Agronomic and Economic Comparison of Potential Winter Oilseed Species and Varieties for Tennessee

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ABSTRACT

Winter oilseed crops are annual cool season Brassica crops which fit well within typical corn and soybean rotations. They are currently being adopted in Midwestern conventional agriculture systems. The ability to produce sustainable aviation fuel (SAF) from oil pressed from the seeds is the driving force of recent interest in the crops. The three main crops of interest in this study are canola (*Brassica napus*), pennycress (*Thlaspi arvense* L.), and camelina (*Camelina sativa*). To determine if production of winter oilseeds is feasible in Tennessee, three experiments were conducted. First, a field study variety trial was evaluated for winter oilseed ground coverage, seed yield, oil content, and subsequent soybean yield and quality. After two years of study at two locations in Tennessee, canola and pennycress performed well, while camelina did not survive the winters. Second, a bioassay was conducted to determine possible allelopathic effects of water extractable chemicals from canola and pennycress roots and stubble on the subsequent crop and spring weeds. Seeds of soybean (*Glycine max*), mare's tail (*Erigeron canadensis*), and palmer amaranth (*Amaranthus palmeri*) were treated with extracts and evaluated for germination percentage, radicle length, and hypocotyl length. Water extractable compounds from canola and pennycress inhibit growth and germination of the herbicide resistant weeds, while not affecting soybean. Lastly, an economic analysis of winter oilseed production was conducted. Based on practices and yields from the field study, budgets were created for canola and pennycress, and breakeven and profitability analyses conducted. At present yields, inputs, and projected prices, canola production in Tennessee for biofuel production is profitable while pennycress is not profitable. With further research, increased breeding efforts, and the creation of a market for biofuels from winter oilseeds in Tennessee, winter oilseeds may become a valuable double crop to Tennessee producers.

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CHAPTER ONE: INTRODUCTION AND LITERATURE REVIEW

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Core Ideas:

1. Winter oilseed crops have the potential to address both environmental and economic sustainability issues.
2. Winter oilseed crops provide winter cover, biofuel production, and revenue without interfering with the food supply.
3. Canola production is well established in the US, and pennycress and camelina production is increasing.
4. Winter oilseeds may have untapped potential for production in the Mid-South region of the US.

National Winter Oilseeds Review for Potential in the U.S. Mid-South: Pennycress, Canola, and Camelina

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Abstract

Winter oilseeds are cool season Brassica crops currently being grown in the upper Midwest and North-West of the United States. They have the potential to function as dual crops when grown in rotation with corn, soybean, and small grains. They provide many of the benefits of typical

cover crops over winter, with the added benefit of extra revenue to growers who sell the seeds for uses such as biofuel, industrial products, human consumption, or animal feed. This review gathers current agronomic and industrial use information about canola (*Brassica napus* L.), camelina *(Camelina sativa* (L.) Crantz), and pennycress (*Thlaspi arvense* L.). Currently, most research involving these crops is specific to the Midwest. This review also poses questions regarding how these crops could be adapted to grow in the Mid-South, with further research being necessary in several areas before promoting adoption in the region.

Introduction

Winter oilseed crops have the potential to function as winter cover crops in rotation with many summer annual crops (Ehrensing & Guy, 2008; Mohammed et al., 2020; Moore et al., 2020a; Myers 2018; Wortman, 2020). Due to the long growing season of corn (*Zea mays*) and soybean (*Glycine max*), many Midwest farmers find establishing a winter cover crop difficult (Mohammed et al., 2020). They choose to leave fields fallow instead, which can lead to soil erosion, nutrient leaching, and weed infestation (Moore et al., 2020b). Beyond simple timing problems, farmers may forgo planting cover crops because they do not receive a direct economic gain from this practice (Moore et al., 2020a). Winter oilseed crops may mitigate both noted problems by functioning as winter covers planted after corn/soybean harvest (Moore et al., 2020b; Myers, 2018; Wortman, 2020.), and as cash crops if harvested in the spring before planting the next rotation of corn/soybeans (Betancor et al., 2021; Herbek, 2012; Mohammad et al., 2018; Moore et al., 2020a). Winter oilseed crops have been studied recently in the upper Midwest, Great Plains, and North-West regions of the United States, but more research is necessary in the Mid-South (Kentucky, Tennessee, Arkansas, northern Mississippi, and southeastern Missouri) to determine the viability of winter oilseed production in this region. This

review compiles current information available surrounding general agronomic practices for growing winter oilseed crops in the Midwest and address potential for adapting these practices in the Mid-South. Further research needs before promoting adoption of these crops in the Mid-South are also addressed.

Crop Species

Three species of winter oilseed crops are of particular interest for production in conventional agriculture: pennycress, canola, and camelina. All three species are in the mustard family (*Brassicaceae*). Each crop can be sold for several uses, has a high seed oil content, and can be grown as a winter annual. Current markets exist for camelina and canola, however there is no commercial market for pennycress. Table 1.1 below gives a botanical description and basic overview of each crop. The remainder of this review provides detailed descriptions of each crop's growing needs, oil content, and marketable uses.

1. Field Pennycress

Pennycress is a predominantly winter annual native to Eurasia that is a naturalized common weed throughout North America and Europe (Anderson et al., 2016; Moore et al., 2020b; Cubins et al., 2019). There are many descriptions of pennycress as a weed (Anderson et al., 2016), however recent research demonstrates pennycress's potential as an environmentally useful cash cover crop (Forcella et al., 2020; Mohammed et al., 2020; Moore et al., 2020a; Moore et al., 2020b; Wortman, 2020). Pennycress is a broadleaf herbaceous annual plant with an upright growth habit and branching stems (Anderson et al., 2016).

Table 1.1 Botanical descriptions and comparisons of pennycress, canola, and camelina.*

Species Information	Field Pennycress	Winter Canola	Winter Camelina
Scientific Name	*Thlaspi arvense* L.	*Brassica napus* L.	*Camelina sativa* (L.) Crantz
Plant Height	10-81 cm	81-150 cm	30-100 cm
Leaves	Simple leaves with toothed margins	Rounded to arrow-shaped leaves with deeply toothed margins	Arrow-shaped with smooth to undulated margins
Seeds	Small circular seeds. Wild seeds can remain viable for up to 20 years. Black or golden in color.	Small circular seeds. Brown to black in color.	Small, rough texture. No dormancy. Brown to reddish in color.
Average Weight per 1,000 Seeds	0.97-1.12 g	3-6 g	0.8-2 g
Seed Oil Content	26-39% oil. High levels erucic acid. Suitable for biofuel and bio-jet fuel production.	30-50% oil. Low erucic acid, suitable for human and livestock consumption. High in polyunsaturated fatty acids. Suitable for biofuel production.	30-41% oil. High in omega-3 fatty acids. Low in saturated fatty acids and erucic acid. Suitable for human and livestock consumption. Contains Vitamin E. Suitable for biofuel and bio-jet fuel production.
Soil	Wide range of acceptable soil types. Moderately tolerant to salinity.	Wide range of acceptable soil types but requires good drainage. Moderately tolerant to salinity.	Wide range of acceptable soil types. Thrives where other crops may be stressed but requires decent drainage. Tolerant to salinity.

Table 1.1 Cont.

Species Information	Field Pennycress	Winter Canola	Winter Camelina
Water Needs	Typically rainfed	Typically rainfed	Grows well under drought conditions. Well suited for low rainfall regions.
Pest Problems	Can host soybean cyst nematode	White mold stem rot, Blackleg fungus, Aster Yellow. Insects not shown to be economically damaging except in high residue environments. Not a host to soybean cyst nematode.	Sclerotinia stem rot, Downy Mildew (when grown in the South, or in spring camelina). Insects not shown to be economically damaging. Not a host of soybean cyst nematode and may reduce populations.
Seeding	Broadcast or drilled. Tilled or no-till. 5 to 6 kg ha^{-1} seeding density.	Drilled. Tilled or no-till. 3-5 kg ha^{-1} seeding density or 550,000 seeds ha^{-1} seeding density.	Broadcast or drilled. Tilled or no-till. 2 to 6 kg ha^{-1} seeding density.
Harvest Options	Direct combining. Unclear if desiccant helpful to minimize shattering loss.	Direct combining. Swathing. Use of desiccant.	Direct combining. Swathing (may not be necessary due to low affinity to shatter).

* Information presented derived from Acharya et al., 2019; Anderson et al., 2016; Bandehagh et al., 2021; Berti et al., 2011; Berti et al., 2016; Bushong et al., 2018; CanolaCouncil, 2012; Does et al., 2017; Ehrensing & Guy, 2008; Gesch et al., 2017; Leclere, 2021; Liu et al., 2022; Matthees et al., 2018; Moore et al., 2020a; Myers, 2018; Oplinger et al, 1989; Riaz et al., 2022; Schillinger et al., 2012; Veljković et al., 2022; Walia et al., 2018; Wittenberg et al., 2019; Zanetti et al., 2017.

1.1 Growing Pennycress

Pennycress is currently not commercially grown on a large scale in the United States and best production practices and standard management systems are not yet decided (Cubins et al., 2019; Moore et al., 2020a). Most research in the US on pennycress has occurred in the Midwest, and little is agreed upon for planting dates and strategies. Several studies have concluded early September planting dates favor better germination as well as winter survival in the upper Midwest (Cubins et al., 2019). Pennycress germinates best in cool conditions with adequate moisture (Cubins et al., 2019), which can make finding the optimal planting date challenging. Seed germination is also sensitive to moisture stress, with water availability on the soil surface being the dominate environmental limiting factor to seed germination (Hazebroek & Metzger, 1990). The ideal method of seeding is debated as well. Pennycress seed can be drilled or broadcast, and studies vary on their conclusions stating yield effects of each (Moore et al., 2020a). Broadcasting is feasible because pennycress is positively photoblastic (Cubins et al., 2019; Moore et al., 2020a) and may improve the economic feasibility of adopting pennycress as a cover crop because drilling seed is more expensive (Moore et al., 2020a). Seedling emergence is inhibited by far red light and can be inhibited when light is filtered through a canopy (Hazebroek & Metzger, 1990; Wortman, 2020). This allows interseeding as a planting method, as a grower can seed before harvest of the summer crop and pennycress will not begin to grow until post-harvest. Several studies investigated the possibility of inter-seeding pennycress into corn and soybean fields in early fall (Mohammed et al., 2020; Wortman, 2020). In one study in Lincoln, Nebraska, when inter-seeded into soybean, pennycress germinated in late August/early September with no significant yield loss of the cash crop (Wortman, 2020). A study by Mohammed et al. (2020) conducted in Iowa, Minnesota, and North Dakota, inter-seeded

pennycress into both corn and soybean systems in the fall. They found no negative effects of inter-seeding on cash crop yield nor soil water content. These findings indicate inter-seeding is a viable option for fall pennycress cover crop establishment. A Minnesota study found soybeans could be inter-seeded into stands of winter oilseeds before harvest. Inter-seeded soybeans had lower yields than mono-cropped soybeans, however net income was equivalent for both systems (Ott et al., 2019). To complete the rotation, pennycress will be ready for harvest in late May/early June, around the time soybeans and corn need to be planted again for the summer (Wortman, 2020). Based on a study from Minnesota, dry bean (*Phaseolus vulgaris*), proso millet (*Panicum miliaceum*), buckwheat (*Fagopyrum esculentum*), and sweet corn (*Zea mays*) are also recommended crops to immediately follow a winter cover of pennycress (Moore et al., 2020a).

Nutrient requirements for pennycress have not been determined. One study found no significant differences between different fertilizer rates applied (Moore et al., 2020a). Other studies have concluded that residual nutrients from previous crops may provide adequate fertility (Cubins et al., 2019). A publication describing pennycress growth stages and potential management timing by Verhoff et al. (2022) will help develop future management guides.

Discrepancies arise when deciding on the best practices for pennycress harvesting as well. Pennycress can be machine harvested with a small grains combine, but may need to be harvested at physiological maturity (roughly 40% seed moisture) two weeks earlier than typical harvest (when moisture reaches 8%) to avoid large yield losses from seed shattering (Cubins et al., 2019; Oplinger et al., 1989). Seed loss due to low moisture content and seed shatter at maturity is well documented. Further research is necessary to determine the usefulness of harvest aids and sprays to quickly dry the crop once it reaches physiological maturity (Cubins et al., 2019).

There are few studies conducted on pennycress yield, with most results from the upper Midwest. These studies noted inconsistent seed yields in pennycress due to variable stand densities and environments (Cubins et al., 2019). The average yield reported ranges from 200 kg ha^{-1} to 800 kg ha^{-1} in Illinois, Minnesota, and South Dakota (Cubins et al., 2019). Moore et al. (2020a) found pennycress yields to be low in each of their trials, with seed shattering and external environmental factors thought to play a large role in overall pennycress yield potential. Further research is needed to determine best management practices to optimize yields, which will then allow farmers to project potential market sales and economics in advance.

1.2 Pennycress Seed Oil

Seed oil content in pennycress ranges from 26-39% and may vary based on soil temperature at planting (Does et al., 2017). One study found that November plantings with a soil temperature less than 5°C had a low seed oil content (26-30%), but late August planted trials had higher soil temperatures and much higher oil contents at harvest (36%) (Does et al., 2017). The composition of pennycress seed oil, as well as its high seed oil percentage, have made pennycress a favored feedstock for biofuel, industrial lubricants, and jet fuel production (Cubins et al., 2019). Studies have shown that pennycress yield of 1500 kg ha^{-1} equate to roughly 600-1200 L ha^{-1} of oil for biofuel production (Tsogtbaatar et al., 2015). These values may be overstated. Oilseed crops oil generally weighs 0.9 kg L^{-1}. Based on yield weight, percent oil present in seed, and weight of oil per liter, a more realistic range is 433-650 L ha^{-1} of oil production. The naturally high levels of erucic acid, a monosaturated fatty acid with 22 carbons, which accumulate in pennycress seeds, make the crop suitable for biofuel production. Several tests have determined the physical and chemical characteristics of pennycress seed oils meet US biofuel standards (Tsogtbaatar et al., 2015). The high protein and low starch contained within a

pennycress seed embryo contribute to pennycress's suitability for biofuel production (Tsogtbaatar et al., 2015). Specifically, pennycress oil can be used to create sustainable jet fuel, and several companies have committed to looking at pennycress to increase their usage of renewable energy (Mousavi-Avval & Shah, 2021; Trejo-Pech et al., 2019).

Sustainable jet fuel production may be the key to making pennycress a profitable crop. Pennycress feedstock works as a drop-in hydrocarbon biofuel, with a 50% reduction in greenhouse gas emissions compared to petroleum (Fan et al., 2013). When processed, 45.4 kg of pennycress oil can create 27 liters of jet fuel, 3.8 liters of naptha, 12.4 liters of biodiesel, and 9.5 liters of propane (Markel et al., 2018). An economic analysis of growing pennycress for jet fuel production found potential profits if seed were transported, refined, and sent to Nashville International Airport (Trejo-Pech et al., 2019). Other economic analyses show conflicting results for profitability because the yield potential and production costs are not yet well understood. In the creation of sustainable jet fuel, the feedstock has been identified as the largest portion of production cost (Mousavi-Avval & Shah, 2021). While the low input needs of pennycress make it a potentially lower cost feedstock than other oilseeds, pennycress grain supply has been estimated to contribute roughly 45% of total operating costs of jet fuel production (Mousavi-Avval & Shah, 2021). Large amounts of pennycress feedstock are required to create jet fuel. Making biofuels from camelina and canola require a similarly large amount of biomass, and the feedstocks of these plants take up a similar amount of the production budget (Mousavi-Avval & Shah, 2021).

