IMPACT OF HERBICIDES ON WINTER CANOLA (*Brassica napus* L.) PRODUCTION AND FATTY ACID COMPOSITION IN SOUTH TEXAS

A Dissertation

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ABSTRACT

Canola is a cool-season, oilseed crop grown throughout Europe, Canada, and the Northern Great Plains region of the United States. The expansion of canola production into new growing regions, such as the Southern Plains region, has resulted in new production challenges. The Southern Plains region cultivates canola as a winter annual compared to a spring annual for the Northern Great Plains and Canada. Given the difference in climate and weed spectrum, region-specific weed management systems need to be developed. Agronomic practices can affect seed oil content, protein content, and fatty acid composition, however the effect of herbicides on these and other characteristic of canola are unknown. Therefore, experiments were conducted in 2010 and 2011 to evaluate a broad spectrum of herbicides for potential use in South Texas canola production with respect to crop injury, effects on canola seed oil content, fatty acid composition, weed control, biomass yield, and forage quality.

Visual crop injury at 42 DAE was unacceptable for saflufenacil at both 0.12 and 0.06 kg ai ha^{-1} and ethalfluralin at 1.05 kg ai ha^{-1}. Trifluralin at 1.12 and 0.56 kg ai ha^{-1}, *S*-metolachlor at 2.14 and 1.07 kg ai ha^{-1}, pyroxasulfone at 0.24 and 0.12 kg ai ha^{-1}, and pendimethalin at 0.8 kg ai ha^{-1} had lowest visual injury of all treatments. Fluroxypyr applied EPOST caused severe injury at both 0.21 and 0.11 kg ae ha^{-1}. All other EPOST treatments did not cause any visible injury. Seed oil content was not affected by the herbicides evaluated. Fatty acid composition, specifically stearic acid, oleic acid, linolenic acid, and oleic to linolenic acid ratio, was affected by herbicide treatments.

This research found that protoporphyrinogen oxidase (PPG oxidase) inhibitor herbicides, such as carfentrazone-ethyl and saflufenacil, negatively affect canola oil quality. Biomass yield was improved for all herbicide treatments except pendimethalin PRE when compared to the untreated plots. Crude protein content of canola forage was not affected by herbicide treatment. Digestible dry matter appeared to be reduced by treatments that included an EPOST application of sethoxydim.

The research shows that pendimethalin and *S*-metolachlor may be suitable for canola production in South Texas based on low crop injury and effective weed control. Neither pendimethalin nor *S*-metolachlor is currently labeled for use in canola. The herbicides trifluralin, ethalfluralin, quizalofop P-ethyl, ethametsulfuron-methyl, sethoxydim, glyphosate, clethodim, and clopyralid are currently labeled for use in canola and were confirmed suitable for canola production in South Texas. Carfentrazone-ethyl is currently labeled for use in canola but the effects on oil quality should be considered.

DEDICATION

I would like to dedicate this dissertation in the memory of my Dad. My love for agriculture came from the time I shared with my Dad as a young boy on our farm. I know he has and will continue to watch over me.

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1. INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Canola (*Brassica napus* L.) is a cool-season, broadleaf annual, a member of the mustard (*Brassicaceae*) family, and was developed from rapeseed (*Brassica napus* L.). Rapeseed has been grown in Asia for thousands of years and in Europe since the 13th century. The term "canola" was developed by the Western Canadian Oilseed Crushers Association to describe cultivars of low erucic acid rapeseed. Canola cultivars were produced by traditional breeding methods in Canada from rapeseed and were given Generally Regarded as Safe (GRAS) status in 1985 by the United States Food and Drug Administration (Shahidi, 1990). Those breeding efforts resulted in cultivars that contained less than 2% erucic acid in the seed oil and less than 30 µmoles of glucosinolates per g of seed meal, which are the maximum values allowed for canola. The reduction of erucic acid and glucosinolates resulted in oil better suited as cooking oil and a byproduct seed meal suitable for animal feed, respectively.

The primary uses of canola have been cooking oil, industrial uses, and animal feed (USDA ERS, 2012). Canola oil is desirable as cooking oil due to low saturated fat content, which can be unhealthy in high quantities. Additionally, the low polyunsaturated fatty acids, such as linolenic acid, of canola oil eliminates the need for hydrogenation. Both of these qualities make canola oil an excellent replacement for partially hydrogenated soybean oil. Another use for canola oil, primarily in Europe, has been the production of biodiesel. The demand for diesel and policies in the European

Union favor the utilization of canola oil for the production of biodiesel. Following oil extraction, the seed meal is dried and used as an animal feed. The high protein content (34 to 38%) is desirable to animal producers (USDA ERS, 2012). In the United States, the dairy industry utilizes the majority of the byproduct seed meal (USDA ERS, 2012).

Global rapeseed production exceeded 59 million tons in 2010 (FAO, 2012). Production in China, Canada, India, Germany, and France accounted for greater than 70% of global rapeseed production in 2010 (FAO, 2012). The United States produced 1.1 million tons of canola in 2010 (FAO, 2012) on 586,000 hectares (USDA NASS, 2012) accounting for less than 2% of the world's production. In the 2011-2012 growing season, North Dakota accounted for nearly 80% of the total United States production area (USDA NASS, 2012). The Southern Plains region (Kansas, Oklahoma, and Texas) is expected to double winter canola production for the 2012-2013 growing season to over 100,000 ha (Schoonover, 2012) and could become a major production region in the near future. U.S. demand for canola oil in 2008 was 1.3 million tons while production was only 480,000 tons (USDA ERS, 2012). As such, the United States imports canola oil primarily from Canada to meet demand.

1.2 Canola Growth

Canola growth is characterized by the following five major growth stages: seedling, rosette, bolting, flowering, and maturation. The growth stages are separated by distinct visual differences as canola responds to environmental changes.

Canola seedlings emerge approximately a week after planting depending on soil moisture, air temperature, and light conditions (Boyles et al., 2009). Small cotyledons

emerge and begin producing energy for the new plant. The seedling stage is rather short, ending when the first true leaves emerge, which occurs about a week after emergence (Boyles et al., 2009).

The rosette stage is characterized by a decumbent growth-habit and rapid addition of new leaves (Boyles et al., 2009). The root system develops extensively and the stem diameter increases due to the development of a crown. The rapid production of leaves, especially in a narrow-row situation, provides a competitive advantage against weeds as the inter-row space become shaded. In a winter production system, plants with 7 to 8 leaves and a height of 15 to 25 cm are preferred for optimal overwintering whereas smaller or larger plants are more susceptible to winter kill (Boyles et al., 2009). Growth during an overwinter period, such as canola would experience in Texas, would be depressed and some biomass may die. Winter-hardy cultivars of canola require a period of vernalization to hasten reproductive growth. The degree of vernalization requirement and cold tolerance of canola varies by cultivar (Rife and Zeinali, 2003).

As temperatures increase, approaching spring, rapid growth resumes. The formation of a bud begins and is visible at the center of the rosette (Boyles et al., 2009). Bolting begins as the canola plant grows rapidly in a vertical pattern. The plant height increases greatly during this growth phase. New leaves are produced along the vertical stem and the floral bud increases in size. In addition, apical meristems along the stem will produce secondary branches prior to flowering (Boyles et al., 2009).

Flowering begins shortly after bolting with mature buds at the bottom of the stem flowering first (Boyles et al., 2009). Flowering continues in rapid succession up the

main stem and secondary branches. Branch and bud growth continues during flowering, a period that can extend for several weeks, until the plant reaches a maximum number of siliques (pods). The number of pods is determined by favorable growing conditions and photosynthetic capacity of the individual canola plant (Boyles et al., 2009). Once a maximum is reached, additional flowers will abort and the plant will transition into the final growth stage, maturation (Boyles et al., 2009).

