during flowering and/or temperatures >32°C interferes with pollination and seed set (Mündel et al., 1992).

The high root density and aggressive root structure of safflower can penetrate up to 2–3.5 m into the soil, reaching water deep in the soil profile (Engel and Bergman, 1997; Emongor, 2010; Emongor et al., 2013; Moatshe et al., 2016; Moatshe, 2019). Engel and Bergman (1997) showed that available water had a significant positive linear correlation with safflower seed yield, with about 406–560 mm required to produce the first kilogram ha^{-1} of safflower seed, thereafter increasing by about 3.7 kg mm^{-1} of available water in Montana, USA. Seasonal water consumptive use of safflower increased as the irrigation frequency increased from one (145.5 mm) to three (236.0 mm), but water use efficiency (WUE) decreased from 14.2 to 11.0 kg seed/ha mm (Katara and Bansal, 1995). Similarly, Ibrahim et al. (2008) reported increased water consumptive use by safflower with increasing available soil moisture around the root zone and WUE for seed production at 60% of available soil moisture depletion (ASMD) (Ibrahim et al., 2008). In India, the WUE of irrigated safflower (440–460 mm) ranged from 5 to 6 kg seed/ha mm (Kiran, 2021). In Egypt, the WUE of safflower ranged from 4.7 to 4.9 kg seed/ha mm when irrigated at 792 mm and 50% ASMD (Abd El-Lattief, 2013).

5.6 Relative humidity

Safflower prefers medium to low humidity (Engel and Bergman, 1997; Emongor and Oagile, 2017).

5.7 Pollination

Safflower is about 90%−94.5% self-pollinated with 4.5%−10% cross-pollination (Knowles, 1969; Dajue and Mündel, 1996; Kumari and Pandey, 2005; Pandey and Kumari, 2008; Rudolphi et al., 2008; GRDC; 2017; OGTR, 2019; OECD, 2020). The percentage of self-pollination is high due to the style and stigma growing through the surrounding anther column; after elongation, the stigma is covered with pollen from the same floret (Claassen, 1950; Pandey and Kumari, 2008; GRDC, 2017). However, unpollinated elongated stigma can remain receptive for several days, enhancing the probability of outcrossing (Claassen, 1950; Li and Mündel, 1996; Kumari and Pandey, 2005; GRDC, 2017; OECD, 2020). Cross-pollinated safflower has increased a capitula set (Claassen, 1950; Li and Mündel, 1996; Emongor and Oagile, 2017; GRDC, 2017; OGTR, 2019; OECD, 2020). The percentage of cross-pollination depends on insect pollinators, genotype, pollen source size, and environment (Li and Mündel, 1996; Pandey and Kumari, 2008; Rudolphi et al., 2008; GRDC, 2017; OGTR, 2019; OECD, 2020). The major insect pollinators of safflower are honeybees (Khalil et al., 1986; Van Deynze et al., 2005; Kumari and Pandey, 2005; Pandey and Kumari, 2008; Sajjad et al., 2008; AOSCA, 2012; FAO, 2014; Bukero et al., 2015; Emongor and Oagile, 2017). Among commercial crops, safflower ranks high on crops preferred by honeybees (FAO, 2014; Van Deynze et al., 2005). Honeybee pollen collectors have been reported to bypass cotton and fly 8 km to safflower (Kunin, 1997; Van Deynze et al., 2005). Apart from honeybees, other insects are involved in safflower pollination (Khalil et al., 1986; Chand et al., 2000; FAO, 2014; Emongor and Oagile, 2017). The literature reveals that 19 insect species of 5 orders (Hemiptera, Lepidoptera, Coleoptera, Diptera, and Hymenoptera) visit safflower blooms (Langridge and Goodman, 1980; Khalil et al., 1986; Emongor and Oagile, 2017). Safflower pollen is relatively large with a mean diameter of 53−56 μm (USDA-APHIS, 2008) and is not transferred significantly by wind (Claassen, 1950; Li and Mündel, 1996).