An in-depth economic analysis conducted by Mousavi-Avval and Shah (2021) found that for jet fuel production from pennycress to be profitable, the feedstock must be supplied at a low cost ($0.17 per kg) and pennycress meal byproduct must be sold as animal feed. However, the

high glucosinolate content found within pennycress oil makes use as an animal feed uncertain (Mousavi-Avval & Shah, 2021). In a similar analysis conducted by Trejo-Pech et al. (2019), the breakeven price for producers selling pennycress for biofuel is \$0.177 kg^{-1} after growing, harvesting, and transporting the biomass to a production facility. However, in their analysis, biofuel production facilities could pay between \$0.17 to \$0.23 per kg and remain profitable (Trejo-Pech et al., 2019). At 1,000 kg ha^{-1} seed yields, this equates to \$170 to \$230 ha^{-1} for growers. Another earlier study proposed that facilities will pay \$0.07 per kg of seed (Markel et al., 2018), which would be less enticing to a grower.

All projected profitability is sensitive to the cost of pennycress production, the price of oilseeds and meal, and pennycress yields (Trejo-Pech et al., 2019). Total variable expenses for pennycress production at 5.6 kg ha^{-1} seeding density are expected to be ~\$30 per ha, and total fixed expenses are expected to be \$9.41 per ha (Markel et al., 2018). Increasing pennycress grain yield per acre would lower the cost of pennycress production, thereby also lowering the cost of sustainable jet fuel production (Mousavi-Avval & Shah, 2021). A study in 2020 found that based on the current market and policy conditions, the production of bio-jet fuel from pennycress would not be profitable unless the price of crude oil would increase at least 31 to 52 % (from \$100-130 per barrel), petroleum jet fuel prices increased at least 11 to 26 % (from \$1.85 per gallon), pennycress oil price becomes 2 to 6 % less than soybean oil prices in any given year, or a combination of these conditions (Stevens & Taheripour, 2020). With an investment in oil refinery infrastructure, increased pennycress production, and increased use of bio-jet fuel by domestic airports, a projected \$19 billion could be added to the United States economy, and 66,000 jobs would be created over time (Markel et al., 2018).

1.3 Pennycress as a Cover Crop

Pennycress has been described as a low input, nutrient scavenging crop (Cubins et al., 2019), making it an efficient cover crop option. As a cover crop, pennycress has produced sufficient levels of green cover through the winter (between 37-57% groundcover) and low spring biomass (Mohammed et al., 2020; Wortman, 2020). The low biomass accumulation in the spring can be an attractive option for farmers worried about nitrogen immobilization or pest pressure often associated with high biomass cover crops, while still providing needed erosion and nutrient scavenging services (Moore et al., 2020a; Wortman, 2020). When several cover crops were intercropped with soybean, pennycress plots reduced total suspended solids in runoff by 75% compared to the fallow control and radish treatments (Weyers et al., 2021). Other potential purposes for planting pennycress as a cover crop include its abundant flowers in early spring for attracting pollinators (Forcella et al., 2020), its potential use for biofumigation of soil pests, and its allelopathic potential against weed seeds (Wortman, 2020). Utilizing pennycress as a nitrogen catch crop may provide environmental benefits because leftover nitrogen in the soil following cash crop production may leach, contaminate ground water, and cause human health and environmental concerns (Moore et al., 2020a). Leaving land fallow through the winter can exacerbate leaching but using winter annual cover crops can reduce nitrogen loss from the soil by up to 80% (Moore et al., 2020a). A study by Moore et al., (2020a) found that pennycress can significantly reduce nitrogen in the soil, while still producing an average yield, without added fertilizer when grown after corn. Furthermore, they found pennycress was as effective a catch crop as cereal rye, the most common winter cover crop in the Midwest, although environmental factors may impact this year to year (Moore et al., 2020a). In Minnesota, pennycress spring nitrogen uptake ranged from 28 to 49 kg N ha^{-1}, outcompeting winter rye and radish (Weyers et

al., 2019). Nitrogen reductions in soil water were also noted from fall establishment through soybean planting compared to fallow control plots (Weyers et al., 2019). These ecologic benefits make pennycress an ideal candidate for dual-use cover cropping.

1.4 Potential Problems with Pennycress

A few potential pitfalls exist with the adoption of pennycress as a dual use cover crop. Wild accessions of pennycress still exhibit undesirable agronomic characteristics such as a high affinity to shatter. The seeds shattered may persist in the seed bank for decades, negatively impacting the following crops (Cubins et al., 2019). One study cites the ability of the crop to reseed itself as a positive trait, as each fall the winter cover will grow back. However, this limits crop rotation diversity and will increase the likelihood of introducing and supporting Brassica specific pests on the farm (Wortman, 2020). Several states list pennycress as a noxious weed, including Indiana, Kansas, Nebraska, Nevada, Ohio, South Dakota, and Washington, and USDA-APHIS classifies it as a high risk weed (USDA-APHIS, 2015). Concerns include the potential for herbicide resistance in pennycress (Wortman, 2020). Resistance to ALS inhibitor herbicides has been reported in Canada (USDA-APHIS, 2015), which could create weed control issues in the following winter crop rotation after pennycress production. Another potential weed problem with pennycress is seed dormancy. Pennycress seed dormancy can be regulated by far-red light, temperature, and moisture (Hazebroek & Metzger, 1990). Primary dormancy can be broken by red light or exposure to moisture; however, a deep secondary dormancy can be induced if seeds imbibe water when temperatures are below 6˚ C (Hazebroek & Metzger, 1990).

Pest host concerns exist within pennycress production as well. Currently, there are 11 pesticides labeled for use in pennycress production (although there are many used to destroy pennycress) (CMDS, 2023). Pennycress can host soybean cyst nematode (Anderson et al., 2016;

Hoerning et al., 2022), a devastating soybean pest in US agriculture. However, pennycress is a less suitable host than soybean (Hoerning et al., 2022) meaning the presence of pennycress in a field will not likely increase the soybean cyst nematode population.

Stand establishment can be difficult to achieve in pennycress production. Establishment is highly sensitive to planting depth, with an optimal depth of 1 cm (Altendorf, 2017). Broadcast seed may have insufficient contact with the soil, while planting too deep can lead to poor establishment (Altendorf, 2017). Stand density may have a high impact on overall yield, with higher plant density resulting in lower seed yields (Altendorf, 2017). Finding the perfect balance of good stand establishment and optimal plant density will be imperative for growers hoping to grow pennycress on a large scale.

2. Winter Canola

Canola is a derivative of European rapeseed with an extremely low erucic acid content (< 2%) that was purposefully developed in Canada to create food safe vegetable oil (Myers, 2018; Oplinger et al, 1989). Behind soybeans, canola now rotates with palm being the second or third most widely grown oil seed crop worldwide (Myers, 2018; Sainju et al., 2020). In North America, most canola grown is spring type and is grown in Idaho, Minnesota, Montana, North Dakota, Washington, and Wisconsin (USDA FSA, 2022). Winter types of canola can be grown in the lower US Great Plains as well as Ontario and Quebec in Canada (Bushong et al., 2018; Myers, 2018; Oplinger et al., 1989). However, commercial production of winter canola is increasing in recent years in more southern regions because canola lacks freeze hardiness if not given adequate establishment time (U.S. Canola Association, 2022). Northern spring and winter canola work well as a double crop when grown in a corn/canola/soybean rotation. Compared to winter wheat, major benefits of canola in this rotation include low residue, favorable for reduced

till soybean planting and establishment (Myers, 2018), and its earlier harvest date prior to summer cash crop planting (Myers, 2002).

2.1 Typical Growth Characteristics and Production Practices

Canola is an annual plant with both winter and spring varieties (Myers, 2018). For winter varieties, fall planting should occur roughly six weeks before the first fall frost to allow the crop to develop five to six true leaves and good root reserves for overwintering before the first killing frost of the year (deKoff et al., 2016; McGreary et al., 2022; Oplinger et al., 1989). Canola is semi winter hardy; the best winter growth conditions are mild winters or sufficient snow cover throughout the coldest parts of the season (Oplinger et al., 1989). Planting on good internally-drained soils or slopes is another key to winter survival (Myers, 2018). Canola's lack of winter hardiness is one of the main causes for interest in the more winter hardy oilseeds such as camelina and pennycress.

Preparing the seedbed and encouraging sufficient stand establishment is important in canola production due to a lack of early seedling competitiveness. The seed bed should be smooth, firm, and moist throughout for the best over wintering conditions (Bushong et al., 2018; Myers, 2018; Oplinger et al., 1989). Although the crop is adaptable to many soil types, including slightly saline soils, canola will not tolerate poor water drainage (Myers, 2018; Oplinger et al., 1989). Further research suggests early planting, shallow seeding depth, narrow row spacing, and high seeding densities (along with adequate water supply and balanced nutrition) are best management practices for increasing yields in canola (Assefa et al., 2018; Bushong et al., 2018). Planting at a low seeding density, roughly 3 to 5 kg ha^{-1}, will encourage the growth of large crowns needed for overwintering (Myers, 2018).

Similar to corn and soybean, canola has distinct growth stages numbered 0 to 5. Stage 0 is pre-emergence, stage 1 is the seedling, stage 2 is the rosette, stage 3 is the bolting and bud, stage 4 is bloom, and stage 5 is ripening (Oplinger et al., 1989). Heat stress during stage four has been linked to floral sterility and yield losses. Daily maximum temperatures exceeding 30°C during bloom result in seed yield losses (Morrison & Stewart, 2002).

Weed control in early fall, if thorough, is generally enough to prevent dramatic spring weed growth (Myers, 2018). The best pre-plant fall weed control strategies include tillage and herbicide use. However, canola is susceptible to some broadleaf herbicides so reading herbicide labels is especially important before use (Myers, 2018; Oplinger et al., 1989). Herbicide drift can also prove challenging to canola crops (Myers, 2018). Glyphosate and imazamox herbicide tolerant cultivars are available if spraying post-emergent herbicide for weed control is desired (deKoff et al., 2016).

Common disease problems of canola include white mold stem rot (*Sclerotinia sclerotiorum*), blackleg fungus (*Leptosphaeria maculans*), and aster yellows (Bushong et al., 2018; deKoff et al., 2016). Clubroot (*Plasmodiophora brassicae*) is an emerging disease problem first reported in the United States in North Dakota in 2013 (Chittem et al., 2014). Within five years after being discovered in Canada in 2003, clubroot became the most important canola disease in the country (Chittem et al., 2014). In a 2020 survey, spread of clubroot in canola seems to be restricted to North Dakota in the United States (Chapara, 2022). Climatic conditions of high soil moisture, warm soil temperatures between 20 and 24ºC, and acidic soil can exacerbate clubroot spread and damage to the crop (American Society of Agronomy, 2015). Continual monitoring will be required to prevent the spread of clubroot, especially if the disease begins trending south.

Insect pests of canola can occur through the entire growing season and can reduce yields by damaging flowers or seed pods, defoliating plants, damaging roots, or transmitting aster yellow virus (Bushong et al., 2018). In some areas, insects have not been economically damaging to canola except for seedlings grown in high residue environments (Myers, 2018). However, in the Great Plains, economic and treatment thresholds are readily available for winter canola production for the following pests: aphids, army cutworm, beat armyworm, cabbage looper, diamondback moth, false chinch bug, flea beetle, harlequin bug, grasshopper, lygus bug, white grub, and wireworm (Bushong et al., 2018).

Nutrition recommendations for canola exist for many regions of the United States. General recommendations for winter canola include applying 18 to 23 kg of nitrogen (N) per acre in the fall, and 90 to 112 kg N ha^{-1} in the spring. However, these additions can be much lower if following a legume in rotation (Myers, 2018). Nitrogen is the most limiting nutrient for canola production (McGeary et al., 2022). In a study conducted in Tennessee, plots fertilized with 112, 168, and 224 kg N ha^{-1} all had greater yields and lower shattering incidence compared to lower rates (McGeary et al., 2022). Too high N application rates can hinder oil concentration in the canola seeds, however. An inverse relationship between N application rate and oil concentration was found in the same Tennessee study (McGeary et al., 2022). Too high N application rates can also increase lodging in canola, making harvest difficult, as the plants grow long and leggy. Conversely, N deficient plants have weak stems prone to lodging as well (Canola Council, 2020). Finding a balance between N fertility for growth and oil production is important for growers. Soil testing is recommended to determine the need for phosphorous (P), potassium (K), and sulfur (S) additions (Myers, 2018). Boron (B) and sulfur applications are more important in canola compared to other crops. Canola is sensitive to low B levels, and a

deficiency may negatively impact yield. Boron is typically recommended at 1.0 to 2.5 kg ha^{-1}, which can be blended into other dry fertilizers or applied through foliar application (Isleib, 2017). Low S availability can drastically lower yields in canola as well, so applying 22 to 33 kg S ha^{-1} is recommended. Many growers do not routinely test for S, but this could be an important soil check for canola production. Elemental S is not recommended to apply due to slow break down, unless applied immediately before planting. Applying sulfate fertilizers will quicken S availability to the crop (Franzen, 2017).

Winter canola is harvested in the late spring to early summer when the pods turn to tan or brown (Myers, 2018). Because preharvest shattering is a major concern, ripe canola should be harvested immediately. If performed correctly, canola can be swathed, desiccated, or harvested directly to achieve optimum harvest (Bushong et al., 2018). Desiccants are commonly used in canola production when direct harvest is desired and should be sprayed when 70 to 80 % of seeds have changed color (Bushong et al., 2018). In major growing areas, canola is swathed when 30 to 40% of the seed pods change color from green to brown. However, if the crop is severely lodged, swathing can wait until 40 to 50% of the pods have turned brown (Oplinger et al., 1989). Canola can be harvested once dried to 10% moisture, but if the crop is to be stored long term it is recommended to wait until 8% moisture (deKoff et al., 2016; Myers, 2018; Oplinger et al., 1989). During harvest, combine sieves are typically closed more than for wheat, and all holes in combine should be patched to reduce yield losses (deKoff et al., 2016). The standard test weight of canola is 50 lbs $bushel^{-1}$.

Storage of canola must be tightly sealed and dry. If stored seed is not dried sufficiently, seed can heat, sweat, and spoil even at 9% moisture. Due to the small size of seed, thin layers are necessary to support adequate air flow (Oplinger et al., 1989). Seed stored at 13°C and 7%

moisture will store safely for 5 months (Bushong et al., 2018). To prevent the attraction of insects and blockage of air flow, seed should be cleaned to less than 2.5% foreign material before storage (Bushong et al., 2018).

2.2 Canola Uses

Canola has several agricultural, industrial, and culinary uses. Cash crop uses include vegetable oil, biodiesel, livestock feed, and biosurfactants (Ibrahim et al., 2020; Myers, 2018). While human consumption is the main use of canola oil, the crop can serve many other purposes. In Germany, many farmers grow canola to create biodiesel to run their tractors and then use the leftover meal to feed livestock (Myers, 2018). In some biodiesel production processes, an alkali waste stream is created after pressing canola. This waste stream can be neutralized with phosphoric acid, creating sodium phosphate that can be sold as fertilizer (Gholami et al., 2021). For farmers looking to sell canola off farm, there are numerous avenues for markets (Herbek, 2012). Research is currently being conducted that furthers the usage of canola in several industries. Canola oil is used in studies to determine the usefulness of oil degrading bacterium in their ability as biosurfactants to clean oil spills (Ibrahim et al., 2020). In microbiology, canola was used in several studies to determine the role crop rotation plays in microbiome diversity, and the results are being used to improve ecological management of canola production in Canada. (Floc'h et al., 2020).