During maturation, secondary branches may continue to flower and set pods while the main branch is finished. Embryo and seed development occurs and seeds will reach maximum weight in 35 to 45 days (Boyles et al., 2009). Following seed fill, the plant matures and pods will ripen and begin to dry. Canola is typically swathed or harvested prior to the plant completely drying in order to minimize harvest loss due to pod shattering.

1.3 Canola Production

Canola is commonly grown in rotation with small grains such as wheat (*Triticum aestivum* L.) or immediately following a fallow period (Berglund et al., 2007). Two considerations with respect to rotation are herbicide carryover and disease cycles. Canola is susceptible to several commonly used herbicides for small grain production (Boyles et al., 2009). Most herbicides from the sulfonylurea and imidazolinone families have rotation restrictions of 2 to 3 years with respect to canola (Boyles et al., 2009). Diseases such as blackleg (*Leptosphaeria maculans*), Sclerotinia stem rot (*Sclerotinia sclerotiorum*), and several others, such as Alternaria black spot (*Alternaria spp.*), downy mildew (*Peronospora parasitica*), and powdery mildew (*Erysiphe cruciferarum*) are of

concern to canola production (Boyles et al., 2009). Short rotation intervals and producing canola after crops with similar disease susceptibilities can greatly affect productivity. When these issues are taken into consideration, canola production is quite successful in rotation with small grain crops. In fact, canola yield following wheat has been increased by 24% when compared to continuous canola production (Hang et al., 2009). Similarly, wheat yield has been shown to increase by 20 to 30% following canola (Zentner et al., 1986; Larney and Lindwall, 1994; Brandt and Zentner, 1995; Hang et al., 2009). Seed composition for No. 1 grade canola in western Canada, based on a 10-year average, is 43.8% oil and 21.2% protein on an 8.5% moisture basis (Canadian Grain Commission, 2012). Canola seed fatty acid composition can be affected by agronomic practices (Gao et al., 2010). The following fatty acids constitute the majority of canola seed oil: oleic (60 to 65%), linoleic (18 to 22%), linolenic (6 to 10%), palmitic (3 to 5%), and stearic (1 to 3%) (Ackman, 1990; Carvalho et al., 2006; Gao et al., 2010). Canola forage in Canada averages 15% crude protein (CP), 36% acid detergent fiber (ADF), and 60% total digestible nutrients (TDN) when harvested at late-bloom to mid-pod stage (Manitoba Agriculture, Food and Rural Initiatives, 2004).

Agronomic practices for the production of canola are well established. As a small-seeded crop, site preparation prior to planting is very important to canola production. A firm seedbed with minimal crop residue is important and soil crusting following planting is a concern (Raymer, et al., 1990). Canola is typically seeded in 15- to 38-cm rows using a standard small-grain drill (Berglund et al., 2007; Boyles et al., 2009; Raymer, et al., 1990). Yield is similar within this range of row widths (Kondra,

1975; Johnson and Hanson, 2003). Narrow rows are favored due to early canopy closure, reduced weed competition, and lower pre-harvest losses (Boyles et al., 2009). Seeding rate can range from 4.5 to 11 kg ha^{-1} (Boyles et al., 2009) with 5.6 kg ha^{-1} being the most common seeding rate (Berglund et al., 2007). An optimum stand of established canola is approximately 160 plants m^{-2} (Raymer, et al., 1990; Berglund et al., 2007). Seeding depth is shallow with a recommended depth of 1.25 to 2.5 cm (Berglund et al., 2007; Boyles et al., 2009; Hang et al., 2009).

Planting date varies for spring and winter canola, which is determined by location. Spring cultivars of canola are grown in the Northern Great Plains region of the United States. Recommended planting dates for North Dakota are from late April to early May (Berglund et al., 2007). Later planting dates result in significant yield loss due to heat and drought stress (Johnston et al., 2002; Berglund et al., 2007). Winter canola cultivars, which require vernalization, are planted in the Southern Great Plains region in the fall. Planting dates begin in late August for northern Kansas and continue into late October for northern Texas (Boyles et al., 2009). Locations with mild winters could produce spring cultivars during the fall growing season (Raymer, et al., 1990).

Fertilization recommendation should be based on soil fertility tests and realistic yield expectations. A previous review by Grant and Bailey (1993) determined that nitrogen (N), phosphorus (P), and sulfur (S) most limit canola productivity. Potassium (K) is less likely to affect yield due to adequate availability in common production regions.

Grant and Bailey (1993) determined that nitrogen is essential for canola growth and positively influences the reproductive capabilities of canola plants. Excessive quantities of N fertilizer can negatively affect canola production by increasing lodging and delaying maturity thereby reducing harvestable seed and seed quality; they also found yield increased when applied N plus soil NO_3-N approached 200 kg ha^{-1}. Jackson (2000) noted a positive response in yield to nitrogen with application rates up to 252 kg ha^{-1}. The degree of yield response to N fertility may be determined by canola cultivar (Karamanos et al., 2005). In Alberta, Canada, two cultivars maximized yield at 135 kg N ha^{-1} while another continued to increase yield with an application rate of 155 kg N ha^{-1}. With respect to seed composition, higher N application rates resulted in reduced seed oil concentration (Jackson, 2000; Brennan and Bolland, 2009; Gao et al., 2010). Nitrogen fertility has also been shown to affect fatty acid composition of canola (Gao et al., 2010). Gao et al. (2010) found that 168 kg N ha^{-1} increased saturated fatty acid content compared to 84 kg N ha^{-1}. Additionally, the O/(L+LN) ratio decreased at the higher nitrogen application rate (Gao et al., 2010). Brennan and Bolland (2009) also noted that seed protein concentration increased as seed oil content decreased. Previous research by Brennan et al. (2000) suggests that seed oil plus protein content was fairly constant at 30 diverse locations in a 2-year experiment. These findings are consistent with the review by Grant and Bailey (1993).

Phosphorus is required for the formation of nucleic acids and phospholipids as well as photosynthetic activity (Grant and Bailey, 1993). A review by Grant and Bailey (1993) showed canola yield increased with additions of 20 to 30 kg P ha^{-1}. Soils very

low in available P will negatively affect canola yield without proper fertilizer additions of P. Karamanos et al. (2005) found canola yield was maximized once P deficiency was corrected, based on soil test, and that additional P fertilizer did not further increase yields. Additionally, canola effectively utilizes soil available phosphorus and application requirements are lower than cereal crops (Grant and Bailey, 1993). When comparing relative yield of wheat and canola, Bolland (1997) also found less P was required by canola. This is supported by the findings of Brennan and Bolland (2009) in which canola required approximately 25% less P than wheat to attain 90% of maximum yield. Seed quality, specifically percent oil, may be affected by P fertility however; the experiments cited had opposing results (Grant and Bailey, 1993). Brennan and Bolland (2009) found no connection between P fertilizer and canola seed protein or oil content in a 4-year experiment conducted at seven locations in south-western Australia.