6. Safflower production

Safflower (*C. tinctorius* L.) as a species has broad genetic diversity and is adapted to many semi-arid regions where soil salinity is a major abiotic stress factor limiting crop production (Mündel et al., 1997; Garnatje et al., 2006; Kaya, 2009; Hussain et al., 2016; Ali et al., 2019; OGTR, 2019; OECD, 2020). With the predicted increase in global warming, the frequency, severity, and duration of droughts, floods, and heat waves will also increase (Chinnusamy et al., 2005; IPCC, 2007; Mittler and Blumwald, 2010). Safflower is a good alternative crop in arid and semi-arid agroecosystems due to its drought, salinity, and extreme temperature tolerance (Li and Mündel, 1996; Weiss, 2000; Yau, 2004; Kar et al. 2007; Lovelli et al. 2007; Emongor et al., 2017; OGTR, 2019; OECD, 2020). Despite safflower's excellent adaptation attributes and current and potential uses, including industrial (biodiesel, paints, varnishes) and pharmaceuticals (insulin, cardiovascular, and fertility drugs), global safflower production remains low compared to other oil crops (Dajue and Mündel, 1996; Ekin, 2005; Sehgal et al., 2009; Emongor, 2010; FAO, 2020).

6.1 Seedbed preparation

The land should be cleared, plowed, and harrowed to a fine soil tilth. During cultivation, avoid overworking, which can destroy soil structure, reducing safflower seedling establishment in soils prevalent to crusting (GRDC, 2017; Moatshe, 2019). The safflower seedbed should be weed-free before planting because the crop is a poor competitor of weeds at the rosette stage (Blackshaw et al., 1990; Tanaka et al., 1997; Carapetian, 2001; Emongor and Oagile, 2017; GRDC, 2017; Bergman and Kandel, 2019).

6.2 Planting

Safflower can be planted directly into seedbeds or direct-drilled into the previous crop's stubble (Emongor and Oagile, 2017; GRDC, 2017; Bergman and Kandel, 2019). Safflower can also be planted on raised beds in clay soils prone to waterlogging to lower the risk of root diseases (Dajue and Mündel, 1996; Nasehi et al., 2013; Emongor and Oagile, 2017; Esfahani et al., 2018).

Safflower genotypes and hybrids with different morphological and physiological traits are available for different macroclimatic conditions (Jonchike et al., 2002; Singh and Nimbkar, 2006; Esendal et al., 2009; GRDC, 2017; Moatshe, 2019; Moatshe et al., 2020b). Safflower accessions respond differently depending on the environmental conditions, genotypic characteristics, and management practices (Rahamatalla et al., 2001; Jonchike et al., 2002; Singh and Nimbkar, 2006; Emongor et al., 2017; Moatshe et al., 2020a). Proper inter- and intrarow spacing affect the growth, seed yield, and oil content of safflower depending on the genetic potential, cultivar, environmental conditions, and production system (Abaza, 2010; Amoghein et al., 2012; Emongor et al., 2013, 2017; Karimi et al., 2013; Moatshe et al., 2020a).

Planting density varies from 40,000 to >1,000,000 plants/ha depending on location, climatic conditions, agronomic practices, moisture availability, and cultivar (Blackshaw, 1993; Rowland, 1993; Gonzalez et al., 1994; Kwarteng and Towler, 1994; Dajue and Mündel, 1996; Oad et al., 2002; Sharifmoghaddassi and Omidi, 2009; Ahadi et al., 2011; Emami et al., 2011; Shakeri-Amoughin et al., 2012; Emongor et al., 2013; Sampaio et al., 2017; Moatshe, 2019). In Australia, the recommended safflower planting density is 200,000–400,000, 150,000–300,000, and 400,000–500,000 plants/ha for favorable, dry, and irrigated conditions, respectively (GRDC, 2017). In arid and semi-arid South Africa, especially Botswana, the recommended planting density is 100,000 plants/ha, with spacing of 40 × 25 cm or 50 × 20 cm (Emongor et al., 2013, 2015, 2017; Moatshe et al., 2020a, b). In the USA, safflower seeds are drilled at seeding rates similar to barley (28–39 kg seed/ha) for a planting density of 65 plants/m^2 (650,000 plants/ha) to promote better weed competition (Oelke et al., 1992; Bergman and Kandel, 2019). A planting depth of 2.0–5.0 cm is optimum for safflower (Kedikanetse, 2012; Emongor et al., 2015; GRDC, 2017; Bergman and Kandel, 2019; OECD, 2020). Generally, safflower is planted with standard cereal sowing equipment in rows 18–36 cm apart. Narrower rows help suppress weeds, while wider spacing allows for better airflow for disease control (Oelke et al., 1992; GRDC, 2010, 2017; Bergman and Kandel, 2019; OECD, 2020).