2.3 Canola Economics

In 2020, 723,983 hectares of canola were planted in the United States, with an average yield of 2,164 kg ha^{-1} (NASS, 2021). The recent average price of canola per kilogram ranged from $0.39 ($17.50 per Cwt) in 2017 to $0.32 ($14.50 per Cwt) in 2019 (NASS, 2020). Fairly rapid growth in production indicates that growers believe canola to be a profitable crop (U. S.

Canola Association, 2022). For example, the University of Tennessee Extension canola crop budget uses an estimated yield of 2,802 kg ha^{-1} (50 bushels per acre) (Morris, 2015). Assuming a producer receives $0.35 per kg ($8 per bushel), and taking into account the variable expenses of seed, chemicals, fertilizer, machinery, crop insurance, scouting, interest, and labor, the return above variable expenses will be $106.25 per hectare ($43 per acre) if yield is 2,802 kg ha^{-1} (50 bushels per acre) (Morris, 2015). If the yield is increased to 3,363 kg ha^{-1} (60 bushels per acre), the return above variable expenses will be $303.93 per hectare ($123 per acre) (Morris, 2015). These prices have been adjusted for inflation to be comparable year to year.

Canola is the only one of the three winter oilseed crops discussed in this review that is currently produced as a large-scale commercial crop in the United States. According to the USDA August 2022 Agriculture Prices Report, in June and July growers received between $0.94 ($42.70 per cwt) to $1.00 (45.60 per cwt) per kg for canola (USDA-NASS, 2022). As a summer cash crop, soybean is often dual cropped with canola. If returns from a 2,802 kg ha^{-1} canola yield and a 1,961 kg ha^{-1} soybean yield are combined, the return above variable expenses equal $382.99 per hectare ($155 per acre) assuming a price of $0.35 kg^{-1} ($8 bu^{-1}) of canola and $0.39 kg^{-1} ($8.94 bu^{-1}) of soybean (Morris, 2015).

3. Camelina

Camelina is a common weed in Europe native to Southeast Europe and Southwest Asia (Zanetti et al., 2017). Until the 1940s, it was grown commonly throughout Europe as an oilseed but has since been phased out in favor of higher yielding crops such as soybean, corn, and rapeseed (Zanetti et al., 2017). There had been little plant breeding and crop improvement efforts in camelina production (Ehrensing & Guy, 2008). However recent interest in crop diversification, agricultural sustainability, and biofuel production have brought camelina into the

forefront of current winter oilseed research (Berti et al., 2016; Betancor et al., 2021; Leclere et al., 2021; Mohammad et al., 2018). Camelina has untapped potential, and it may become a more prominent crop in the near future. Several companies in Canada as well as universities in the northwestern United States currently have camelina breeding programs looking to improve this ancient oilseed crop.

3.1 Growing Camelina

Camelina is well suited as a winter crop due to its ability to be grown with minimal input costs on marginal lands and in many different environments (Berti et al., 2016; Ehrensing & Guy, 2008; Leclere et al., 2021; Zanetti et al., 2017). The crop has a high tolerance for Brassica pests (Seguin-Swartz et al., 2009), low water needs (Bronson et al., 2019), and low nutrient needs (Leclere et al., 2021). Not only is growing camelina a possibility to address sustainability concerns on current agricultural lands (Leclere et al., 2021), but it could also make otherwise unusable lands productive and profitable in the future (Ehrensing & Guy, 2008). Camelina is highly adaptable to different environments, making it ideal for introduction into established crop rotations in North America and Europe (Zanetti et al., 2017). Refer to Table 1 for further description of the plant and its growing needs.

Camelina has both winter and spring biotypes (Wittenberg et al., 2019). Winter biotypes are fall planted and require four to eight weeks of vernalization to enter the reproductive phase (Anderson et al., 2018; Wittenberg et al., 2019). Winter biotypes are extremely winter hardy (Wittenberg et al., 2019) and have abundant expression of a gene coded for floral repression prior to vernalization (Anderson et al., 2018). The gene, Csa20 g015400, is found on *Flowering Locus C* (Anderson et al., 2018).

Best management practices for planting camelina vary by region. In the Pacific Northwest, little seedbed preparation is required. Seeds can be broadcast or shallow drilled in the fall through early spring (Schillinger et al., 2012), even into previous stubble and onto frozen ground. Allen et al. (2014) found in laboratory conditions, seeds will still germinate to nearly 100% stand establishment if the soil temperature is as low as 0ºC. Seeding depth can have a strong effect on establishment and yield. When drilled at 1-2 cm, no negative impacts are seen on yield or establishment, however, if seeds reach a depth of 4 cm at sowing, a 64% reduction in stand establishment and 22% loss in yield was observed in tilled fields (Gesch et al., 2017). No yield or establishment differences were observed between drilling or broadcasting seed by Schillinger et al. (2012), so broadcasting may be the most economically efficient planting method. However, broadcasting may not be effective for drought-prone areas of the country. A seeding density of 3 to 6 kg ha^{-1} is recommended to ensure sufficient stand density (Gesch et al., 2017). This allows fall-planted camelina to compete with spring weeds. The crop has been shown to compete well against weeds and can in some scenarios be grown without herbicides (Gesch & Cermak, 2011). However, there are a few herbicides now labeled for use in camelina (Poast from BASF is one example of an available post-emergence herbicide for controlling grasses).

In a corn/camelina/soybean rotation, camelina can be interseeded into standing corn from R4 to R6, and soybean can be interseeded into standing camelina (Cecchin et al., 2021; Mohammed et al., 2020). When compared to a control rotation of corn/fallow/soybean, interseeded camelina had a 20% reduction in N_2O emissions, lower eutrophication, and reduced erosion, but reduced soil organic carbon values (Cecchin et al., 2021). Even with these ecological benefits, the economic feasibility of this system is entirely dependent on camelina and soybean

yields. Many experiments report reduced soybean yield (Cecchin et al., 2021; Gesch et al., 2014; Patel et al., 2021). Some studies report camelina yield does not offset cash crop losses at current production levels (Cecchin et al., 2021; Patel et al., 2021). Other studies report camelina yields do offset the soybean losses (Gesch et al., 2014).

Camelina is extremely sensitive to herbicide drift and the effects of residual herbicides, so measures should be taken to ensure these do not affect crop growth (Ehrensing & Guy, 2008). Other potential impediments to growth include disease. Camelina is susceptible to downy mildew (*Peronospora sparsa*) (Leclere et al., 2021). However, camelina is resistant to alternaria blight, crown necrosis, and black leg (*Leptosphaeria maculans* (Seguin-Swartz et al., 2009). Some genotypes may be resistant to sclerotinia, rhizoctonia, or downy mildew (Seguin-Swartz et al., 2009). Additionally, few insects have been observed to cause loss to camelina, and none have been observed to cause economic damage (Ehrensing & Guy, 2008). Camelina is not a host to soybean cyst nematode and may contribute to reducing populations (Acharya et al., 2019).

Harvesting camelina can be done with an unmodified small grains combine (Veljković et al., 2022). Seed oil content has the highest quality at physiological maturity, however this declines as seed is left to dry naturally in the field (Walia et al., 2018). Physiological maturity occurs when 50 to 75% of camelina pods are brown (Veljković et al., 2022). The use of desiccants or swathing is recommended at physiological maturity to prevent the loss of quality or seed yield from natural dry down (Walia et al., 2018). Mature pods are dark tan or brown in color. Due to tiny seed size, sealing any leaks within the harvest equipment is imperative, and the combine should be operated on low air flow (Veljković et al., 2022). If being stored for oil extraction, seeds should be stored between 7 to 9% moisture. Camelina seeds are often dried to meet this requirement before being stored and transported to an oil crushing facility (Veljković et

al., 2022). Tightly sealed storage is required to prevent large seed losses during storage and transport (Veljković et al., 2022).

Camelina yield and oil content may be highly related to plant nutrition and water availability. Average yields of spring camelina range from 100 to 2,900 kg ha^{-1} in the Pacific Northwest and may greatly depend on water availability (Schillinger et al., 2012), while yields from winter biotypes are typically lower. Extremely low yields (100 kg ha^{-1}) occurred during extreme drought (Schillinger et al., 2012). In Oregon and Arizona, 1000 to 1800 kg ha^{-1} yields were observed with 330 to 380 mm of irrigation plus rain over the season (Bronson et al., 2019; Ehrensing & Guy, 2008), and high yields of 2,690 kg ha^{-1} were observed in Oregon at 640 mm of rain Ehrensing & Guy, 2008). In a study conducted across Canada and Europe, yields of spring camelina in locations with average temperatures ranging from 15 to 17°C and 170 mm of precipitation during the growing season reached 3000 kg ha^{-1} (Zanetti et al., 2017).

A study conducted in France found yield could be positively correlated to nitrogen status at flowering, although nitrogen needs seem to vary based on genotype, soil type, and competing plants (Leclere et al., 2021). Current research suggests N fertility rates for optimum camelina yield are much lower than any other oilseed currently in production (Leclere et al., 2021). Oil content within seeds decreases with increased nitrogen availability (Bronson et al., 2019; Nleya et al., 2021; Solis et al., 2013) but increases with increasing water rates.

One study claims sufficient irrigation or rainfall combined with 150 kg N ha^{-1} will likely produce high-oil camelina with high yields (Bronson et al., 2019), which is supported by a study in 2013 which achieved highest seed yields with 150 kg N ha^{-1} (Solis et al., 2013). This is an extremely large amount of N additions for any crop. However, another study found that maximum yield was achieved with 54 kg N ha^{-1}, and the economic optimal addition fell around

18 to 43 kg N ha^{-1} in rainfed systems, with N use efficiency decreasing above 22 kg N ha^{-1} (Obeng et al., 2020).

Another study found planting date to affect nitrogen requirements in spring camelina in Wyoming. When planted early (April to early May) N applications reduced seed oil content, but, when planted late (late May), N increased seed yield and had no effect on oil content (Sintim et al., 2015). The same study found that applying N above 56 kg ha^{-1} did not increase yields at any planting date for spring camelina (Sintim et al., 2015). Sulfur application shows no impact on oil content or yield (Obeng et al., 2020; Sintim et al., 2015); however, it may increase protein concentration of seeds (Obeng et al., 2020).

Camelina seeds contain 30-41% oil, polyunsaturated fats, and monounsaturated fats. No significant correlation between yield and oil content was found in a study comparing different on-farm conditions in Northern France (Leclere et al., 2021). After oil extraction, the leftover meal contains up to 40% crude protein. In the same study, seed oil content was negatively correlated with protein content. Overall, seed oil content, yield, and protein content vary across genotype, environmental conditions, and extraction method (Berti et al., 2016; Leclere et al., 2021). The most limiting factors for oil production were insufficient growing degree days during grain fill, and the introduction of downy mildew (Leclere et al., 2021), with nutrient and water availability also playing a large role (Bronson et al., 2019; Nleya et al., 2021; Solis et al., 2013).

3.2 Camelina Uses

Camelina has uses similar to other current oilseeds and has general use in the food, feed, industrial, and biofuel industries (Berti et al., 2016; Ehrensing & Guy, 2008; Leclere et al., 2021; Mohammad et al., 2018). Due to the various uses and potential markets for camelina, it is

considered a flex crop, allowing farmers to grow camelina and simply adjust their market yearly to obtain the highest profit margins possible (Leclere et al., 2021).

Specific examples of camelina uses include edible products such as salad dressing, health supplements, and cooking oil (Berti et al., 2016). Seed oil contains unsaturated fatty acids, including alpha linolenic acid, linoleic acid, oleic acid, and eicosenoic acid, all of which contribute to the immune system (Ibrahim, 2015), and are determined to be generally recognized as safe (GRAS) by the FDA (FDA, 2016). The chemical composition of camelina seeds and byproducts makes it a good candidate for animal feed for cattle, chickens, swine, sheep, and fish (Berti et al., 2016). Camelina oil and cake is high in long chain polyunsaturated fatty acids and when eaten by ruminants, production of methane is low (Riaz et al., 2022). The cake is low in glucosinolates, has 38-42% crude protein, and 10-12% fiber (Riaz et al., 2022). These numbers are lower than soybean meal used for livestock feed, however, are equivalent to sunflower meal and rapeseed meal (Riaz et al., 2022). Specifically, pressed cake made of camelina meal after oil extraction contains roughly 400 g kg^{-1} of protein, 100 to 150 g kg^{-1} of fiber, and 100 to 150 g kg^{-1} of oil. When sold as pressed cake for livestock feed, camelina meal is valued around \$100 Mg^{-1} (Berti et al., 2016).

Aquaculture has recently turned to camelina as a feed source, using the oil to replace the fish oil typically used to feed production fish populations (Betancor et al., 2021). Camelina oil sufficiently replaces the omega-3 fatty acids typically provided by finite, expensive populations of small fish, giving the fast-growing aquaculture industry more potential avenues towards environmental and economic sustainability (Betancor et al., 2021).

As a cover crop, camelina provides useful ecologic benefits. Camelina can serve as a catch crop for nitrogen, taking up 28 to 49 kg N ha^{-1} in the spring in Minnesota before harvest

(Weyers et al., 2019). In the same study, fall-planted camelina reduced nitrogen in soil water from fall establishment until spring harvest compared to fallow plots (Weyers et al., 2019). This combination of winter cover crop ecological benefits and potential economic gains make camelina a standout dual crop.

Other uses of camelina include cosmetics, skin care products, soaps, detergents, and adjuvants in agricultural spraying applications (Ehrensing & Guy, 2008). Camelina meal has been used to create fungicides, bio-herbicides, adhesives, and bio-oils as well (Berti et al., 2016).

3.3 Biofuel Potential

One of the most interesting areas of use and research in camelina for environmental sustainability, however, is for biodiesel (Leclere et al., 2021; Mohammad et al., 2018). Due to camelina's high oil content, the crop shows promise as an economical biofuel source (Mohammad et al., 2018). Several studies have modeled the feasibility of camelina for general characteristics of a biofuel source, as well as the economic feasibility of growing camelina for biofuel production (Keske et al., 2013; Ciubota-Rosie et al., 2013). Camelina oil has properties that allow the creation of hydroprocessed renewable jet fuel as well as biodiesel (Berti et al., 2016; Dangol et al., 2017; Resurreccion et al., 2021; Shonnard et al., 2010). One study found that using the entire plant (both seeds and straw) is an environmentally and economically sustainable way to create biodiesel, ethanol, and glycerin without laborious extraction methods that would counteract the environmental benefits of creating a cleaner fuel (Mohammad et al., 2018). This study found that 10% of camelina seed is made up of soluble sugars, which do not require high energy expense to extract, lowering operation energy and costs and allowing a 15% reduction of required energy input per volume of ethanol produced in kJ L^{-1}. When comparing oilseed crops, 30% seed oil content is considered substantial and highly competitive for biodiesel production

(Mohammad et al., 2018). Camelina has been recorded with up to 41% seed oil content (Bronson et al., 2019).

Camelina biodiesel is a clean burning fuel, with the potential to reduce greenhouse gas emissions by an average of 40 to 70% versus mainstream petroleum fuel (Dangol et al., 2017; Krohn and Fripp, 2012; Mohammad et al., 2018; Shonnard et al., 2010). The product has similar properties to biodiesel produced from sunflower oil (Riaz et al., 2022) and can be blended with standardized jet fuel. Biodiesel created from camelina has been successfully tested and used by the US Air Force in several fighter jets (Berti et al., 2016; Liu et al., 2013).

The economic feasibility of large scale biojet fuel and biodiesel production from camelina is unclear (Dangol et al., 2017; Ott et al., 2019; Shila & Johnson, 2021). Biodiesel is currently more economical to produce than biojet fuel (Dangol et al., 2017; Shila & Johnson, 2021), however local production costs and by-product production and sale will impact profitability (Shila & Johnson, 2021).