Sulfur, as with nitrogen, is required for amino acid and protein synthesis (Grant and Bailey, 1993). Canola requires greater sulfur than cereal crops (Grant and Bailey, 1993). This requirement is due to higher oil content as well as producing more sulfur-containing amino acids (Anderson, 1975; Clandinin, 1981). Visual symptoms of deficiency may not occur until severe deficiency however; yield can be reduced under mild S deficiency (Grant and Bailey, 1993). Grant and Bailey (1993) noted several instances in which canola yield was improved with S fertilizer application. Jackson (2000) determined the critical level of soil test sulfur to attain 90% of maximum yield to be 70 kg S ha^{-1}. A soil test value below 70 kg S ha^{-1} warrants S fertilizer application of 20 kg S ha^{-1}. Berglund et al. (2007) suggests 22 to 34 kg S ha^{-1} for medium to low S soil

test results. In a review by Malhi et al. (2005) the authors found an application of 15 to 30 kg S ha^{-1} prior to planting, on S-deficient soils, will prevent S deficiency. In-season applications are effective at correcting S deficiency and restoring yield potentials even late in the growing season. Given the common usage of nitrogen and sulfur, it has been recommended to maintain a N:S ratio of 5:1 to 8:1 following fertilizer application (Grant and Bailey, 1993; Manitoba Agriculture and Food, 2001; Hang et al., 2009). A proper balance of N:S is supported by the review conducted by Malhi et al. (2005). Karamanos et al. (2005) determined no N x S interaction existed for hybrid canola cultivars as long as fertility requirements were met. Conventional cultivars did show a N x S interaction as previously noted (Karamanos et al., 2005). Seed protein content responds positively to S fertilizer applications (Nuttall et al., 1987; Finlayson et al., 1970). Seed oil content may be affected by S fertilizer; however, previous research showed differing results (Nuttal et al., 1987; Ridley, 1972; Ridley, 1973; Wetter et al., 1970;).

Potassium uptake is higher than cereal crops; however, minimal quantities are removed in the harvested seed (Grant and Bailey, 1993). If grown as a forage, K removal in the biomass should be considered. Canola biomass can contain 150 to 300 kg K ha^{-1} (Holmes, 1980). Soils of major production regions generally provide adequate K for canola production (Grant and Bailey, 1993). Yield responses to K fertilizer occurred only if soil exchangeable K was below 35 mg kg^{-1} (Grant and Baily, 1993). Regions with low K availability do benefit from K fertilizer application (Brennan and Bolland, 2007). Grant and Baily (1993) reported that K had no effect on seed oil or protein content.

1.4 Weed Management

The competitive ability of a crop is an important factor in a comprehensive weed management strategy. Some attributes of a competitive crop are early emergence, rapid growth, plant height, canopy density, and time to canopy closure. Research by O'Donovan (1994) found suppression of the weed Tartary buckwheat (*Fagopyrum tataricum*) by canola depends more on crop planting density than row spacing. Canola seed yield was approximately 80%, 65%, and 50% of maximum at densities of 200, 100, and 50 plants m^{-2}, respectively, when comparing the effect of 0 and 250 Tartary buckwheat plants m^{-2} (O'Donovan, 1994). Holman et al. (2004) also noted improved canola yield stability with higher planting density when competing with Persian darnel (*Lolium persicum*). Intensity of tillage operations can also affect the competitive ability of canola. Canola grown in a conservation compared to conventional tillage system emerges earlier than several common weeds providing a competitive advantage (Bullied and Van Acker, 2003). Competitiveness of canola varies by cultivar with hybrid cultivars outperforming open-pollinated cultivars (Zand and Beckie, 2002; Beckie et al., 2008). When grown in competition with annual ryegrass (*Lolium multiflorum*), hybrid canola suppressed weed growth and maintained yield better than conventional or triazine-resistant open-pollinated cultivars (Lemerle et al., 2010). Comparing hybrid and open-pollinated canola, plant height and canopy dynamics explain the improved weed suppression found by hybrid canola (Zand and Beckie, 2002).

Canola production also relies on herbicides for an effective weed management system. Currently very few herbicides are labeled for canola. Prior to the introduction

of herbicide-resistant cultivars, canola producers utilized multiple modes of action and application timings to effectively control weeds. Trifluralin and ethalfluralin are preplant incorporated herbicides that provide control of several grass and broadleaf weed species. The herbicides clethodim, quizalofop, and sethoxydim provide postemergence grass control. Clopyralid is the only postemergence herbicide for sale in the United States that provides postemergence broadleaf control in conventional canola. Ethametsulfuron also controls broadleaf weeds in conventional canola; however, it is not sold in the U.S. In the 1990s, glyphosate-, glufosinate-, and imidazolinone-resistant canola cultivars were introduced. Glyphosate, glufosinate, and imazamox, when used with their respective herbicide-resistant cultivars, provide broadspectrum postemergence weed control. Availability of herbicide-resistant cultivars changed the management system toward reliance on postemergence products. Herbicide-resistant cultivars were quickly adopted in Canada with over 95% of acres utilizing these cultivars beginning in 2004 (Smyth et al., 2011). Glyphosate- and glufosinate-resistant cultivars each constitute 40 to 45% of all acres in Canada with imidazolinone-resistant cultivars produced on 10 to 15% (Beckie et al., 2011).

Weed management systems in modern agriculture rely heavily on herbicides and the efficacy of those herbicides is critical. When grown in rotation with wheat, volunteer wheat, other grass species, as well as common broadleaf species for the region will be the main weeds competing with canola. Therefore, a broadspectrum control program is necessary. Volunteer wheat is effectively controlled by several herbicides (Morley et al., 2006). Trifluralin preplant incorporated followed by quizalofop

postemergence or two postemergence applications of glyphosate provide excellent control of volunteer wheat, Italian ryegrass (*Lolium perenne*), and feral cereal rye (*Secale cereale*) (Bushong et al., 2011). Ethametsulfuron is an important herbicide for canola production in Canada. Ethametsulfuron controls several broadleaf weeds in the *Cruciferae* family, including wild mustard (*Sinapis arvensis* L.), that other herbicides used in canola cannot control (Blackshaw, 1989). Tank mixes of multiple herbicides is a common approach to improving broadspectrum control with a single application in many crops. With respect to canola, tank mixes of ethametsulfuron and aryloxphenoxy propionate herbicides that control grasses results in unacceptable injury to canola (Harker et al., 1995). Yield losses of 59 to 97% were observed (Harker et al., 1995). However, cyclohexanedione herbicides that also control grasses, such as sethoxydim, can be tax mixed with ethametsulfuron without reducing canola growth (Blackshaw and Harker, 1992). A tank mix of sethoxydim, clopyralid, and ethametsulfuron controls a broad spectrum of weeds common to canola production, but cost of the tank mix may prohibit its application (Blackshaw and Harker, 1992). A single in-season application of glyphosate provides similar weed control and canola yields (Blackshaw and Harker, 1992). Application of glyphosate early in the growing season results in the highest canola yield in most situations (Clayton et al., 2002). Sequential applications of glyphosate, especially early in growth, can reduce growth of glyphosate-resistant canola compared to untreated plants (Schilling et al., 2006). A single application at the two-leaf stage reduced shoot dry weight by approximately 15% whereas sequential applications at

the two-, four-, and six-leaf stage reduced shoot dry weight by approximately 40% (Schilling et al., 2006).

Adoption of herbicide-resistant canola has provided benefits beyond improved weed control and potentially lower application costs. Smyth et al. (2011) determined that utilization of herbicide-resistant canola reduces tillage operations, environmental impact of herbicide application, chemical exposure to farmers, and the quantity of active ingredients applied (Smyth et al., 2011). Additionally, net revenues compared to conventional systems can be higher (O'Donovan et al., 2006). Concerns exist with utilizing herbicide-resistant canola production systems. Continue usage of herbicide resistance technologies could favor development of herbicide-resistant weed populations in canola (Beckie et al., 2011). A major concern with herbicide-resistant canola is escape and development of multiple resistances within individual plants due to gene flow (Knispel, et al., 2008). Several locations with escapes, in Manitoba, produced progeny resistant to both glyphosate and glufosinate (Knispel, et al., 2008). Previous research has shown that herbicides such as 2,4-D, MCPA, and metribuzin (Beckie et al., 2004), as well as paraquat tank mixed with diuron (Rainbolt et al., 2004), can control volunteer herbicide-resistant canola.