6.3 Fertilizer requirements

Crops, including safflower, require mineral elements supplied by the soil for their growth and development (Mengel and Kirkby, 2001; Marschner, 2005; Emongor and Mabe, 2012; Mazhani, 2017). In modern crop production systems, all harvested biomass is withdrawn from the field, but it contains nutrients that are no longer returned to the soil or growth medium. Therefore, maintenance of soil (media) fertility and crop yield production depends on the counterbalancing fertilizer inputs (Dahnke et al., 1992; Marschner, 2005; Emongor and Mabe; 2012; GRDC, 2017).

Safflower requires an adequate supply of nutrients for its maximum production potential even under limiting moisture conditions (Rao, 1985; Kubsad et al., 2001; Weinberg et al., 2007; Haghighati, 2010; Taleshi et al., 2012; Sampaio et al., 2016; GRDC, 2017; Mazhani, 2017; Santos et al., 2018). Safflower nutrient requirements increase with increasing yield (Mündel et al., 2004; Mazhani, 2017). Safflower removes more phosphorus (P) and sulfur (S) from soil than wheat (Haghighati, 2010; Sampaio et al., 2016; GRDC, 2017). Safflower plants remove 5, 1.2, and 3.8 kg ha^{-1} of nitrogen (N), phosphate (P_2O_5), and potash (K_2O) for every 100 kg of seed produced (Mündel et al., 2004). Therefore, soil testing is important to determine residual nutrient levels and apply the correct fertilizer amount corresponding to the estimated seed yield (Emongor and Mabe, 2012; Sampaio et al., 2016; GRDC, 2017; Mazhani, 2017). Application of nitrogen (N) (Siddiqui and Oad, 2006; Dordas and Sioulas, 2008; Dordas, 2009; Yau and Ryan, 2010; El-Mohsen and Mahmoud, 2013; GRDC, 2017; Mazhani, 2017; Santos et al., 2018), P (Haghighati, 2010; Abbadi and Gerendas, 2011; Golzarfar et al., 2012) and potassium (K) fertilizers (Hussien and Wuhaib, 2010; Palizdar et al., 2011; Abbasieh et al., 2013; GRDC, 2017) significantly enhances safflower growth, development, yield, yield components, and oil content and composition. Deep-rooted safflower can partially recover residual soil N that accumulates below the root zone of most cereal crops (Mündel et al., 2004; Emongor, 2010; Mazhani, 2017). The recommended N and P ranges from 60 to 180 kg/ha for N and 30–100 kg ha^{-1}

for P_2O_5 (Siddiqui and Oad, 2006; Dordas and Sioulas, 2008; Mirzakhani et al., 2009; Haghrighati, 2010; Afzal et al., 2017; Golzarfar et al., 2012; El-Mohsen and Mahmoud, 2013; Malek and Ferri, 2014; Sampaio et al., 2016; Afzal et al., 2017, 2017; Mazhani, 2017; Santos et al., 2018). However, the correct fertilizer amount for safflower will depend on soil type, pH, moisture availability, genotype (cultivar), growing season, and previous crops (Haghighati, 2010; Afzal et al., 2017; GRDC, 2017; Mazhani, 2017; Bueno et al., 2020).