3.4 Potential Problems with Producing Camelina

Currently, there is no established market for camelina in the United States and economic feasibility of production for growers is uncertain (Berti et al., 2016; Dangol et al., 2017; Ott et al., 2019; Shila & Johnson, 2021). Recent production is limited to spring type camelina in California, Montana, Oregon, Washington, and Western Canada (Berti et al., 2016) making the creation of an open market imperative to the success of producing winter camelina.

The extremely small seed size of camelina may hamper efficient mechanical harvest on a large production scale, as well as post-harvest processing including storing and transporting (Berti et al., 2016). Camelina is roughly one-third the size of canola seeds and around 1.0-1.5 g per 1,000 seed weight (Gesch et al., 2017). Zanetti et al (2017), found that the most productive

cultivar tested also had the largest seed size. Breeding efforts for larger seed size will be important for the adoption of camelina production on an increased scale.

Potential for Production in the Mid-South

4. Climate of the Mid-South Region of the United States

We define the Mid-South as a region in the United States including Kentucky, Tennessee, Arkansas, northern Mississippi, and southeastern Missouri. The Mid-South produces many of the same agronomic crops across the region and experiences similar climatic patterns. The region experiences four seasons a year. The first frost of the year typically occurs mid to late October, while the last frost occurs early to mid-April (Ary et al., 2022). According to the Southern Regional Climate Center (2022), average summer temperatures range from 22ºC to 25ºC in June; average winter temperatures range from -1ºC to 7ºC in January. Humidity is high in this region year-round. Average summer precipitation ranges from 100 to 120 mm in June, while average winter precipitation ranges from 50 to 130 mm in January (Southern Regional Climate Center, 2022). Monthly thirty-year averages for temperature and precipitation in west Tennessee (the middle of the Mid-South region) throughout the winter oilseed growing season are listed below (Table 1.2).

5. Fitting Winter Oilseeds into Mid-South Crop Rotations

Much of the Mid-South produces some variation of a corn/soybean/cotton rotation. Winter oilseeds fit well as a winter annual cash cover crop within this rotation. Corn is typically harvested in late August to mid-September in the Mid-South. There is potential for soil temperatures to be too high for planting at this time. Winter oilseeds can be planted from mid-September through mid-October to meet recommendations to ensure sufficient growth for overwintering (deKoff et al., 2016; Mclure, 2016) before the first frost in mid to late October

Table 1.2. Monthly thirty-year average temperature, precipitation, and snowfall (1991-2021), Milan, TN as reported by the US National Oceanic and Atmospheric Administration (NOAA) (2022).

	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Average Temp (°C)	22.1	15.8	9.5	5.1	3.3	5.4	10.1	15.4	20.5	24.8
Average Precipitation (mm)	107	94	122	138	106	119	135	134	159	112
Average Snowfall (mm)	0	0	3	5	38	23	8	0	0	0

(Ary et al., 2022). Soybean and cotton are typically harvested too late to leave time for adequate winter oilseed establishment. However, winter camelina may need to be planted from late October to early November to ensure winter survivability in the warmer falls of the Mid-South based on planting date trials in the Corn Belt (Gesch & Cermak, 2011; Wittenberg et al., 2020). This could allow camelina planting following soybean or cotton harvest. Should late summer weather delay corn harvest, winter oilseeds can still be planted and will germinate if the soil temperature remains above 0ºC (Allen et al., 2014). This could be advantageous to growers in the Mid-South, as soils remain warmer longer than in the Midwest. Plant back restrictions on corn herbicides used in the summer prior may prevent the described optimal planting scheme if the winter oilseeds are to be used for human or livestock consumption (Wysocki & Sirovatka, 2008).

Different environmental conditions are likely to create different growing season challenges than to those currently stated in the literature. Average temperature differences will be especially important. For example, winter biotypes of camelina are extremely winter hardy (Wittenberg et al., 2019), however in the Mid-South there is concern these varieties will be triggered to flower during freeze-thaw cycles in later winter before the threat of a hard freeze has passed. Photoperiod sensitivity may affect winter camelina flowering as well (Wittenberg et al., 2019). Currently, both winter and spring biotypes of camelina are being trialed as fall planted crops in the Mid-South (Keadle et al., 2023). Conversely, canola performs best during mild winters (Oplinger et al., 1989). In a 2021 national survey, winter canola had medium to high winter survivability at all locations below 39°N latitude (Secchi et al., 2021), which includes the Mid-South. Heat stress during bloom resulting in yield losses (Morrison & Stewart, 2002) is more likely problematic for Mid-South canola production. Growers must select heat tolerant

varieties. Differences in average rainfall during the growing season may be important to yield. From October to May, the average rainfall accumulation in the Mid-South reaches roughly 840 mm (Southern Regional Climate Center, 2022), which should be more than sufficient for rainfed winter oilseed production (Assefa et al., 2018; Bronson et al., 2019). More research is needed to determine how high year-round humidity effects water needs of the winter oilseeds.

Key pests and management strategies will differ by region as well. In canola specifically, major pests include aphids (Aphididae) and the cabbage seedpod weevil (*Ceutorhynchus assimilis*) in Georgia and Tennessee (Buntin & Raymore, 1994; deKoff et al., 2016). One study found two applications of a pyrethroid insecticide reduced adult cabbage seedpod weevils to below economic thresholds, as well as preventing larvae from infesting the seed pods (Buntin, 1999). Insecticide control of aphids should occur during the seedling and rosette growth stages of canola in the Mid-South (Buntin & Raymore, 1994). Further research is needed to determine key pests of pennycress and camelina in the Mid-South region.

When fall planted in the Mid-South, winter canola is typically harvested in early June (deKoff et al., 2016) and pennycress and camelina are harvested in mid-May (Keadle et al., 2023). These harvest times align well with soybean planting in the region, preventing fields from laying fallow for extended periods of time. The use of desiccants on pennycress or camelina may allow time for cotton planting in early May in rotation some years as well. Desiccants are recommended by Walia et al. (2018) to prevent yield losses in camelina and allow harvest to occur roughly three weeks ahead of natural dry down. Desiccants to prevent seed loss due to seed shatter have been identified as an area of further research for pennycress as well (Cubins et al., 2019).

One major barrier to the adoption of winter oilseeds into mid-southern cropping systems is the lack of a viable market. One commercial canola pressing facility was open in Kentucky (Morris, 2015), and one grain elevator in Memphis, Tennessee currently accepts canola seed (Bennett, 2019). An economic analysis of growing pennycress for jet fuel production found potential profits for both growers and refiners if adopted in the Mid-South and transported to the Nashville airport in Tennessee (Trejo-Pech et al., 2019). Potential problems that extend from a lack of market include the lack of crop insurance and crop protection products for growers. An increase in farmer interest and improved infrastructure could make any of the winter oilseeds discussed into a viable market for the region.

Variety trials must first be conducted to determine which winter oilseed varieties will perform well in the region. Further research is needed to fine tune the planting dates and harvest methods of winter oilseeds in the Mid-South as well. However, the establishment and growing needs of winter oilseeds can be met by the average climate within the confines of already established conventional row cropping rotations. Commercial production of winter canola in the Mid-South is already increasing in recent years (U.S. Canola Association, 2022). Assuming more accessible commercial markets are created in the region, and more research can be carried out, the Mid-South may become an important area for winter oilseed production.

Conclusion

Based on the information reviewed, we conclude that winter oilseeds are diverse crops with numerous uses and benefits to growers. Winter oilseeds could help offset fossil fuel use through the creation of biofuels. They offer increased revenue to growers without interrupting current food production, and they offer many of the agroecological benefits of traditional winter cover crops. The crops have largely untapped potential due to the lack of refineries, especially in

the Mid-South. Camelina and pennycress offer similar benefits as canola but are lacking crop insurance policies, labelled crop protection products, and reliable markets. Important research on best management practices for all three crops is needed within the double crop system. These include identification of optimal fertilization rates, planting dates, rotational or allelopathic interactions on cash crops and weeds, economics of seed processing and biofuel refining, impacts on soil health and organic matter accumulation, potential organic production, and farmer willingness to adopt. These crops have been studied more extensively in the Midwest, but based on climate and common crop rotations, may also be a good fit for Mid-South systems. In the pursuit of increasing the overall environmental, economic, and social sustainability of agriculture, researchers owe it to the growers to look further into these potentially high-value underutilized crops.

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CHAPTER TWO: COMPARISON OF YIELD AND ECOLOGICAL IMPACT OF POTENTIAL WINTER OILSEED SPECIES AND VARIETIES FOR TENNESSEE

Core Ideas:

1. Winter oilseed crops fit well within conventional Mid-South crop rotations.
2. Canola, pennycress, and camelina can be “cash cover crops.”
3. In Tennessee, canola performed well, yielding, on average, 2,802 kg ha^{-1}.
4. In Tennessee, pennycress performed similarly to trials in the Midwest, yielding, on average, 673 kg ha^{-1}.
5. In Tennessee, camelina failed due to early bolting followed by winter kill across two growing seasons.

Comparison of Yield and Ecological Impact of Potential Winter Oilseed Species and Varieties for Tennessee

Abstract

Cover crops provide numerous ecological benefits, but growers may be discouraged from planting fall cover crops because they do not provide immediate economic gain. Canola (*Brassica napus*), pennycress (*Thlaspi arvense* L.), and camelina (*Camelina sativa*) are species of interest for their potential as a winter cover and biofuel crop. Most research on these crops has taken place in the upper Midwest and Great Plains. The objective of this study was to evaluate winter cover and survivability, yield, oil content and quality, soil health effects, and rotational effects of growing winter oilseeds in the Mid-South. Three varieties each of pennycress, camelina, and canola were grown in Springfield and Milan, Tennessee and compared to fallow control plots in both a tilled and a no-till trial across two years. Over winter, canola provided the most ground cover, while pennycress provided similar ground cover to the fallow plots (i.e. winter weeds). Camelina completely winter-killed after bolting in late fall. Canola yielded on

average 2,802 kg ha^{-1}, while pennycress yielded on average 673 kg ha^{-1}. No soil nutrient differences were observed. On average, canola seeds contained 450 g kg^{-1} oil and pennycress seeds contained 300 g kg^{-1} oil. At the Springfield location, soybean yield deficits were observed when planted after canola due to large volunteer canola populations. Overall, canola appears best adapted to production in the Mid-South. Pennycress shows potential but still requires further breeding efforts and identification of best management practices for Mid-South production.

Introduction

Due to the long growing season of corn and soybeans, many farmers find establishing a winter cover crop difficult (Mohammed et al., 2020), choosing to leave fields fallow instead. This practice can lead to soil erosion, nutrient leaching, and weed infestation (Wyse 2017). Fall planted cover crops can be used to combat these problems; however, many farmers avoid cover crops because they do not produce an obvious economic gain (Moore et al., 2020a). Winter oilseed production is one possible solution, providing both winter cover and additional profit.

Winter oilseeds are annual cool season Brassica crops which function as cover crops when fall planted after corn or soybean harvest (Myers 2018; Moore et al., 2020b; Wortman, 2020.). They become cash crops if harvested in the spring before planting the next rotation of corn or soybeans (Mohammad et al., 2018; Betancor et al., 2021; Herbek 2012; Moore et al., 2020a). This practice is known as dual-cropping or double-cropping.

Winter oilseed species of particular interest to growers for double-cropping include *Brassica napus* (canola), *Thalaspi arvense* L. (pennycress), and *Camelina sativa* (camelina). Each crop species has several uses and can be sold to many different markets upon harvest, increasing the grower's ability to produce a profit. General uses for each crop include biofuel

production, the creation of industrial products from the oils, and forages from the crop residue (Mohammed et al., 2018; Ehrensing and Guy, 2008; Ibrahim et al., 2020; Myers, 2018).

Much is known about canola production in the USA; however, pennycress and camelina are newer crops within the market. Current research revolving around the two has largely taken place in the upper Midwest and Great Plains, with almost no research taking place within the Mid-South. Suggested planting dates, management practices, and agronomic benefits describing the growth of winter oilseeds are largely tailored to the upper Midwest for this reason. Due to the ability to double crop, as well as the various avenues to market, it was hypothesized that growing winter oilseeds in rotation with corn and soybeans will be environmentally and economically beneficial to growers in the Mid-South. In this study, the main goal was to determine if canola, pennycress, and camelina were suitable crops for Tennessee by evaluating winter cover and survivability, yield, oil content and quality, soil health effects, and effects on crops in rotation.

Materials and Methods

6. Study Design

Three species of winter oilseed, canola, camelina, and pennycress, were evaluated for their adaptation and ecological impact within a conventional corn and soybean system in Tennessee. Three varieties of each species were evaluated. Varieties were nested within species. For canola, the varieties ‘HeKip’, ‘Inspiration’, and ‘Phoenix CL’ were grown. For camelina, ‘Joelle’, ‘Suneson’, and ‘Blaine Creek’ were grown. ‘Joelle’ is a winter biotype while ‘Suneson’ and ‘Blaine Creek’ are spring biotypes. For pennycress, ‘Beecher’ and ‘MN106’ in both years, ‘Spring Type’ in year one (2020-21), and ‘GE Golden’ in year two (2021-22) were grown. ‘Spring Type’ and ‘GE Golden’ were not included in analysis because they differed by year. Spring biotypes were included due to lack of available winter biotypes and because it was

unclear how the different biotypes would perform in the mild Mid-South winters. A fallow main plot was included as well for a total of 10 treatments. Main plots were arranged in a randomized complete block design with three replications each. This design was planted in both a tilled and a no-till trial. The entire design was replicated at two locations in Tennessee: Springfield, TN at the Highland Rim AgResearch and Education Center (36.476648, -86.821195; soil type Sango Silt Loam) (HRREC) and at Milan, TN at the AgResearch and Education Center at Milan (35.934679, -88.715231; soil type Loring) (RECM). These locations represent middle and west Tennessee, respectively. Both locations grow conventional corn and soybean in a typical Mid-South agricultural system. Across years, trials were planted in a corn/winter oilseed/soybean rotation.

7. Planting and Establishment

Prior to planting, no-till trial fields were mown with a rotary mower to shorten the corn stubble. Tilled trial fields were worked one to two weeks prior to planting with a chisel plow and disk. Sulfur, nitrogen, and boron were applied pre-planting at each location based on soil tests for each field using recommendations for canola. All winter oilseed species were planted following corn harvest to a depth of 1 cm using a Hege 1000 Cone Plot Drill (Colwich, Kansas). Camelina and pennycress seeds were planted at a rate of 5.6 kg ha^{-1} (5 lbs ac^{-1}), while canola was planted at a rate of 543,631 seeds ha^{-1} (220,000 seeds ac^{-1}).

Our target planting date for each year of the study was 15 September. In year one, planting occurred on 29 September 2020 in Milan and 19 September 2020 in Springfield. Delayed corn harvest due to weather pushed back target planting date in year two to 12 October 2021 in Milan and on 1 October 2021 in Springfield. Delayed corn harvest due to weather pushed back target planting date in year two.

In year one, the first frost of the year did not occur until early December, allowing ample time for the oilseeds to grow and develop before dormancy. In year two, the first frost of the season occurred near the middle of October, as expected for the region.

Ground coverage from the oilseeds was evaluated in the first week of December during both years of the study. Two square photos (53 by 53 cm) were taken in each plot then analyzed for percentage of green coverage in APS Assess 2.2 software (vs. 2.2, St. Paul, MN). The percentage of weeds present in each plot was visually assessed within the same square. The number of plants present per square meter was also recorded.