Seed oil content of canola does not appear to be affected by glyphosate, glufosinate, or imazamox when applied to the respective herbicide-resistant cultivars (Grey et al., 2006). However, the effects of other herbicides on canola seed oil content, fatty acid composition, forage biomass, and forage quality have not been reported in the literature. The objectives of the research are to 1) evaluate a broad spectrum of

herbicides for potential use in South Texas canola production with respect to crop injury; 2) determine if these herbicides have any effects on canola seed oil content or fatty acid composition; 3) evaluate selected herbicides from initial screening for weed control potential in a winter canola production system; and 4) determine if there are any effects on canola forage yield or forage quality.

2. HERBICIDE IMPACT

2.1 Introduction

Canola (*Brassica napus* L.) is a cool-season, broadleaf annual, and member of the mustard (*Brassicaceae*) family. Canola was developed in Canada from rapeseed (*Brassica napus* L.) by traditional breeding methods (Bell, 1982; Bell, 1984; Shahidi, 1990). Canola contains less than 2% erucic acid in the seed oil and less than 30 µmoles of glucosinolates per gram of seed meal, which improves the cooking oil and seed meal quality compared to rapeseed. The low saturated fatty acid and polyunsaturated fatty acid content of canola oil (Ackman, 1990; Carvalho et al., 2006; Gao et al., 2010) make it an excellent replacement for partially hydrogenated soybean oil in the cooking oil industry.

Canola is commonly grown in rotation with wheat (*Triticum aestivum*) in the Northern Great Plains region of the United States. Global canola and rapeseed production in 2010 was 59 million tons with the United States accounting for less than 2% of the total production (FAO, 2012). North Dakota produces nearly 80% of the canola grown in the United States (USDA NASS, 2012); however, the Southern Plains region is expected to increase production significantly (Schoonover, 2012). A canola-wheat rotation increases the yield of both canola (Hang et al., 2009) and wheat (Zentner et al., 1986; Larney and Lindwall, 1994; Brandt and Zentner, 1995; Hang et al., 2009).

Herbicide carryover in a canola-wheat rotation is a concern. For example, herbicides from the sulfonylurea and imidazolinone families, commonly utilized in

wheat production, have rotation restrictions of 2 to 3 years with respect to planting canola. Additionally, weed control systems will likely differ in the Southern Plains due to production season and common weed species. Canola is grown as a spring annual in North Dakota (Berglund et al., 2007); however, it is grown as a winter annual in the Southern Plains (Boyles et al., 2009). As such, the weed spectrum present challenges which require the development of location-specific control programs. Additionally, agronomic practices have been shown to affect seed oil content (Jackson, 2000; Brennan and Bolland, 2009; Gao et al., 2010), protein content (Brennan and Bolland, 2009; Nuttall et al., 1987; Finlayson et al., 1970), and fatty acid composition (Gao et al., 2010). Seed oil content of canola does not appear to be affected by glyphosate, glufosinate, or imazamox when applied to the respective herbicide-resistant cultivars (Grey et al., 2006). However, the effects of other herbicides on canola seed oil content, fatty acid composition, forage biomass, and forage quality have not been reported in the literature. The objectives of this research are to evaluate a broad spectrum of herbicides for potential use in South Texas canola production with respect to crop injury, effects on canola seed oil content, fatty acid composition, weed control, biomass yield, and forage quality.

2.2 Materials and Methods

2.2.1 Field Experiments

Field research was conducted at the Texas A&M AgriLife Research Farm, Agronomy Field Laboratory in Burleson County (30°32.226'N, 96°25.301'W), near College Station, Texas. The soil was a Belk clay (fine, mixed, active, thermic Entic

Hapluderts) with pH of 7.9 and organic matter of 1.5%. Field experiments were established in 2010 and 2011 to evaluate effect of herbicides on winter canola grown in South Texas.

The first experiment was established at two locations in November 2010 to evaluate crop injury of several herbicides at two application rates. The glyphosate tolerant winter canola cultivar 'DKW47-15' was planted using a 7-row no-till grain drill with a row width of 19 cm. Plots were planted on November 11, 2010 at a seeding rate of 5.6 kg ha^{-1}. Plots were 1.5 m long and were arranged in a randomized complete block design (RCBD) with four replications per location. Granular ammonium sulfate and urea fertilizers were applied on February 17, 2011 to supply 56 kg ha^{-1} of nitrogen and 13.5 kg ha^{-1} of sulfur. Supplemental sprinkler irrigation was utilized to maintain adequate soil moisture for canola growth. Herbicides selected encompassed a range of application timings and modes of action. Herbicide treatments were applied at 140 L ha^{-1} using a CO_2 backpack sprayer at a 1x and 0.5x maximum label rate. The spray boom was 1.5-m long equipped with three 11002 flat-fan nozzles spaced 0.5 m apart. Crop injury ratings for the preplant (PPL), preplant incorporated (PPI), and preemergence (PRE) treatments were collected at 14, 28, and 42 days after crop emergence (DAE). Crop injury ratings for the postemergence (POST) treatments were collected at 14, 28, and 42 days after POST application (DAP). Crop injury ratings were a composite of the visual symptoms of stunting, chlorosis, necrosis, plant deformation, or plant death. Crop injury rating scale was 0 to 100% with 0% = no injury and 100% = plant death. Plots were hand harvested on May 24, 2011 and seed were collected from a stationary plot

thresher. Collected seed was subjected to oil content and fatty acid composition analyses.

The second experiment was established at three locations in November 2011 to evaluate control of key weed species, winter canola forage yield, and forage quality utilizing herbicides selected from the first experiment. The glyphosate tolerant winter canola cultivar 'DKW47-15' was planted using a 4-row no-till grain drill with row width of 38 cm. Plots were planted on November 30, 2011 at a seeding rate of 5.6 kg ha^{-1}. Plots consisted of eight 6-m long rows that were arranged in a RCBD with four replications per location. Locations were selected in areas with natural populations of henbit (*Lamium amplexicaule*). Annual ryegrass (*Lolium multiflorum*) was overseeded in a 1.5-m swath perpendicular to crop rows. Hard red winter wheat (*Triticum aestivm* L.) was seeded perpendicular to crop rows in four rows spaced 38 cm apart to simulate a volunteer stand of wheat. Herbicide treatments were applied at 140 L ha^{-1} using a tractor-mounted sprayer. The spray boom was 3-m long equipped with six 11002 flat-fan nozzles spaced 0.5 m apart. Weed control ratings were collected at 14 and 35 DAE and at 16, 30, and 44 DAP. Granular ammonium sulfate and urea fertilizers were applied on February 23, 2012 to supply 56 kg ha^{-1} of nitrogen and 13.5 kg ha^{-1} of sulfur. Supplemental irrigation was utilized to maintain adequate soil moisture for canola growth. Canola forage was harvested with a walk-behind sickle mower from April 11 to 13, 2012. Harvested biomass was weighed and a subsample from each plot was chopped, weighed, and dried at 145°C to calculate dry matter yield. The dried

subsamples were sent to the Texas A&M AgriLife Extension Service Soil, Water and Forage Testing Laboratory for forage analysis.