Safflower sown in winter is usually ready for harvest 4–6 weeks later than wheat sown at a similar time. Safflower is ready for harvest once the leaves have turned brown, and the latest flowering heads are no longer green. At maturity, the seeds should be white and easily threshed by hand (Oelke et al., 1992). Harvest dates vary between commercial growers (see Fig. 24.6), ensuring safflower seed supply throughout the year. In Australia, the recommended seed moisture at the time of harvest should be less than 8% to avoid overheating and mold formation during processing and storage. Rain during harvest can cause staining or seed sprouting, both of which reduce the value of the seed (Oelke et al., 1992; Bockisch, 1998; GRDC, 2010). In parts of Canada, seed is harvested at a moisture content of 12%–15% and then dried by aeration (Mündel et al., 2004). Safflower is generally harvested without swathing; direct heading is possible since the capitula do not shatter easily. Safflower can be harvested with the same machinery used for cereals but at slower ground speeds to reduce seed losses (Oelke et al., 1992; Thalji and Alqarallah, 2015). Periodic cleaning of equipment to remove bristles from radiators and hot engine components may be necessary to minimize the risk of fire (GRDC, 2010). In addition, harvesting during cooler or more humid parts of the day is recommended to reduce the risk of fire and increase seed cleanliness (Jochinke et al., 2008). In Australia, seed loss during harvest (direct heading) is about 3%–4% (GRDC, 2010).

6.4 Weed control

Safflower is a poor competitor of weeds during the rosette stage, so weed control is important for maximizing seed yields (Blackshaw et al., 1990; Tanaka et al., 1997; Carapetian, 2001; Emongor, 2010; Emongor and Oagile, 2017; GRDC, 2017; OECD, 2020). Broadleaved weeds decrease safflower seed yield by up to 73% (Anderson, 1987; Blackshaw et al., 1990; Li and Mündel, 1996; GRDC, 2017). In Iran, Mohmadali-Nejad and Moosavi (2015) reported that weeds reduced safflower plant height, height of first auxiliary branch, head number per auxiliary branch, and seed yield by 10.36%, 22.28%, 25.21%, and 33.9%, respectively. Herbicides and cultivation between rows can be used to manage weeds in safflower (Blackshaw et al., 1990; Emongor and Oagile, 2017; GRDC, 2017; Bergman and Kandel, 2019). Under small-scale production or where land is limited for safflower monoculture, intercropping safflower and beans (*Phaseolus vulgaris* L.) can suppress weeds, more so at intercropping ratios of one row of safflower to six rows of beans or two rows of safflower to four rows of beans (Sadeghi and Sasanfar, 2013). Herbicides for managing weeds in safflower include metolachlor (Eptam or EPTC), trifluralin, ethalfluralin (Sonalan), dual/generic S/metolachlor, harmony SG (thifensulfuron), sulfonylurea, sethoxydim (poast), select max (clethodim), and select/generic clethodim. Preharvest herbicides include roundup/generic glyphosate, valor + MSO adjuvant (flumioxazin), and drexel defol (sodium chlorate) (Blackshaw et al., 1990). Postemergent herbicides for controlling broadleaved weeds such as *Kochia scoporia* L. (kochia) and *Salsola iberia* L. (Russian thistle) include chlorsulfuron, metsulfuron, and thiafensulfuron (Anderson, 1985, 1987; Wichman, 1987; Wichman et al., 1987, 1988; Riveland and Bradbury, 1993). Grassy weeds can be controlled with sethoxydim, clethodim, and quizalofop (Wichman, 1987; Riveland, 1993).

6.5 Irrigation

Safflower is a drought-tolerant crop due to its deep tap root reaching deep soil water (Bassir et al., 1977; Weiss, 2000; Bassil and Kaffka, 2002; Tuncturk and Yildirim, 2004; Emongor, 2010). Drought stress reduces crop growth, development, and yield in arid and semi-arid regions (Mollasadeghi et al., 2011; GRDC, 2017; OECD, 2020). In regions receiving less than 250 mm of precipitation during the safflower growing cycle, supplemental irrigation is necessary at the onset of flowering and the achene filling stage. Irrigation improves safflower yield components, seed and oil yield, and oil content and composition (Katara and Bansal, 1995; Tuncturk and Yildirim, 2004; Nabipour et al., 2007; Abd El-Lattief, 2013; Abdel-Motagally et al., 2015). In saline-affected arid and semi-arid regions, safflower uses surplus water from recharge zones, drawing down the water table with the salts dissolved in it, preventing saline seeps expansion (Dajue and Mündel, 1996). For safflower irrigation frequency and WUE, see section 5.5 under rainfall.