In March each year, sulfur, nitrogen, and boron were applied at each location based on recommendations from soil testing each field. Recommendations were provided by the UT Soil Plant and Pest Center (Nashville, TN) and based on nutrient needs for canola production. Phosphorus and potassium were also added if needed.

8. Harvest

All oilseed crops were allowed to grow and mature through the winter and spring. Crops were harvested at maturity following natural dry down within the field. Prior to harvest, agronomic traits such as lodging, shattering, and height were assessed. Lodging and shattering were visually assessed and scored on a one to five scale per plot, with one meaning no lodging or shattering and five meaning greater than 75 % of the plot had lodged or shattered.

Pennycress and camelina dried down earlier in the year than canola. In both years of the study, pennycress and camelina harvest took place between 23 and 26 May at both locations. For harvest, two randomly selected square samples (53 by 53 cm) were collected by hand per plot. The number of plants per sample was recorded and wet weights were taken. Samples were then put into a dryer at 90º C without the burner on for 72 hours, then weighed again to determine

total biomass. After drying, plants were threshed to remove seeds, sifted to remove large seed hulls and twigs, and poured through a Seed Tech Systems STS-WM2E Separator (Wilton, CA) to remove all particulates. The seed per sample was weighed, and the weight of 100 seeds per sample was determined.

The same process was repeated for canola harvest. Canola harvest timing varied across locations and years. Canola was harvested at both locations in year one on 15 to 16 June 2021. In year two, canola was harvested in Springfield on 9 June 2022, and in Milan on 21 June 2022.

Machinability of each crop was observed as well. An Almaco Model SPC40 plot combine (Nevada, Iowa) was used to harvest one half of all canola and pennycress plots in year one, and only to harvest canola plots in year two.

9. Post-Harvest Oil Analysis

All seed samples were stored at room temperature (21°C) after harvest until oil analysis. Samples were divided to be tested for glucosinolate content and oil percentage. Percent oil analysis was analyzed by Waters Agricultural Laboratories Inc. (Owensboro, KY). Total oil analysis was done by ether extract following Ankom Method AOCS-Am5-04. Moisture content was determined as described by AOAC method 934.01.

Glucosinolate content within the seed was determined using high performance liquid chromatography (HPLC). Homogeneous samples of each plot were extracted and analyzed on an Agilent 1100 Series HPLC (Santa Clara, CA) according to the procedure of Barickman et al., 2013. Data was processed using ChemStation Software (Rev. C 01.07 SR2 [255]).

10. Soil Sampling

Soil samples were taken in the top yielding cultivar plots of each species and in randomly selected fallow plots one month after canola harvest each year. The same cultivars were sampled in both year one and year two. Samples were taken using a standard soil probe within the top 0 to 15 cm of soil and sent to the UT Soil, Plant, and Pest Center in Nashville, TN for analysis. All samples were analyzed using Mehlich-1 extraction methods for available phosphorous, potassium, calcium, magnesium, boron, iron, manganese, sodium, and zinc, as well as for water extractable carbon.

11. Soybean Planting and Harvest

Soybean was planted at the same time within each field after all winter oilseed species harvest had concluded. Immediately after canola harvest, burndown herbicides, including Sharpen (0.073 L ha^{-1}), Glory (0.219 L ha^{-1}), and AgSaver 54 (2.923 L ha^{-1}), were applied to all trials to prepare for soybean planting. Bayer AG47XF0 XtendFlex soybeans were no-till planted across the entire field in both the tilled and no-till trials using an Almaco Model AJ4RPP 4 row Cone Plot Planter (Nevada, Iowa). At Springfield, soybean was planted on 21 June 2021 in year one and on 10 June 2022 in year two. At Milan, soybean was planted on 28 June 2021 in year one and on 23 June 2022 in year two.

Soybean was harvested in early November each year using an Almaco Model SPC40 Plot Combine (Nevada, Iowa). Yield and moisture data were collected with the combine at harvest. Oil and protein content were all measured per plot using a FOSS Infratec Grain Analyser (Eden Prairie, MN) machine.

12. Statistical Analysis

Analysis of variance was conducted using a mixed model in SAS (vs. 9.4, Cary, NC) with the

glimmix procedure. Means were separated using Tukey's HSD. An alpha value of 0.05 was used to determine significance. Fixed effects included species, management, location, year, and variety(species). All variables were checked for normality and equal variance.

Results

13. Winter Cover

Winter ground cover and weed cover in the first week of December had a significant interaction of year*variety(species) (Figure 2.1). In year 1, all species had a higher green ground cover percent than any species in year 2 (Figure 2.1a). This difference is likely due to the warmer fall and winter weather in year 1 as compared to the more average fall and winter temperatures and later planting dates in year 2. In year 1, canola plots provided a higher percent of ground cover (85%) compared to pennycress and fallow plots (45%) (Figure 2.1a), while also having the lowest number of weeds in the plot (5%) (Figure 2.1b). In year 2, the canola varieties 'Inspiration' and 'Phoenix CL' had the highest amount of green cover (30%) (Figure 2.1a), however, all species and varieties had a statistically similar number of weeds (25%) (Figure 2.1b). In both years of study, pennycress plots provided the same amount of winter ground cover as fallow control plots (Figure 2.1a).

14. Camelina Observations

All camelina varieties have been excluded from the rest of the results due to total stand death in year one and extremely poor stand quality in year two. In year one, the first frost of the fall did not occur until early December. Camelina was observed bolting before this frost occurred due to the warm weather and was subsequently winter killed. In year 2, camelina plants were able to overwinter following October frosts, however, plants were observed bolting during warm

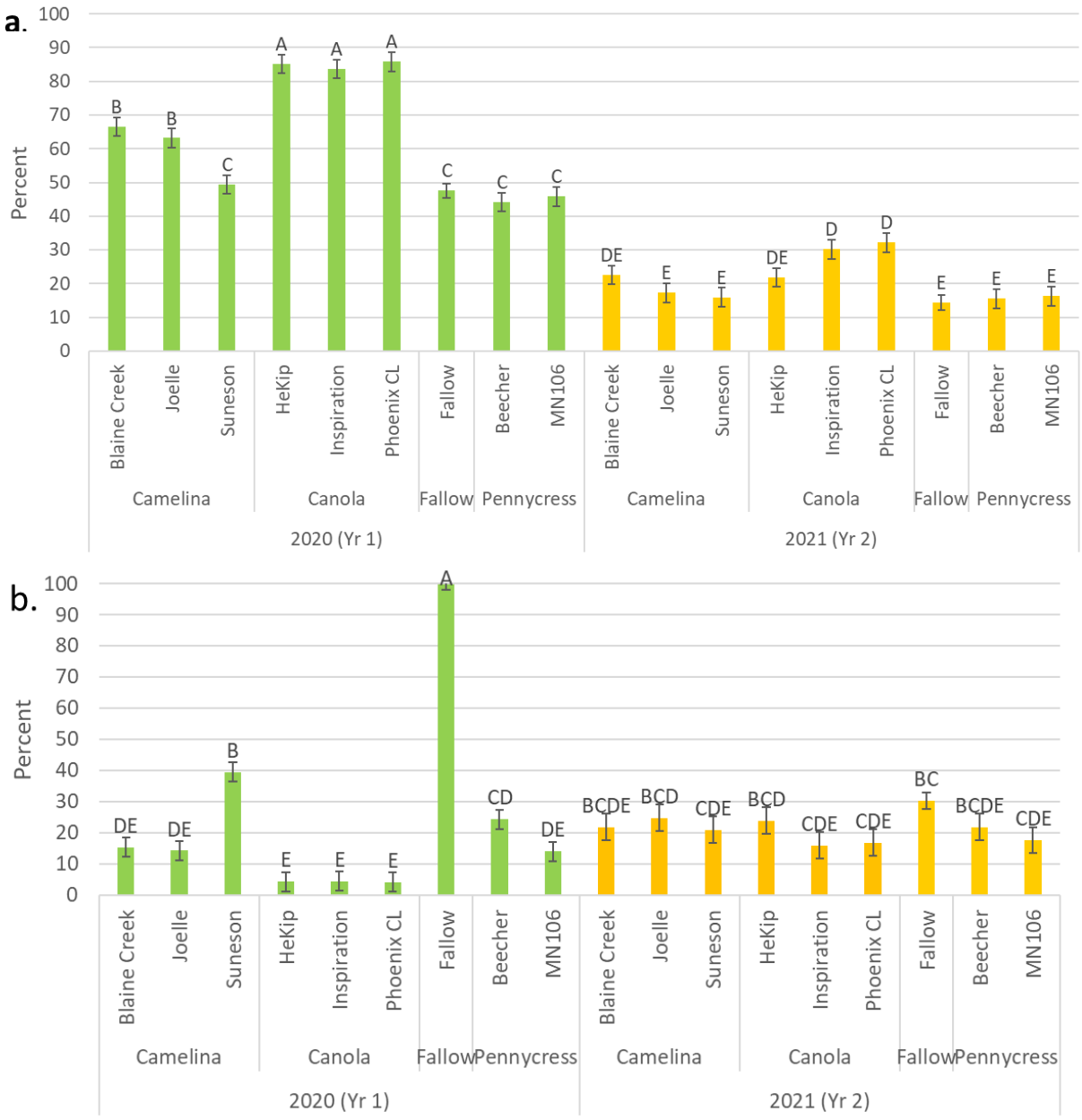

Figure 2.1. (a.) The percent of total green winter cover present within a 53 by 53 cm square (crop+weed) in year 1 (December 2020) and year 2 (December 2021) as determined by digital image analysis of quarter meter squares within plots (p=0.011). (b.) The percent of total green winter cover that is weeds within the 53 x 53 cm square (p= 0.001). Bars denoted with different letters are statistically different at p<0.05 based on Tukey's HSD.

February days then dying of winter kill during early season spring frosts. No harvestable plots of camelina were observed in either year of the study. Camelina has been removed from further analysis.

15. Yield and Agronomic Traits

In year 1, no significant lodging or shattering was observed in either species. In year 2, however, increased lodging occurred in pennycress due to severe storms immediately prior to harvest. A slight increase in shattering was observed in both species in year 2 as well, likely due to the storms for pennycress and due to bird feeding in canola. At harvest, the average height of canola was 140 cm, and pennycress was 46 cm.

A significant interaction of year*species(variety) for yield (Figure 2.2) was documented. All varieties of canola out-yielded pennycress in both years except for 'HeKip' in year 2 (Figure 2.2). All varieties of canola suffered a significant yield drop in year 2 as compared to year 1 (Figure 2.2). This yield drop is likely due to environmental differences throughout the growing season. Pennycress yields remained statistically the same across both varieties and years (Figure 2.2). Within years, no observed difference in yield among varieties of the same species was found (Figure 2.2). The average canola yield across both years of study and both management types (2,802 kg ha^{-1}) (Table 2.1) slightly exceeded the national average canola yield for 2021 of 2,241 kg ha^{-1} (NASS, 2021). Average pennycress yields observed (673 kg ha^{-1}) are similar to experimental yields being reported from studies in the Midwest which typically range from 200 to 600 kg ha^{-1} (Cubins et al., 2019).

Yield also exhibited a significant interaction effect of management*species*year (Figure 2.3). Canola yield differed by management type in year 1 (Figure 2.3). Canola planted in the tilled trial out-yielded canola planted in the no-till trial in year 1 by 1,000 kg ha^{-1}. In year 2,

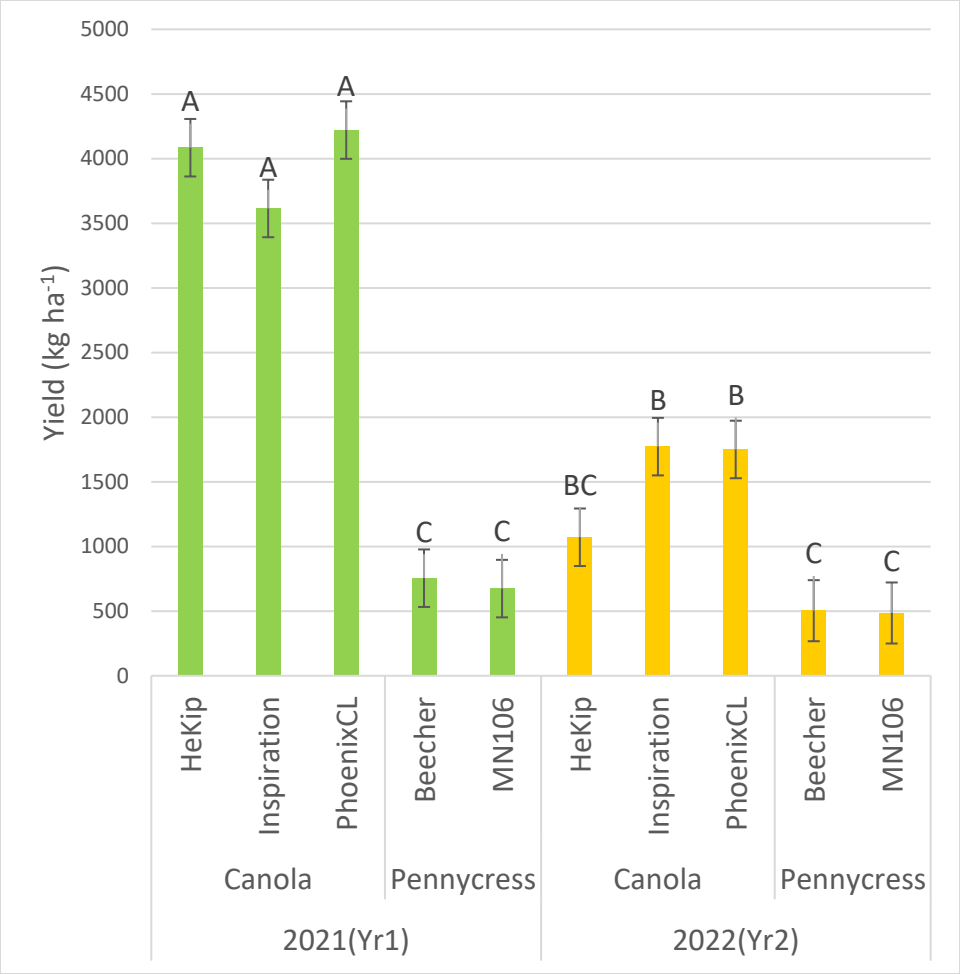

Figure 2.2. Yield (kg ha^{-1}) separated by year, species, and variety (p=0.0039). Bars denoted with different letters are significant at p<0.05 as determined by Tukey's HSD.