2.2.2 Total Oil Content

Seed oil was extracted by accelerated solvent extraction (ASE) using a modified procedure described by Gao et al. (2010). An ASE 200 (Dionex Corporation, Sunnyvale, CA) was utilized for the extraction process. A subsample of canola seed collected from harvested plots was finely ground and weighed to 1g. All samples were run in duplicate at the same time. An 11-mL stainless-steel extraction cell with glass filters and stainless-steel frits was used for the extraction. The weighed seed was placed in the extraction cell and mixed with an equal volume of diatomaceous earth. Additional diatomaceous earth was added to fill the extraction cell. Seed oil was extracted using hexane solvent and the following ASE conditions: oven temperature of 105°C, preheat for 5 min, heat for 5 min, extraction pressure of 1015 psi, 10-min static time, two static cycles, flush volume of 75%, and 60 seconds purge time. Following extraction, extracted oils in solvent hexane were transferred to pre-weighed and numbered vials. The solvent hexane was evaporated from the vials by compressed N_2 gas in a heated evaporator at 50°C. The vials were placed in a forced air oven for approximately 120 min at 105°C to evaporate any residual hexane or water. Final weight of the extracted oils was obtained by the difference in initial and post-extraction vial weight. AOCS Official Method AM 2-93 (AOCS, 2000) was used to calculate total oil content on a dry weight basis. Seed moisture content was obtained by a GAC 2100 (DICKEY-john Corporation, Auburn, IL) grain moisture analyzer for dry weight basis adjustment.

2.2.3 Fatty Acid Composition

Canola oil fatty acids were extracted and subsequently methylated in a fatty acid methyl ester (FAME) reaction utilizing a modified procedure described by Hammond (1991) and Gao et al. (2010). A subsample of canola seed collected from harvested plots was finely ground and weighed to 1g. All samples were run in duplicate at the same time. The weighed seed was placed in a 4-mL extraction vial and 2 mL of hexane was added for fatty acid extraction. Extraction time was for a period of 2 hours and vials were periodically mixed with a vortexer. Following extraction, a 100-µL supernatant was transferred to a second 4-mL extraction vial and 0.5 mL of 1M sodium methoxide was added to methylate the fatty acids. The mixture was heated at 40°C for a period of 30 min and vials were periodically mixed with a vortexer. Following methylation, 2 mL of deionized water was added to stop the reaction. An addition 1 mL of hexane was added to the vial to facilitate FAME collection. The mixture was allowed to separate into two layers. The top layer, hexane with the FAME reaction products, was pipetted into a 2 mL vial for analysis by gas chromatography.

FAME analysis was conducted with an Agilent Technologies (Santa Clara, CA) 7890A gas chromatograph (GC) with a Flame Ionization Detector (FID) at Aspen Research Corporation (Maple Grove, MN) utilizing a modified procedure described by Gao et al. (2010). The column was a 30m x 0.53mm x 0.5µm Suplecowax 10 capillary column. GC-FID settings were as follows: 3 preinjection hexane solvent rinses of 8 µL, 2 preinjection sample washes of 8 µL, oven temperature increased from 195°C to 240°C at 4°C min^{-1}, hold time of 3.75 min at 240°C, 1-µl injection volume, 10:1 split ratio, inlet

temperature of 260°C, detector temperature of 300°C, and helium carrier gas at 3.3 ml min^{-1}. The methylated fatty acids of interest were palmate, stearate, oleate, linoleate, and linolenate. Retention times were confirmed with methylated analytical standards. Percentage of total peak area for the individual fatty acid methyl esters was determined by Agilent's MSD Chemstation software (version E.02.00.493). Percentage of total peak area for methyl oleate and methyl linolenate were used to calculate an oleic:linolenic (O:LN) ratio.

2.2.4 Forage Analysis

Forage samples were sent to the Texas A&M AgriLife Extension Service Soil, Water and Forage Testing Laboratory to determine plant nitrogen (%) and acid detergent fiber content (ADF). Nitrogen content was determined by combustion (Sweeney, 1989) and utilized to calculate crude protein content of the canola forage. ADF was determined using a standard filter bag technique (Komarek, 1993) and utilized to calculate digestible dry matter content (Schroeder, 1994).

2.2.5 Statistical Analysis

All experiments were arranged in a RCBD with four replications. Data were analyzed using the generalized linear model (GLM) of the Statistical Analysis Systems (SAS) software (SAS Institute, 2008) and the least significant difference (LSD) test. Differences were considered significant at $P \leq 0.05$. Locations and replications were considered random effects and herbicide treatments considered fixed effects. Replications were nested within locations.

2.3 Results and Discussion

2.3.1 Crop Injury

Injury due to PPI, PPL, and PRE herbicides was similar at both locations. Level of crop injury differed between treatments (Table 1). Ethalfluralin at 1.05 and 0.53 kg ai ha^{-1}, carfentazone-ethyl at 0.035 and 0.018 kg ai ha^{-1}, saflufenacil at 0.12 and 0.06 kg ai ha^{-1}, and pendimethalin at 1.6 kg ai ha^{-1} had the highest levels of crop injury. The most severe injury was from PPL application of saflufenacil at 0.12 and 0.06 kg ai ha^{-1} and the PPI application of ethalfluralin at 1.05 kg ai ha^{-1}. Injury ratings for those three treatments at 42 DAE were 74%, 54%, and 50%, respectively, which would be unacceptable to producers. Triflualin at 1.12 and 0.56 kg ai ha^{-1}, *S*-metolachlor at 2.14 and 1.07 kg ai ha^{-1}, pyroxasulfone at 0.24 and 0.12 kg ai ha^{-1}, and pendimethalin at 0.8 kg ai ha^{-1} caused limited crop injury, which ranged from 6% to 18%. Crop injury for all treatments remained stable across all evaluation timings due to slow growth in the rosette phase of canola growth.

The EPOST herbicides quizalofop P-ethyl at 0.093 and 0.046 kg ai ha^{-1}, ethametsulfuron-methyl at 0.023 and 0.011 kg ai ha^{-1}, sethoxydim at 0.53 and 0.26 kg ai ha^{-1}, glyphosate at 1.06 and 0.53 kg ae ha^{-1}, clethodim at 0.10 and 0.05 kg ai ha^{-1}, and clopyralid at 0.21 and 0.11 kg ae ha^{-1} did not cause any visible injury to canola compared to the untreated control (Table 2). Fluroxypyr injury at 14 DAP was 88% and 59% at application rates of 0.21 and 0.11 kg ae ha^{-1}, respectively. Canola plants did eventually recover from the initial fluoxypry injury at the 0.11 kg ae ha^{-1} rate with an injury rating of 16% at 42 DAP.

Table 1

Canola injury due to preplant incorporated, preplant, and preemergence herbicide applications in 2010 near College Station, TX.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Crop injury[a] 14 DAE	28 DAE	42 DAE
			%		
Untreated	-	-	0	0	0
Trifluralin	1.12	PPI	22 e	23 e	15 de
Trifluralin	0.56	PPI	9 gh	12 gh	9 de
Ethalfluralin	1.05	PPI	46 bc	53 b	50 b
Ethalfluralin	0.53	PPI	31 d	33 d	31 c
Carfentrazone-ethyl	0.035	PPL	41 c	43 c	38 c
Carfentrazone-ethyl	0.018	PPL	29 d	33 d	29 c
Saflufenacil	0.12	PPL	73 a	75 a	74 a
Saflufenacil	0.06	PPL	53 b	54 b	54 b
S-metolachlor	2.14	PRE	13 fg	20 ef	18 d
S-metolachlor	1.07	PRE	6 h	11 h	9 de
Pyroxasulfone	0.24	PRE	21 e	19 efg	16 d
Pyroxasulfone	0.12	PRE	8 gh	8 h	6 e
Pendimethalin	1.6	PRE	29 d	33 d	32 c
Pendimethalin	0.8	PRE	16 ef	14 fgh	12 de

Table 1

Continued.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Crop injury[a] 14 DAE	28 DAE	42 DAE
			%		
Coeff of variation			23.59	25.98	33.33

PPI: preplant incorporated; PPL: preplant; PRE: preemergence; DAE: days after emergence (crop).