6.6 Harvest

Safflower takes 90–280 days to reach physiological maturity (Weiss, 2000; Emongor, 2010; Emongor et al., 2013; Moatshe, 2019). Terminal capitula matures first, followed by capitula on the secondary branches approximately 2 weeks later (Emongor and Oagile, 2017; GRDC, 2017). On average, it takes 30 days from full bloom to physiological maturity. At physiological maturity, most leaves turn brown, with a hint of green remaining on the bracts of the latest capitula. Seeds should rub freely from the heads, indicating that the seed (achene) moisture content is less than 8% (Emongor and Oagile, 2017; GRDC, 2017; Bergman and Kandel, 2019; OECD, 2020). Safflower should be harvested as soon as it is mature to reduce the risk of seed damage from excessive moisture. Excessive rain and high humidity after physiological maturity cause seeds to sprout in the capitula before harvest (vivipary) (Emongor and Oagile, 2017; GRDC, 2017; Bergman and Kandel, 2019).

During harvest, high temperatures and dry conditions make safflower plants very brittle, shattering into small pieces (GRDC, 2017). Safflower capitula are resistant to wind-shattering but easily shatter on the cutter bar of harvesting machinery in very dry conditions during harvest (Emongor and Oagile, 2017; GRDC, 2017). Plant shattering can be overcome by harvesting very dry crops during cooler conditions, such as the evening or very early in the morning (Mündel et al., 2004; Emongor and Oagile, 2017). Header settings will vary with conditions, crop yield, and machinery type. Reels should be set to push the crop gently over the cutter bar without dislodging seed from the capitula. To avoid seed cracking, the combine cylinder speed should not exceed a peripheral speed of 914.4 m per minute. This translates to approximately 500 rpm for a 55.9 cm cylinder (Mündel et al., 2004; Emongor and Oagile, 2017; GRDC, 2017). The concave clearance should be 1.6 cm at the front and 1.27 cm at the back. Air must be adjusted to remove most of the empty or unfilled seeds. During harvest, a white fuzz from the seed heads is abundant in the air, which can block combine radiators and air inlets, leading to overheating (Mündel et al., 2004; Emongor and Oagile, 2017; GRDC, 2017). Small-meshed screen enclosures should be mounted over these cooling mechanisms and radiators blown out with air once or twice daily to minimize this problem (Mündel et al., 2004; Emongor and Oagile, 2017; GRDC, 2017).

6.7 Storage

Before storing safflower seed, the seed moisture content must be less than 8% (Weiss, 2000; Emongor and Oagile, 2017; GRDC, 2017; Bergman and Kandel, 2019). Safflower seeds can be dried at temperatures not exceeding 43°C to prevent seed damage and maintain quality (GDRC, 2017). Four practices are recommended when storing safflower seeds: aeration, hygiene, monitoring, and airtight storage facilities or silos (Emongor and Oagile, 2017; GRDC, 2017; OECD, 2020). On-farm storage facilities should be well-aerated to reduce grain temperature and maintain uniform grain moisture to minimize grain molds and insect pest infestations (Emongor and Oagile, 2017; GRDC, 2017). Strict hygiene must be maintained in the storage facility to minimize pest infestation and grain contamination (Emongor and Oagile, 2017; GRDC, 2017). Grain should be monitored frequently (3–4-week intervals) for insect pests, quality, and storage temperature. The storage facility should be airtight to facilitate fumigation for storage pest control (Emongor and Oagile, 2017; GRDC, 2010, 2017).

7. Economics of safflower production

The safflower plant is a climate-smart crop with favorable attributes for cultivation in arid and semi-arid areas. Safflower production occurs in China, India, Tanzania, Ethiopia, Kenya, Argentina, Australia, Mexico, Canada, Spain, Italy, Turkey, Iraq, Iran, Syria, Kazakhstan, Uzbekistan, Israel, Morocco, Pakistan, Australia, Brazil, and Russia (Dajue and Mündel, 1996; Singh and Nimbkar, 2006; Emongor, 2010; Abdipour et al., 2019; Bergman and Kandel, 2019; FAO, 2020a; Tridge, 2021). Economic analyses in different regions have different and variable outcomes, some indicating profitability while others negative returns. The profitability of safflower seems to depend on its intended use. For example, safflower is more profitable when produced for livestock feed, cooking oil, and oil for making dyes (Australia, Europe, Tanzania, and the USA), cut flowers (Europe and Kenya), and pharmaceutical purposes (China, Canada, and Pakistan).