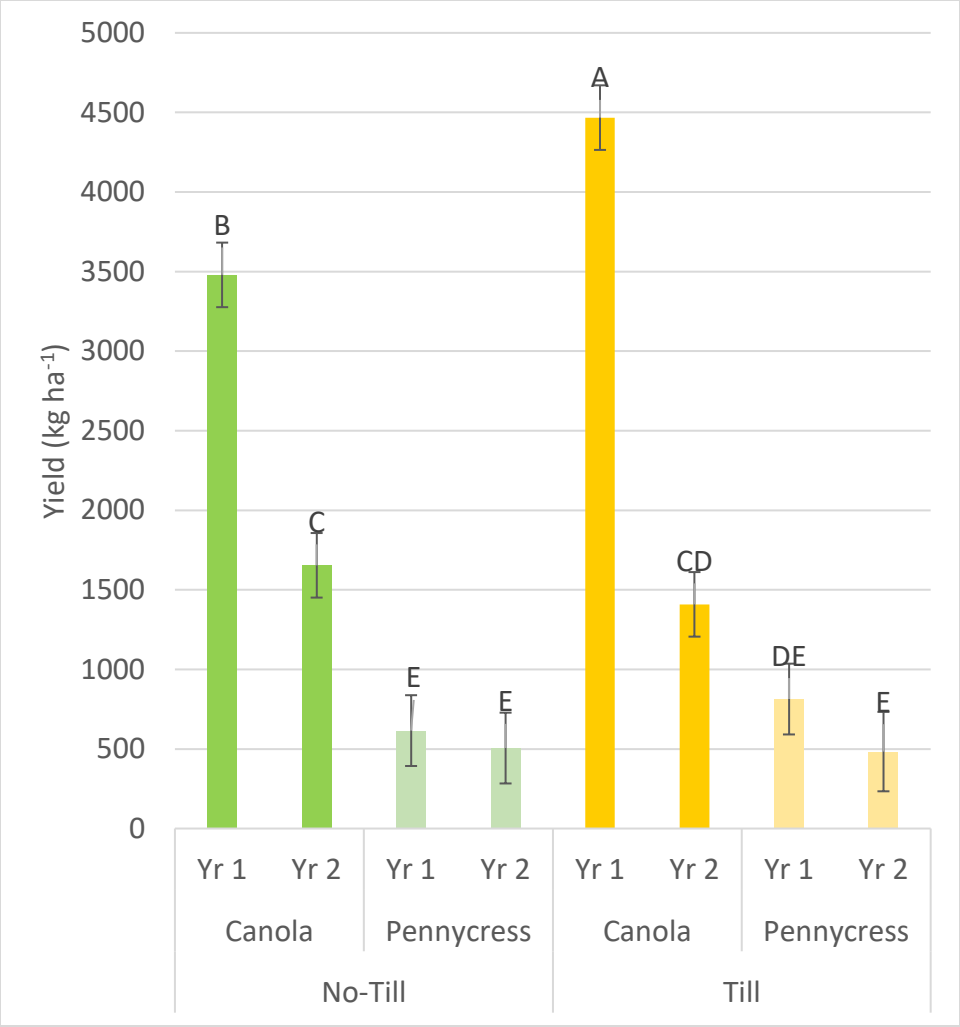

Figure 2.3. Average yield (kg ha^{-1}) by species when separated by management type (tilled or no-till trials), species, and year (p= 0.0158). Bars denoted with different letters are statistically different at p<0.05 as determined by Tukey's mean separation.

Table 2.1. Average yield by species across both study years and management types (tilled and no-till).

Crop Species	Yield in kg ha^{-1}
Canola	2802 A
Pennycress	673 B

Footnote: Values followed by different letters are significantly different at $p<0.05$ as determined by Tukey's HSD.

canola yield was statistically similar for till and no-till. Pennycress yield was statistically similar for till and no-till in both study years.

16. Soil Health

Across both years, few significant differences in soil parameters by species were observed. For the variables pH, water extractable carbon, phosphorus, potassium, magnesium, calcium, boron, iron, and manganese, the only observed differences were by management, location, or year, all of which can be explained by each of those variables corresponding to a different field. The majority of soil health factor differences observed are likely based on historical management of particular fields and not on the presence of winter oilseeds after one growing season. Two soil health factors did have significant differences including species: sodium and zinc.

Available zinc in the soil following winter oilseed harvest was significant by species ($p= 0.0369$), with no other significant interactions present involving species (Table 2.2). Plots planted in pennycress had less available zinc after harvest than a field that lay fallow all winter and spring (Table 2.2). Canola plots had statistically similar available zinc levels (1.9 kg ha^{-1}) as both pennycress (1.8 kg ha^{-1}) and fallow plots (2.1 kg ha^{-1}) (Table 2.2).

Available sodium exhibited a significant interaction of location*management*species*year ($p=0.0056$). However, major differences did not occur within species and management type, with differences only becoming apparent by year and location (Table 2.3), leading to the same conclusion again that differences in soil available sodium are likely due to historic management of the different fields, and not due to the presence of winter oilseeds after one year.

Table 2.2. Soil available zinc following winter oilseed harvest as determined by Mehlich-1 extraction.

Crop Species	Zinc in kg ha^{-1}
Canola	1.9 AB
Pennycress	1.8 B
Fallow	2.1 A

Footnote: Values followed by different letters are significantly different at $p<0.05$ as determined by Tukey's HSD.

Table 2.3. Soil available sodium following winter oilseed harvest as determined by Mehlich-1 extraction.

Management	Crop	Location	Year	Sodium kg ha^{-1}	MS
No-till	Canola	Springfield	2021	24.3	A
No-till	Canola	Springfield	2022	13.5	CDEF
No-till	Canola	Milan	2021	17.5	ABCDEF
No-till	Canola	Milan	2022	10.8	F
No-till	Fallow	Springfield	2021	22.4	A
No-till	Fallow	Springfield	2022	21.1	AB
No-till	Fallow	Milan	2021	20.5	ABC
No-till	Fallow	Milan	2022	13.0	DEF
No-till	Pennycress	Springfield	2021	24.2	A
No-till	Pennycress	Springfield	2022	14.6	BCDEF
No-till	Pennycress	Milan	2021	17.1	ABCDEF
No-till	Pennycress	Milan	2022	11.6	EF
Till	Canola	Springfield	2021	20.5	ABC
Till	Canola	Springfield	2022	11.2	F
Till	Canola	Milan	2021	19.8	ABCD
Till	Canola	Milan	2022	11.2	F
Till	Fallow	Springfield	2021	21.3	AB
Till	Fallow	Springfield	2022	11.1	F
Till	Fallow	Milan	2021	18.6	ABCD
Till	Fallow	Milan	2022	13.8	BCDEF
Till	Pennycress	Springfield	2021	18.3	ABCDE
Till	Pennycress	Springfield	2022	10.8	F
Till	Pennycress	Milan	2021	24.1	A
Till	Pennycress	Milan	2022	13.0	DEF

Footnote: Values with different letters are significantly different at $p<0.05$ as determined by Tukey's HSD.

17. Oil Analysis

Total oil percent exhibited a significant interaction of year*location*management*species(variety) (Figure 2.4). Seed oil content greater than 300 g kg^{-1} is considered highly competitive when growing and marketing oilseeds for the biofuel market (Tsogtbaatar et al., 2015). In year 1 of the study, all species and varieties at both locations and management practices exceeded 300 g kg^{-1} oil (Figure 2.4). In year 2, all pennycress varieties across locations and management were at or slightly under 300 g kg^{-1} oil, while all canola varieties continued to exceed 400 g kg^{-1} oil (Figure 2.4). At the Milan location, canola had a lower oil percentage in year 2 as compared to year 1 (Figure 2.4). Within locations, no differences existed between till and no-till management (Figure 2.4). Seed oil content is determined by the environment during seed filling stage of plant growth. In canola, for example, higher oil contents are typical in cool springs with heavy rainfall compared to dry, warm springs (Hassan et al., 2005). Based on these results, it can be assumed that the typical spring environment in Tennessee is conducive to producing winter oilseeds with competitive seed oil content for the biofuel production industry.

Glucosinolates present within the seed oil are listed below in Table 2.4. Canola oil had eleven glucosinolates present across years, compared to only one compound identified in pennycress oil (Table 2.4). However, the glucosinolate content in canola made up a much smaller overall concentration within the oil (7.79 mg g^{-1}in 2021; 0.76 mg g^{-1} in 2022) compared to the total concentration present in pennycress oil (115.56 mg g^{-1} in 2021; 5.09 mg g^{-1} in 2022) (Table 2.4). Canola has been specifically bred to be low in glucosinolates for human consumption, whereas pennycress has undergone fewer breeding efforts. Different compounds were detected in year one and two in canola (Table 2.4). This is likely due to the availability of

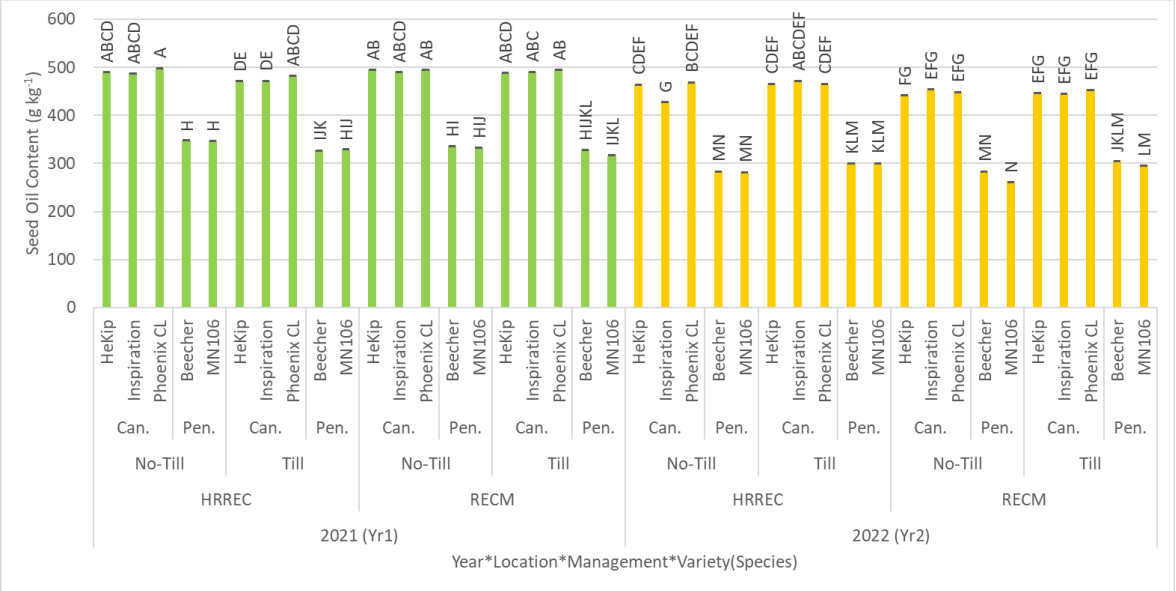

Figure 2.4. Average oil content within seed (g kg^{-1}) when separated by year, location (HRREC or RECM), management type (tilled or no-till trials), species (canola or pennycress), and variety (p=0.0043). Bars denoted with different letters are statistically different at p<0.05 as determined by Tukey's HSD.

Table 2.4. Glucosinolates present within canola and pennycress seed oil as determined by HPLC analysis.

Compound	Canola 2021 Average mg g^{-1}	Canola 2022 Average mg g^{-1}	Pennycress 2021 Average mg g^{-1}	Pennycress 2022 Average mg g^{-1}
Glucoprogoitrin	4.77	0.43	Bd	Bd
Glucosinigrin	0.10	Bd	115.56	5.09
Glucoiberin	Bd*	0.19	Bd	Bd
Glucoepiprogoitrin	Bd	0.03	Bd	Bd
Glucoraphanin	0.11	0.02	Bd	Bd
Glucosinalbin	0.26	0.002	Bd	Bd
Gluconapin	2.16	0.26	Bd	Bd
Glucoerucin	0.08	Bd	Bd	Bd
Glucobrassicin	0.08	Bd	Bd	Bd
4-methylglucobrassicin	0.13	Bd	Bd	Bd
Gluconasturtiin	0.11	0.02	Bd	Bd
Aliphatic	7.21	0.74	115.56	5.09
Aromatic	0.37	0.02	Bd	Bd
Indole	0.21	Bd	Bd	Bd
Total Glucosinolates	**7.79**	**0.76**	**115.56**	**5.09**

* Bd indicates the compound was below detection levels within the seed oil of that specific species

different primers used to analyze the samples each year. Compounds may have been below detection level or unidentified in subsequent years.

Various glucosinolate compounds may be of interest in the study of allelopathy in winter oilseeds. Glucosinolates that degrade to isothiocyanates are often associated with weed suppression (Malik et al., 2010), which are derived from the aromatic family of glucosinolates (Lee et al., 2020). Aromatic glucosinolates were present (0.37 mg g^{-1}) in canola oil (Table 2.4), pointing to possible allelopathic weed control uses. Glucosinigrin is the only compound identified in pennycress and is also present in other edible Brassicas such as brown mustard and horseradish (Hojilla-Evangelista et al., 2014). However, the high concentration of glucosinigrin in pennycress may limit its usefulness as an animal feed due to palatability and toxicity issues.

18. Soybean Yield and Quality

Soybean yields differed significantly by species*year at the Springfield location (Figure 2.5), and by species*location in 2022 (Figure 2.6). Due to a planting error at Milan, TN in year one of this study, soybean yields were only evaluated across two years at the Springfield, TN location. In year two of the study, soybean planted following canola in rotation at Springfield had a 503 to 781 kg ha^{-1} yield deficit compared to soybean following pennycress, or fallow plots (Figure 2.5). These yield deficits were not observed in Milan in 2022 (Figure 2.6). Volunteer canola following soybean planting is the most likely cause of the observed soybean yield deficit in Springfield. Burn down was applied the same day as canola harvest, and the soybean planted one day later. The volunteer canola which germinated at the same time as the soybean was not controlled by the burn down application. Soybean planted in canola plots suffered much more competition compared to the other plots, as the canola shaded out the soybean seedlings. These data contradict results in the current literature which say double cropping with canola will not affect

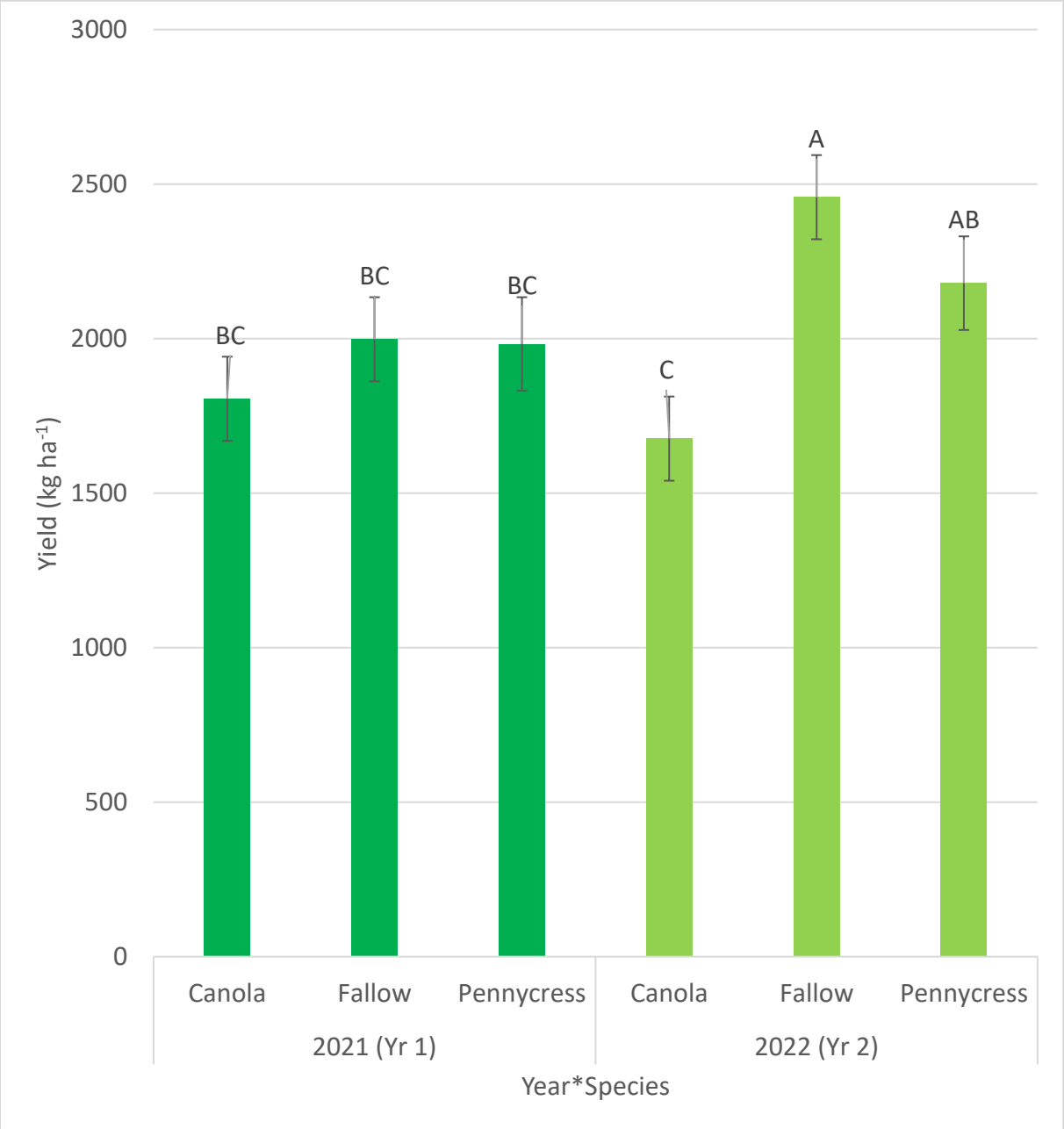

Figure 2.5. Average soybean yield (kg ha^{-1}) across both years of study at the Springfield location separated by year and previously planted winter oilseed species (p= 0.0096). Bars denoted with different letters are statistically different at p<0.05 as determined by Tukey's HSD.