[a] Means within columns followed by the same letter are not significantly different according to the LSD test (P≤0.05).

Table 2

Canola injury due to early postemergence herbicide applications in 2010 near College Station, TX.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Crop injury[a] 14 DAP	28 DAP	42 DAP
			%		
Untreated	-	-	0	0	0
Quizalofop P-ethyl	0.093	EPOST	0 c	0 c	0 c
Quizalofop P-ethyl	0.046	EPOST	0 c	0 c	0 c
Ethametsulfuron-methyl	0.023	EPOST	0 c	0 c	0 c
Ethametsulfuron-methyl	0.011	EPOST	0 c	0 c	0 c
Sethoxydim	0.53	EPOST	0 c	0 c	0 c
Sethoxydim	0.26	EPOST	0 c	0 c	0 c
Glyphosate	1.06	EPOST	0 c	0 c	0 c
Glyphosate	0.53	EPOST	0 c	0 c	0 c
Clethodim	0.10	EPOST	0 c	0 c	0 c
Clethodim	0.05	EPOST	0 c	0 c	0 c
Clopyralid	0.21	EPOST	0 c	0 c	0 c
Clopyralid	0.11	EPOST	0 c	0 c	0 c
Fluroxypyr	0.21	EPOST	88 a	64 a	46 a
Fluroxypyr	0.11	EPOST	59 b	29 b	16 b

Table 2

Continued.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Crop injury[a] 14 DAP	28 DAP	42 DAP
			%		
Coeff of variation			20.49	53.99	62.59

EPOST: early postemergence; DAP: days after postemergence application.

[a] Means within columns followed by the same letter are not significantly different according to the LSD test ($P \leq 0.05$).

2.3.2 Seed Oil Content and Fatty Acid Composition

Seed oil content ranged from 268 to 335 mL kg^{-1},but no statistically significant differences existed between treatments. Fatty acid composition was affected by herbicide treatments (Table 3). Palmitic acid (16:0) and linoleic acid (18:2) showed no differences between treatments. Average percent of total peak area for palmitic and linoleic acid was 4.8% and 21.2%, respectively. Stearic acid (18:0) content was less than 2% for all treatments and no distinct pattern was noted between treatments. Oleic acid (18:1) and linolenic acid (18:3) content were affected by herbicide treatments. The 0.12 kg ai ha^{-1} rate of saflufenacil and the 0.018 kg ai ha^{-1} rate of carfentrazone-ethyl reduced the O:LN ratio compared to untreated plots. Saflufenacil at 0.06 kg ai ha^{-1} and carfentrazone-ethyl at 0.035 kg ai ha^{-1} also had lower O:LN ratio values though not statistically different than the untreated plots. The O:LN ratio shows that protoporphyrinogen oxidase (PPG oxidase) inhibitor herbicides, such as carfentrazone-ethyl and saflufenacil, can negatively affect canola oil quality.

2.3.3 Weed Control

Preemergence control of volunteer wheat, annual ryegrass, and henbit at 35 DAE is reported in Table 4. Volunteer wheat was not adequately controlled by the preemergence herbicides. Wheat control averaged 45%, 59%, and 36% for trifluralin, *S*-metolachlor, and pendimethalin, respectively. *S*-metolachlor provided excellent (99%) control of annual ryegrass. Control from trifluralin and pendimethalin was significantly lower at 60% and 52%, respectively. Henbit control was 97%, 95%, and 67% with trifluralin, *S*-metolachlor, and pendimethalin, respectively.

Table 3

Total seed oil content and fatty acid composition of canola following herbicide applications in 2010 near College Station, TX.

Herbicide treatment	Rate	Timing	Oil	Fatty acid composition[a]					
				P (16:0)	S (18:0)	O (18:1)	L (18:2)	LN (18:3)	O:LN
	ae or ai kg ha^{-1}		mL kg^{-1}	% of total peak area					
Untreated	-	-	311	4.78	1.75 c-h	65.3 a-e	21.2	7.03 b-h	9.34 c-h
Trifluralin	1.12	PPI	280	4.77	1.75 c-h	65.1 a-e	21.6	6.83 e-i	9.66 b-f
Trifluralin	0.56	PPI	284	4.88	1.76 b-g	64.5 c-f	21.7	7.18 b-f	8.99 d-h
Ethalfluralin	1.05	PPI	293	4.75	1.82 a-e	65.1 a-e	21.1	7.17 b-f	9.14 d-h
Ethalfluralin	0.53	PPI	303	4.98	1.80 a-e	65.9 ab	21.0	6.28 j	10.6 a
Carfentrazone-ethyl	0.035	PPL	309	4.74	1.77 b-g	65.1 a-e	20.9	7.43 b	8.78 gh
Carfentrazone-ethyl	0.018	PPL	304	4.78	1.67 fgh	63.4 fg	22.0	8.10 a	7.83 j
Saflufenacil	0.12	PPL	295	4.81	1.63 h	63.2 g	22.4	8.01 a	7.90 ij
Saflufenacil	0.06	PPL	311	4.70	1.74 d-h	65.0 a-e	21.2	7.42 bc	8.82 gh

Table 3

Continued.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Oil mL kg^{-1}	Fatty acid composition[a]					
				P (16:0)	S (18:0)	O (18:1)	L (18:2)	LN (18:3)	O:LN
				% of total peak area					
S-metolachlor	2.14	PRE	317	4.79	1.66 gh	64.2 efg	21.9	7.41 bc	8.70 ghi
S-metolachlor	1.07	PRE	335	4.74	1.81 a-e	66.3 a	20.4	6.83 e-i	9.70 b-e
Pyroxasulfone	0.24	PRE	305	4.75	1.81 a-e	65.9 ab	21.0	6.56 hij	10.1 abc
Pyroxasulfone	0.12	PRE	327	4.66	1.75 c-g	65.1 a-e	21.2	7.30 b-d	8.95 e-h
Pendimethalin	1.6	PRE	314	4.72	1.71 e-h	65.1 a-e	21.4	7.07 b-h	9.28 c-h
Pendimethalin	0.8	PRE	293	4.97	1.87 abc	65.8 ab	20.8	6.50 ij	10.2 ab
Quizalofop P-ethyl	0.093	EPOST	328	4.74	1.81 a-e	65.9 ab	20.4	7.19 b-f	9.28 c-h
Quizalofop P-ethyl	0.046	EPOST	332	4.73	1.71 e-h	66.0 ab	20.5	7.09 b-g	9.36 b-h