In Hyderabad, India, safflower production had a positive benefit-to-cost (B/C) ratio (>2), with irrigated safflower greater than rainfed safflower (Kumar et al., 2016). Narender et al. (2021) reported a B/C ratio of 1.87–2.67 when farmers applied the recommended inputs in safflower production. Munier et al. (2011) reported a B/C ratio >1 in Sacramento Valley, USA, for safflower production. In Botswana, safflower production had a B/C ratio of 1.9 (Emongor and Oagile, 2017).

Australia grows safflower for its oil used in the food industry and to manufacture pharmaceuticals, cosmetics, soap, paint additives, adhesive and sealant compounds, plastics, and lubricants (GRDC, 2017; OECD, 2020). Safflower exports from Australia, as oil or seeds, vary depending on crushing and oil extraction costs (GRDC, 2017; OECD, 2020). Current crushing costs range from $150–300 per ton of seeds, leading to greater importation of safflower seeds than oil (GRDC, 2017; OECD, 2020). Currently, India is the main market for oleic safflower oil for the food industry, with safflower seed imports of approximately 30,000 tons, with Australia supplying 4000 tons (GRDC, 2017). Safflower is grown under contract on a per hectare basis in Australia (GRDC, 2017; OECD, 2020). The prices paid for oleic safflower seeds in 2014 and 2015 were $490 and $520 per ton, respectively, with a minimum oil content of 38% (GRDC, 2017).

In Canada, safflower production is contracted for birdseed and cooking oil (Mündel et al., 2004; AgMRC, 2021). Production contracts are recommended to reduce risk. The mean price of safflower in Canada in 2016 was $10.65/kg^{-1}, with safflower crops valued at over $45 million (AgMRC, 2021).

In Iran, a techno-economic assessment of an integrated biorefinery using safflower seed and safflower straw as feedstock for producing bioethanol as the main product and biodiesel, biogas, glycerol, solid residue, and sodium sulfate as byproducts showed a profitability index of 1.14 (Khounani et al., 2019). Using *Zymomonas mobilis* instead of

Saccharomyces cerevisiae as fermentation microbes increased profitability by lowering ethanol production costs from US\$ 0.12/L^{-1} to US\$ 0.09/L^{-1} and the minimum ethanol selling price from US\$ 0.67/L^{-1} to US\$ 0.43/L^{-1} (Khounani et al., 2019). The study also showed that the discount factor and safflower seed price significantly impacted the profitability of developed biorefineries (Khounani et al., 2019).

8. Conclusion

Safflower has significant potential for the extraction of high-quality edible oil for human health, industrial purposes, birdseed, biofuel (biodiesel, ethanol, biogas), pharmaceuticals, animal feed, vegetables, cut flowers, clothes dyeing, food coloring, shampoos, and lotions in semi-arid regions impacted by drought and salinity. Safflower is a climate-smart crop that is adaptable to variable environmental growing conditions. Therefore, it should be given research priority among oil crops, especially for developing genotypes more tolerant of salinity and drought and high in oil content using genomics and biotechnological techniques. As a multipurpose and industrial crop, safflower has great potential for improving food security, disposable incomes, and livelihoods and alleviating poverty of many farmers in arid and semi-arid regions if effective and specific support policies technological inputs, and pricing and marketing systems are implemented by governments. Improving local capacities and the social, economic, and environmental sustainability of crop production by delivering technologies and services and strengthening institutions will increase the growth of the global safflower industry. Countries afflicted by water deficit and salinity should improve the economic viability of farms and sustainable use of scarce resources, especially water. In line with this, efficient water use and ecosystem conservation should continue to be prioritized alongside efforts to help producers adapt to climate change by growing climate-smart crops such as safflower.

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