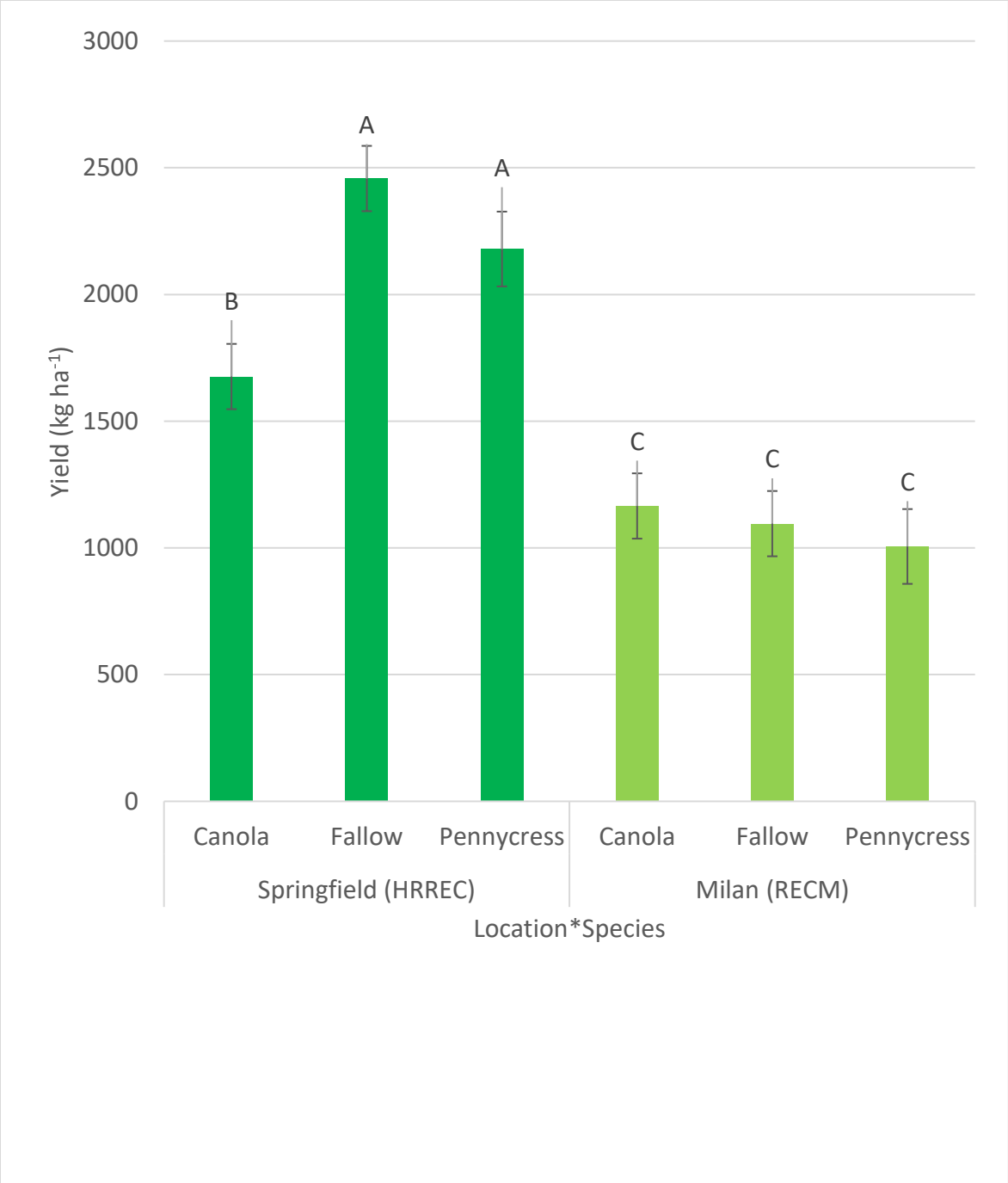

Figure 2.6. Average soybean yield (kg ha^{-1}) in 2022 separated by location and previously planted winter oilseed species (p= 0.0002). Bars denoted with different letters are statistically different at p<0.05 as determined by Tukey's HSD.

soybean yield (Gross et al., 2021; Porter, 1995) but volunteer populations were not discussed in either publication.

Soybean yields differed by location in 2022 (Figure 2.6). All soybean harvested at the Milan location had a 511 to 1,362 kg ha^{-1} lower yield compared to Springfield (Figure 2.6).

Soybean protein content differed by management*year in Springfield across both years (Figure 2.7a) and by location in year two (2022) across the Springfield and Milan locations (Figure 2.7b). Soybean oil content differed by year*management at Springfield across both years (Figure 2.8a) and by management in year two (2022) across the Springfield and Milan locations (Figure 2.8b). Soybean planted in Springfield in 2021 in no-till plots had 10 g kg^{-1} higher protein and 3 to 6 g kg^{-1} lower oil in the seeds than those planted in 2021 tilled plots or either management type in 2022 (Figure 2.7a, Figure 2.8b). Oil content was lower in no-till plots at both the Milan and Springfield locations in 2022 as well (Figure 2.8b). Changes in tillage practices for a winter crop may impact the quality of summer crops even if the summer crop tillage remains constant. Location impacted soybean quality as well. Soybean grown at Springfield had a higher protein concentration than those grown at Milan (Figure 2.7B). Further research is needed to determine the mechanisms of these differences in summer crop quality.

Discussion and Conclusion

With new interest in winter oilseeds for biofuel creation and new varieties available, new questions arose from this first attempt to grow novel winter oilseed crops in Tennessee. Canola and pennycress both provided a small amount of early winter ground cover and competed moderately with weeds. Both species produced promising preliminary yields. Canola appears better adapted to the Mid-South for high yield and oil production; however, it has undergone much more extensive breeding. Pennycress had yields similar to those in the Midwest and

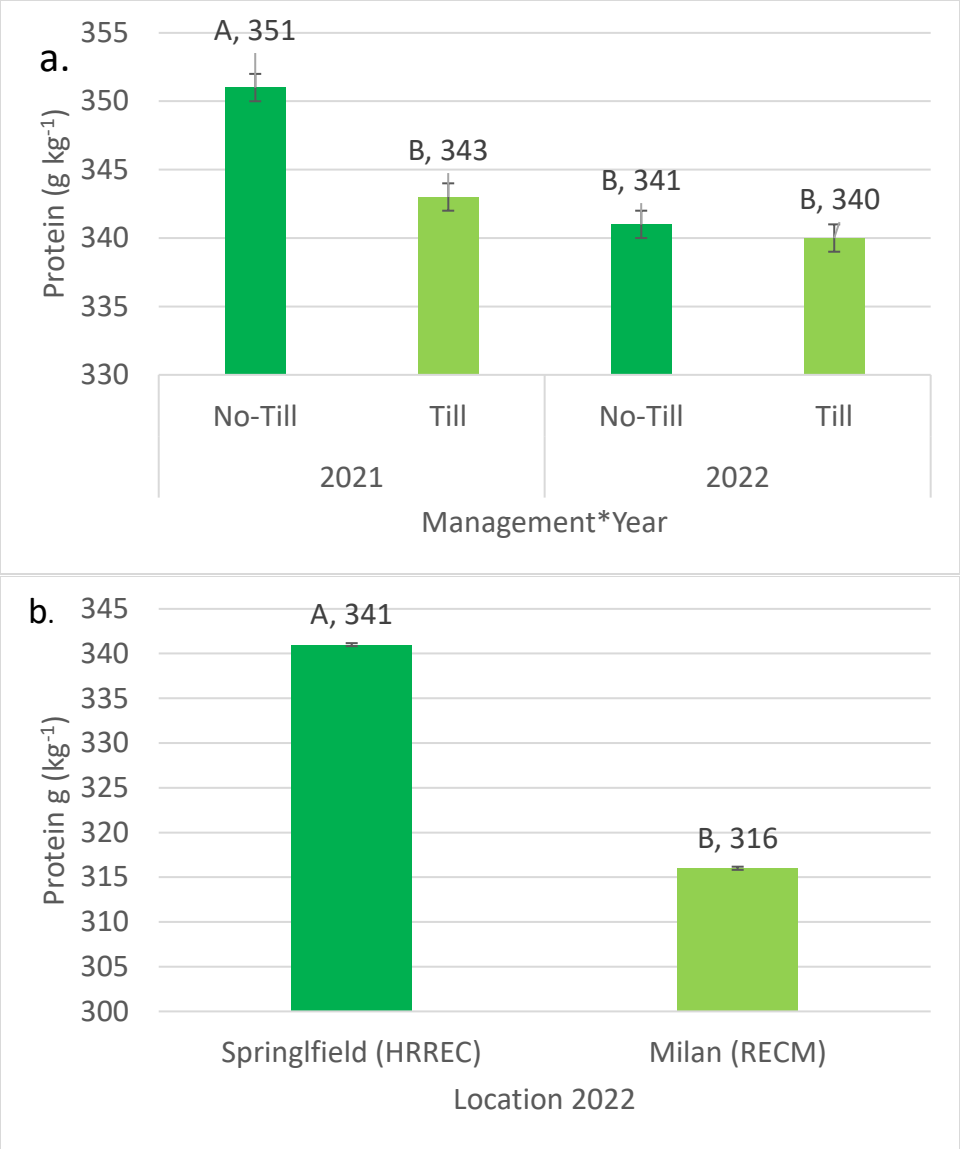

Figure 2.7. (a.) Average soybean protein (g kg^{-1}) separated by year and winter oilseed management type ($p<0.0001$). (b.) Average soybean protein (g kg^{-1}) in 2022 for the interaction by location ($p=0.0188$). Bars denoted with different letters are statistically different at $p<0.05$ as determined by Tukey's HSD.

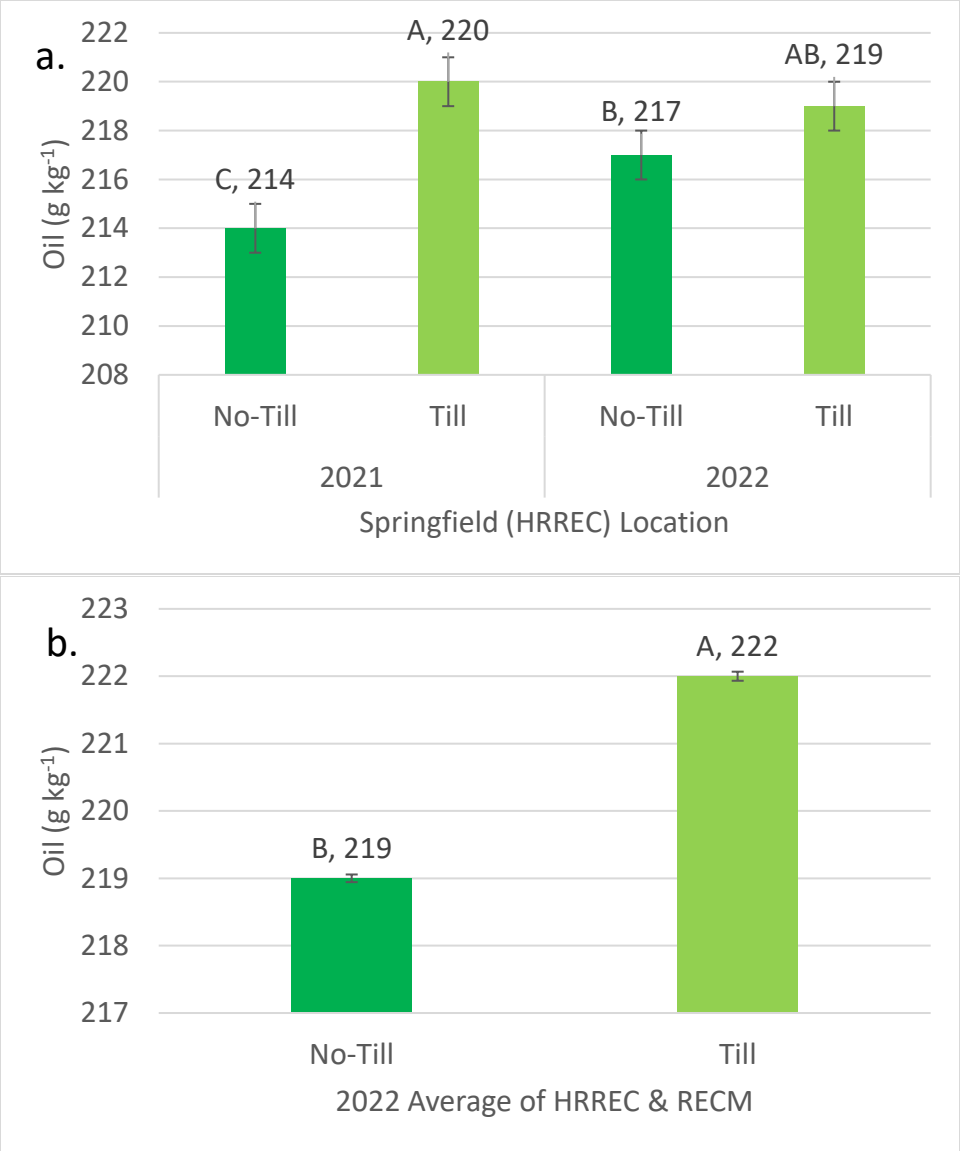

Figure 2.8. (a.) Average soybean oil (g kg^{-1}) at the Springfield location (HRREC) separated by year and winter oilseed management type (p=0.0018). (b.) Average soybean oil (g kg^{-1}) in 2022 separated by winter oilseed management (p=0.0002). Bars denoted with different letters are statistically different at p<0.05 as determined by Tukey's HSD.

competitive oil production, but likely could benefit from further breeding efforts for agronomic and regional adaptation. Pennycress has untapped breeding potential in the Mid-South and could eventually perform admirably in the region. Camelina appears unsuitable for production in the region. Producing winter oilseeds will likely not influence soil health in initial production years if crops are rotated across different fields each year, which is a recommended practice to prevent accumulation of Brassica pests. Yield deficits in soybean grown in rotation may occur when following canola; volunteer canola is the most likely cause. More research is needed to determine if this yield deficit will persist if volunteer canola is effectively controlled.