Table 3

Continued.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Oil mL kg^{-1}	Fatty acid composition[a]					
				P (16:0)	S (18:0)	O (18:1)	L (18:2)	LN (18:3)	O:LN
				% of total peak area					
Ethametsulfuron-methyl	0.023	EPOST	304	4.79	1.75 c-h	64.3 d-g	21.8	7.35 bcd	8.79 gh
Ethametsulfuron-methyl	0.011	EPOST	304	4.76	1.74 d-h	65.3 a-e	21.0	7.22 b-f	9.07 d-h
Sethoxydim	0.53	EPOST	305	4.81	1.78 b-f	64.9 b-e	21.2	7.24 b-d	9.06 d-h
Sethoxydim	0.26	EPOST	305	4.75	1.82 a-e	65.0 a-e	21.1	7.34 b-e	8.89 fgh
Glyphosate	1.06	EPOST	301	4.82	1.75 c-h	64.9 b-e	21.0	7.44 b	8.74 ghi
Glyphosate	0.53	EPOST	268	4.78	1.79 a-f	65.7 abc	21.1	6.65 g-j	10.0 abc
Clethodim	0.10	EPOST	283	4.83	1.79 a-f	64.7 b-e	21.4	7.30 b-e	8.89 e-h
Clethodim	0.05	EPOST	297	4.95	1.85 a-d	65.6 a-d	20.7	6.91 c-i	9.56 b-g

Table 3

Continued.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Oil mL kg^{-1}	Fatty acid composition[a] P (16:0)	S (18:0)	O (18:1)	L (18:2)	LN (18:3)	O:LN
				% of total peak area					
Clopyralid	0.21	EPOST	294	4.75	1.78 b-f	64.3 d-g	21.7	7.47 b	8.61 hij
Clopyralid	0.11	EPOST	301	4.84	1.84 a-d	64.8 b-e	21.2	7.25 b-d	8.98 e-h
Fluroxypyr	0.21	EPOST	281	4.94	1.91 a	65.9 ab	20.5	6.84 d-e	9.83 a-d
Fluroxypyr	0.11	EPOST	296	5.11	1.88 ab	65.3 a-e	21.0	6.72 f-j	9.74 a-e
Coeff of variation			11.41	5.24	6.83	2.02	4.47	7.28	9.47

PPI: preplant incorporated; PPL: preplant; PRE: preemergence; EPOST: early postemergence; P: palmitic acid; S: stearic acid; O: oleic acid; L: linoleic acid; LN: linolenic acid; O:LN: oleic acid to linolenic acid ratio.

[a] Means within columns followed by the same letter are not significantly different at $P \leq 0.05$.

Table 4

Preemergence control of volunteer wheat, annual ryegrass, and henbit in canola in 2011 near College Station, TX.

Herbicide treatment	Rate	Timing	Wheat[a]	Ryegrass	Henbit
	ae or ai kg ha^{-1}		% control – 35 DAE		
Untreated	-	-	0	0	0
Trifluralin	0.84	PPI	45 c	59 b	96 ab
Trifluralin fb	0.84	PPI	45 c	60 b	98 a
ethametsulfuron-methyl	0.015	EPOST			
Trifluralin fb	0.84	PPI	45 c	60 b	98 a
sethoxydim	0.32	EPOST			
Trifluralin fb	0.84	PPI	44 c	60 b	96 ab
glyphosate	0.87	EPOST			
S-metolachlor	1.6	PRE	58 b	99 a	94 b
S-metolachlor fb	1.6	PRE	59 ab	99 a	95 b
ethametsulfuron-methyl	0.015	EPOST			
S-metolachlor fb	1.6	PPI	61 a	99 a	94 b
sethoxydim	0.32	EPOST			
S-metolachlor fb	1.6	PRE	60 ab	99 a	95 b
glyphosate	0.87	EPOST			

Table 4

Continued.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Wheat[a]	Ryegrass	Henbit
			——— % control – 35 DAE ———		
Pendimethalin	0.53	PRE	38 d	54 c	68 c
Pendimethalin fb	0.53	PRE	35 e	54 c	68 c
ethametsulfuron-methyl	0.015	EPOST			
Pendimethalin fb	0.53	PRE	36 de	50 c	67 cd
sethoxydim	0.32	EPOST			
Pendimethalin fb	0.53	PRE	36 de	50 c	65 d
glyphosate	0.87	EPOST			
Ethametsulfuron-methyl	0.015	EPOST	0 f	0 d	0 e
Sethoxydim	0.32	EPOST	0 f	0 d	0 e
Glyphosate	0.87	EPOST	0 f	0 d	0 e
Coeff of variation			8.66	6.94	5.72

PPI: preplant incorporated; PPL: preplant; PRE: preemergence; EPOST: early postemergence; DAE: days after emergence (crop).

[a] Means within columns followed by the same letter are not significantly different at $P \leq 0.05$.

Weed control at 44 DAP is reported in Table 5. Volunteer wheat control improved to >90% for all treatments that received an EPOST application of either sethoxydim or glyphosate. Ethametsulfuron-methyl did not improve wheat control. Annual ryegrass control improved to >95% for all treatments that received an EPOST application of either sethoxydim or glyphosate. Ethametsulfuron-methyl improved annual ryegrass control but was less effective than sethoxydim or glyphosate. Henbit control was >95% for all treatments except the grass herbicide sethoxydim applied alone at EPOST.

2.3.4 Biomass Yield and Forage Quality

Canola biomass yield was affected by herbicide treatments (Table 6). All treatments, except pendimethalin PRE, improved canola biomass yield compared to untreated plots. Poor volunteer wheat and annual ryegrass control of the pendimethalin PRE treatment explain the low biomass yield. The highest biomass yield was the glyphosate EPOST treatment at 3.49 MT ha^{-1}. Crude protein content of the forage was not affected and averaged 22.9%. Digestible dry matter was affected by herbicide treatment. Most treatments with an EPOST of sethoxydim had lower %DDM when compared to untreated plots. Trifluralin fb sethoxydim, pendimethalin fb sethoxydim, and sethoxydim EPOST had DDM values of 67.9%, 68.2%, and 68.3%, respectively, which is lower than the untreated plots (69.5%). All other treatments had similar DDM values to the untreated plots.

Table 5

Control of volunteer wheat, annual ryegrass, and henbit in canola following postemergence herbicide applications in 2011 near College Station, TX.

Herbicide treatment	Rate	Timing	Wheat[a]	Ryegrass	Henbit
	ae or ai kg ha^{-1}		% control – 44 DAP		
Untreated	-	-	0	0	0
Trifluralin	0.84	PPI	38 f	65 d	98 b
Trifluralin fb	0.84	PPI	44 e	90 b	99 a
ethametsulfuron-methyl	0.015	EPOST			
Trifluralin fb	0.84	PPI	96 ab	99 a	98 b
sethoxydim	0.32	EPOST			
Trifluralin fb	0.84	PPI	99 a	99 a	99 a
glyphosate	0.87	EPOST			
S-metolachlor	1.6	PRE	73 c	99 a	99 a
S-metolachlor fb	1.6	PRE	67 d	99 a	99 a
ethametsulfuron-methyl	0.015	EPOST			
S-metolachlor fb	1.6	PPI	96 ab	99 a	99 a
sethoxydim	0.32	EPOST			
S-metolachlor fb	1.6	PRE	99 a	99 a	99 a
glyphosate	0.87	EPOST			

Table 5

Continued.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Wheat[a]	Ryegrass	Henbit
			——— % control – 44 DAP ———		
Pendimethalin	0.53	PRE	25 g	39 e	99 a
Pendimethalin fb	0.53	PRE	28 g	75 c	99 a
ethametsulfuron-methyl	0.015	EPOST			
Pendimethalin fb	0.53	PRE	94 b	99 a	99 a
sethoxydim	0.32	EPOST			
Pendimethalin fb	0.53	PRE	99 a	99 a	99 a
glyphosate	0.87	EPOST			
Ethametsulfuron-methyl	0.015	EPOST	0 h	67 d	97 c
Sethoxydim	0.32	EPOST	93 b	97 a	0 d
Glyphosate	0.87	EPOST	99 a	99 a	99 a
Coeff of variation			7.59	5.92	1.08

PPI: preplant incorporated; PPL: preplant; PRE: preemergence; EPOST: early postemergence; DAP: days after postemergence application.

[a] Means within columns followed by the same letter are not significantly different at $P \leq 0.05$.

Table 6

Biomass yield, crude protein content, and digestible dry matter content of canola forage following herbicide applications in 2011 near College Station, TX.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Biomass[ab] MT ha^{-1}	CP %	DDM %
Untreated	-	-	2.43 d	22.6	69.5 a-d
Trifluralin	0.84	PPI	2.95 bc	22.5	68.6 c-f
Trifluralin fb	0.84	PPI	2.89 bc	22.4	68.7 c-f
ethametsulfuron-methyl	0.015	EPOST			
Trifluralin fb	0.84	PPI	3.11 b	22.9	67.9 f
sethoxydim	0.32	EPOST			
Trifluralin fb	0.84	PPI	2.81 c	23.5	69.6 abc
glyphosate	0.87	EPOST			
S-metolachlor	1.6	PRE	3.00 bc	22.4	68.8 c-f
S-metolachlor fb	1.6	PRE	2.95 bc	22.5	68.9 c-f
ethametsulfuron-methyl	0.015	EPOST			
S-metolachlor fb	1.6	PPI	2.96 bc	23.1	70.2 ab
sethoxydim	0.32	EPOST			
S-metolachlor fb	1.6	PRE	3.11 b	22.6	70.5 a
glyphosate	0.87	EPOST			

Table 6

Continued.

Herbicide treatment	Rate ae or ai kg ha^{-1}	Timing	Biomass[ab] MT ha^{-1}	CP %	DDM %
Pendimethalin	0.53	PRE	2.49 d	22.8	69.2 b-e
Pendimethalin fb	0.53	PRE	2.82 c	22.7	68.7 c-f
ethametsulfuron-methyl	0.015	EPOST			
Pendimethalin fb	0.53	PRE	2.79 c	22.7	68.2 ef
sethoxydim	0.32	EPOST			
Pendimethalin fb	0.53	PRE	3.16 b	23.3	69.4 a-d
glyphosate	0.87	EPOST			
Ethametsulfuron-methyl	0.015	EPOST	2.99 bc	24.0	68.6 c-f
Sethoxydim	0.32	EPOST	3.15 b	23.8	68.3 ef
Glyphosate	0.87	EPOST	3.49 a	23.1	68.4 def
Coeff of variation			11.55	6.55	2.02

PPI: preplant incorporated; PPL: preplant; PRE: preemergence; EPOST: early postemergence; CP: crude protein; DDM: digestible dry matter.

[a] Biomass yield is expressed on a dry matter basis.

[b] Means within columns followed by the same letter are not significantly different at $P \leq 0.05$.

2.4 Conclusions

The research shows that pendimethalin and *S*-metolachlor may be suitable for canola production in South Texas based on low crop injury and effective weed control. Neither pendimethalin nor *S*-metolachlor is currently labeled for use in canola. The herbicides trifluralin, ethalfluralin, quizalofop P-ethyl, ethametsulfuron-methyl, sethoxydim, glyphosate, clethodim, and clopyralid are currently labeled for use in canola in the United States or Canada and were confirmed suitable for canola production in South Texas. Herbicides did not affect total seed oil content. The PPG oxidase inhibitor herbicides carfentrazone-ethyl and saflufenacil, applied PPL, cause both visual injury and potentially reduce canola oil quality with respect to fatty acid composition. Production of singlet oxygen by PPG oxidase inhibitor herbicides, which readily react with lipids (Dayan and Duke, 2003), may explain these findings. Further research would be required to determine the exact cause of this interaction. Effective weed control results in higher biomass yields when compared to untreated plots. Forage digestibility may be affected by sethoxydim; however, the results were not conclusive. Given the expansion of canola production into new regions, continued research with respect to weed management systems is warranted.

3. SUMMARY AND CONCLUSIONS

Canola is a cool-season, oilseed crop grown throughout Europe, Canada, and the Northern Great Plains region of the United States. Canola is commonly grown in rotation with wheat, which can provide yield improvement for both crops. As a consequence, herbicide carryover becomes a concern following wheat production as several herbicides common to wheat production have rotation restrictions of 2 to 3 years with respect to canola. The expansion of canola production into new growing regions, such as the Southern Plains region, has provided new opportunities and challenges. The Southern Plains region grows canola as a winter annual compared to a spring annual for the Northern Great Plains and Canada. Given the difference in climate and weed spectrum, region-specific weed management systems need to be developed. Agronomic practices can affect seed oil content, protein content, and fatty acid composition; however, the effect of herbicides on these and other characteristic of canola are unknown. Therefore, experiments were conducted in 2010 and 2011 to evaluate a broad spectrum of herbicides for potential use in South Texas canola production with respect to crop injury, effects on canola seed oil content, fatty acid composition, weed control, biomass yield, and forage quality.

Visual crop injury at 42 DAE was unacceptable for saflufenacil at 0.12 and 0.06 kg ai ha^{-1} and ethalfluralin at 1.05 kg ai ha^{-1}. Trifluralin at 1.12 and 0.56 kg ai ha^{-1}, *S*-metolachlor at 2.14 and 1.07 kg ai ha^{-1}, pyroxasulfone at 0.24 and 0.12 kg ai ha^{-1}, and pendimethalin at 0.8 kg ai ha^{-1} had lowest visual injury of all treatments. Injury was

relatively stable over time due to slow canola growth. Postemergence herbicides quizalofop P-ethyl, ethametsulfuron-methyl, sethoxydim, glyphosate, clethodim, and clopyralid did not cause any visible injury. Fluroxypyr applied EPOST caused severe injury at both 0.21 and 0.11 kg ae ha^{-1}.

Seed oil content was not affected by any herbicide treatment. Fatty acid composition, specifically stearic acid, oleic acid, linolenic acid, and oleic to linolenic acid ratio, was affected by herbicide treatments. This research found that protoporphyrinogen oxidase (PPG oxidase) inhibitor herbicides, such as carfentrazone-ethyl and saflufenacil, negatively affect canola oil quality.

Weed control following preemergence herbicides varied by weed species. Volunteer wheat control was poor for trifluralin, *S*-metolachlor, and pendimethalin. *S*-metolachlor provided excellent control of both annual ryegrass and henbit. Annual ryegrass control was lower for both trifluralin and pendimethalin. Trifluralin controlled henbit as well as *S*-metolachlor. Pendimethalin provided lower control of henbit at 35 DAE than the other treatments. Postemergence control of volunteer wheat and annual ryegrass was excellent for treatments that received an EPOST application of either sethoxydim or glyphosate. Ethametsulfuron-methyl did not improve wheat control. Henbit control was also excellent for all treatments except the grass herbicide sethoxydim applied alone at EPOST. The research shows that pendimethalin and *S*-metolachlor may be suitable for canola production in South Texas based on low crop injury and effective weed control despite not being labeled for use in canola.

Biomass yield was improved for all treatments except pendimethalin PRE when compared to the untreated plots. Poor volunteer wheat and annual ryegrass control by the pendimethalin PRE treatment explain the low biomass yield. Highest biomass yield occurred in the glyphosate EPOST treatment. Crude protein content of canola forage was not affected by herbicide treatment. Digestible dry matter appeared to be reduced by treatments that included an EPOST application of sethoxydim.

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