The use of winter oilseeds to create sustainable aviation fuel is likely to drive the creation of a viable market for growers in the future; however, the success of the markets will rely on a number of factors. As noted previously, additional efforts to increase yields through breeding and agronomic research are needed. Further efforts to build processing capacity in the region are also essential, as only one oil crushing facility presently exists in the area. Research on the environmental effects of fatty acid profiles under variable spring environments in the Mid-South is needed to ensure quality oil can be delivered consistently as well, especially in warmer years. The deliverance of quality oil for biofuel production will significantly impact the ability of farmers to adopt winter oilseeds as a crop in Tennessee. An economic analysis is needed to determine the profitability of this double-crop system. Results from this study show promise for these crops in the Mid-South, the adoption of which could provide greater profits for growers while enhancing ecological value of corn/soybean production systems.

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CHAPTER THREE: POTENTIAL ALLELOPATHIC INTERACTIONS FROM CANOLA AND PENNYCRESS POST-HARVEST ROOTS AND STUBBLE

Core Ideas:

1. Water extractable allelochemicals in winter oilseed roots and stubble impact herbicide resistant weed germination and growth.
2. Canola and pennycress root extract lowered the germination and root length of herbicide resistant mare's tail.
3. Canola and pennycress root extract shortened roots and lengthened shoots of palmer amaranth.
4. Canola and pennycress root extract did not affect soybean germination and growth.

Potential Allelopathic Interactions from Canola and Pennycress Post-Harvest Roots and Stubble

Abstract

Winter oilseed Brassica plants have several documented allelochemicals; however, most literature revolves around the application of seed meal to fields, or the use of aerial parts of the plant. It is not clear if these chemicals interact with the surrounding environment to the same extent if the winter oilseeds are harvested as a cash crop in the spring. To determine this, we conducted a bioassay using water extractable compounds from canola (*Brassica napus*) and pennycress (*Thlaspi arvense* L.) roots diluted to 25 and 50 % (v/v). These four extracts, as well as DI water for control, were used to irrigate plates filled with the indicator species of soybean (*Glycine max*), palmer amaranth (*Amaranthus palmeri*), and mare's tail (*Erigeron canadensis*). Mare's tail germination was lowered by 25% on day 8 by 50% pennycress extracts, and root length was stunted by both canola and pennycress extracts by 3 to 5 mm. Palmer amaranth root length was stunted by 10 to 15 mm by both species' extracts, as well as shoots lengthened by 5 to 10 mm. Extract treatments did not affect soybean germination or growth. These interactions

indicate potential for allelopathic interactions in the field following harvest of dual cropped winter oilseed and herbicide resistant weeds and warrants further study into the topic.

Introduction

Allelopathy is defined as the usually negative influence of one plant on another through toxic chemical exudation (Zimdahl, 2018). Allelochemicals can be released into the environment through precipitation washing them off the aerial parts of the plant, volatile compound exudation from the aerial parts of the plant, root exudation, and the decay of plant residue within the soil (Shah et al., 2016). The most common allelopathic interactions include the interference of plant growth and development, germination inhibition, reduction of radicle or shoot growth, necrosis, and lower reproductive capacity. Environmental factors such as soil moisture, precipitation, temperature, light intensity, and others will affect the process and effectiveness of allelopathy (Shah et al., 2016).

Brassica crops have long been of interest in the study of allelopathy. Most Brassica species have the ability to exude allelochemicals that are potentially toxic to soil-borne pathogens, weeds, nematodes, and fungi (Shah et al., 2016). Brassicas produce glucosinolates within the plant. As hydrolysis of the glucosinolates takes place, allelochemical products such as isothiocyanates, nitriles, thiocyanates, cyanides, and others are created. In canola, specifically, eight root exudates have been identified as potential allelochemicals, including sinapyl alcohol, p-hydroxybenzoic acid, 3,5,6,7,8-pentahydroxy flavone, jasmonic acid and methyl-jasmonate (Asaduzzaman, 2015). In pennycress, two major phytotoxins have been identified: 2-propen-1-yl (allyl) isothiocyanate (AITC) and allyl thiocyanate (ATC) (Vaughn et al., 2005). These specific allelochemicals found within Brassica winter oilseeds have been shown to inhibit the growth and

germination of other plant species grown at the same time, as well as those grown in rotation (Shah et al., 2016).

Allelochemicals remaining in the soil following winter oilseed harvest may impact the following cash crop as well as weeds. Soybean is often double cropped with winter oilseeds, and several studies have examined the interactions of winter oilseed crops on soybean germination and growth. Conflicting information exists for interactions between soybean and canola, with some studies claiming that canola extract increased the germination percentage of soybean and decreased root fresh weight (Syed & Shinwari, 2016), while others claim that canola extracts reduce soybean germination (Sheldon et al., 2021; Niakan et al., 2006). These effects may be cultivar dependent (Niakan et al., 2006). In camelina, however, a study conducted in Brazil concluded that camelina had a positive influence on soybean germination, and a negative effect on weed germination (Silva et al., 2011). Many Brassicas are currently being used as fall cover crops to lower the need for spring herbicide applications through allelopathy (Shah et al., 2016). Several studies found that pennycress seed meal can almost completely suppress weed germination, including sicklepod, velvetleaf, annual ryegrass, and wheat, when incorporated into the soil (Cubins et al., 2019).

The roots of Brassica plants tend to have the least amount of toxic allelochemicals present, while the leaves have the most (Shah et al., 2016). In a bioassay conducted by Niakan et al. (2006), 0.5 mL canola root extracts had a lesser effect than 0.5 mL shoot extracts on inhibiting soybean germination. Most studies have focused on the allelopathic effects of using the whole plant as residue or applying ground-up seed meal across the field. The objective of this study is to determine if any allelopathic effects remain when the Brassica crops are harvested as a double crop and the majority of plant biomass is removed. Winter oilseeds are harvested for

their seed for biofuel production, as well as above ground biomass for animal feed, leaving behind only roots and stubble. We hypothesize that the root exudates of canola and pennycress will maintain an allelopathic effect on the following crops and weeds. In this study, the effect of root extracts from canola (*Brassica napus*) and pennycress (*Thlaspi arvense* L.) were evaluated on the germination of soybean (*Glycine max*), mare's tail (*Erigeron canadensis*), and palmer amaranth (*Amaranthus palmeri*).

Materials and Methods

19. Plant Material

Two species of winter oilseed crops, canola and pennycress, were field grown in Tennessee during the winters of 2020-2021 and 2021-2022. Both species were grown at the Highland Rim Research and Education Center in Springfield, TN (36.476648, -86.821195; soil type Sango Silt Loam) and the Research and Education Center at Milan in Milan, TN (35.934679, -88.715231; soil type Loring). Oilseeds were planted in October, allowed to grow through the spring season, then harvested at maturity (pennycress was harvested in May and canola was harvested in June). Plants were grown in a randomized complete block design with three varieties of each crop nested within species and three replicates per field. Canola varieties included 'HeKip', 'Inspiration', and 'Phoenix CL'. Pennycress varieties included 'Beecher', 'MN106' in both years, as well as 'Spring Type' in year one and 'GE Golden' in year two. Roots were dug by hand at the conclusion of winter oilseed harvest in 2021 and 2022. Plots were 3 m wide by 9 m long. Roots were sampled from the first replicate in each field each year, allowing for roots to be collected from one plot of each variety. Six plants from each plot were randomly selected for sampling. The roots were oven dried for 72 hours at 100ºC and then ground to pass through a

1mm screen. The powdered tissues were then bagged and stored in the refrigerator at 2 to 4ºC until use (roughly six months prior to run 1 and roughly one month prior to run 2).

20. Extract Creation

Extracts used in this study were prepared following a protocol from Sheldon et al., 2021. One day before the study began, samples from Springfield and Milan were combined to ensure adequate material was available for extract creation in year one. Although more material was collected in year two, locations were combined again to maintain consistency. Forty grams of each sample were dissolved in 400 mL of deionized water for 24 hours at 25°C. The next day, the beaker containing the extract solution was placed on a Corning stir plate with magnetic stir bar for 15 minutes at level 7. Next, the extract was filtered through 4 layers of cheese cloth and centrifuged at 4000 rpm for 30 minutes. The extract was then filtered through Whatman no. 2 paper. These stock extracts were made fresh the day prior to the experiment and refrigerated for the remainder of the experiment.

21. Seed Bioassay

Two dilutions were made with deionized water for each crop species from the stock extract, giving the final extract dilutions of 50% (v/v) canola (50C), 25% (v/v) canola (25C), 50% (v/v) pennycress (50P), and 25% (v/v) pennycress (25P). Sterile deionized water served as a control treatment, creating five treatments total. Three indicator species were used: untreated 'Ellis' soybean, palmer amaranth (collected at the West Tennessee Research and Education Center in Jackson, TN), and herbicide resistant mare's tail (population maintained in the greenhouse at the University of Tennessee in Knoxville, TN by Dr. Neal Stewart). Soybean seeds were surface sterilized with 2% bleach for three minutes, rinsed with DI water, and air dried. The remaining indicator species seeds were not able to be surface sterilized, as the small seed size made them

difficult to recover from the solution. Four mL of each winter oilseed crop extract were then pipetted onto Whatman no. 2 filter paper inside a 9 cm petri dish. 10 seeds of soybean and 20 seeds of palmer and mare's tail were placed in a petri dish, and the petri dishes were placed on a lab bench and kept in room temperature conditions at 25°C. Each petri dish of indicator species and extract treatment was replicated five times. Four mL of each treatment were added to their respective dishes every other day for 8 days. The bioassay was completed in January 2022 using roots collected from the 2021 harvest and repeated in August 2022 using roots collected from the 2022 harvest.

22. Data Collection

On day four of the experiment, the germination percent of each dish was calculated. Germination was considered as any seed with an emerged radicle. On day eight, germination percent was calculated again, and measurements were taken for radicle and hypocotyl length (mm) of all germinated seedlings for each petri dish.

23. Glucosinolate Analysis

Glucosinolate content within the root material was determined after completion of the bioassay using high performance liquid chromatography (HPLC). Samples were separated by species (canola or pennycress) and year (2021 or 2022). Dry samples were extracted from leftover root powder for each species and analyzed on an Agilent 1100 Series HPLC (Santa Clara, CA) according to the procedure of Barickman et al., 2013. Data was processed using ChemStation Software (Rev. C 01.07 SR2 [255]). Each species*year sample was replicated five times.

24. Statistical Analysis

Treatments were arranged in a randomized complete block design. A mixed model ANOVA was performed using the glimmix procedure in SAS (vs. 9.4, Cary, NC). Mean separation was performed using Tukey's HSD. Significance was determined at $P < 0.05$. All variables were checked for normality and equal variance. Variables for radicle and hypocotyl length were transformed via natural log to meet equal variance requirements for analysis. Resulting means were then transformed back to be displayed graphically. Main effects of extract, species, and year were considered fixed effects. Block was considered random.

Results

25. Germination

Germination differed significantly by species*treatment (Figures 3.1 & 3.4), year*treatment (Figures 3.2 & 3.5), and year*species (Figures 3.3 & 3.6) on both day four and eight of the bioassay. No germination differences from control plates occurred in soybean or palmer amaranth plates (Figures 3.1&3.4). On day four, mare's tail treated with 50C, 25P, and 50P had a lower germination percent than the mare's tail control plates (Figure 3.1). On day eight, only mare's tail treated with 50P had a lower germination percent than the control plates (Figure 3.4). In year 2 of the bioassay, plates treated with 50P had a lower germination percent than plates treated with 50P in year 1 (Figures 3.2 & 3.5). Mare's tail had a higher overall germination percent regardless of extract treatment in year 2 as compared to year 1 (Figures 3.3 & 3.6), likely due to seeds meeting vernalization requirements during storage in the refrigerator between bioassay runs.

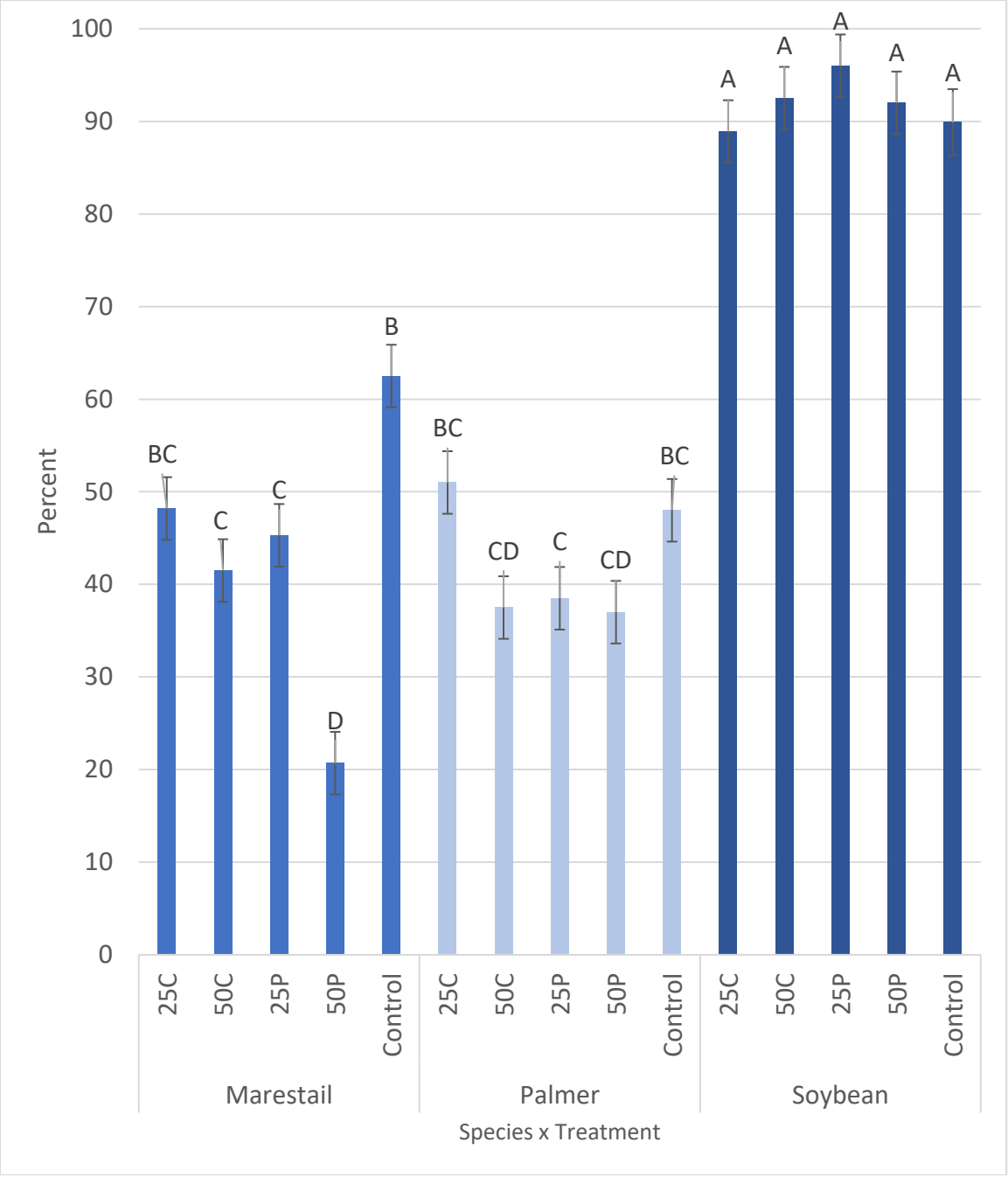

Figure 3.1. Germination percent within plates on day 4 of the bioassay ($p<0.0001$). Bars denoted with a different letter are statistically significant at $p<0.05$. Tukey's HSD was used for mean separation.

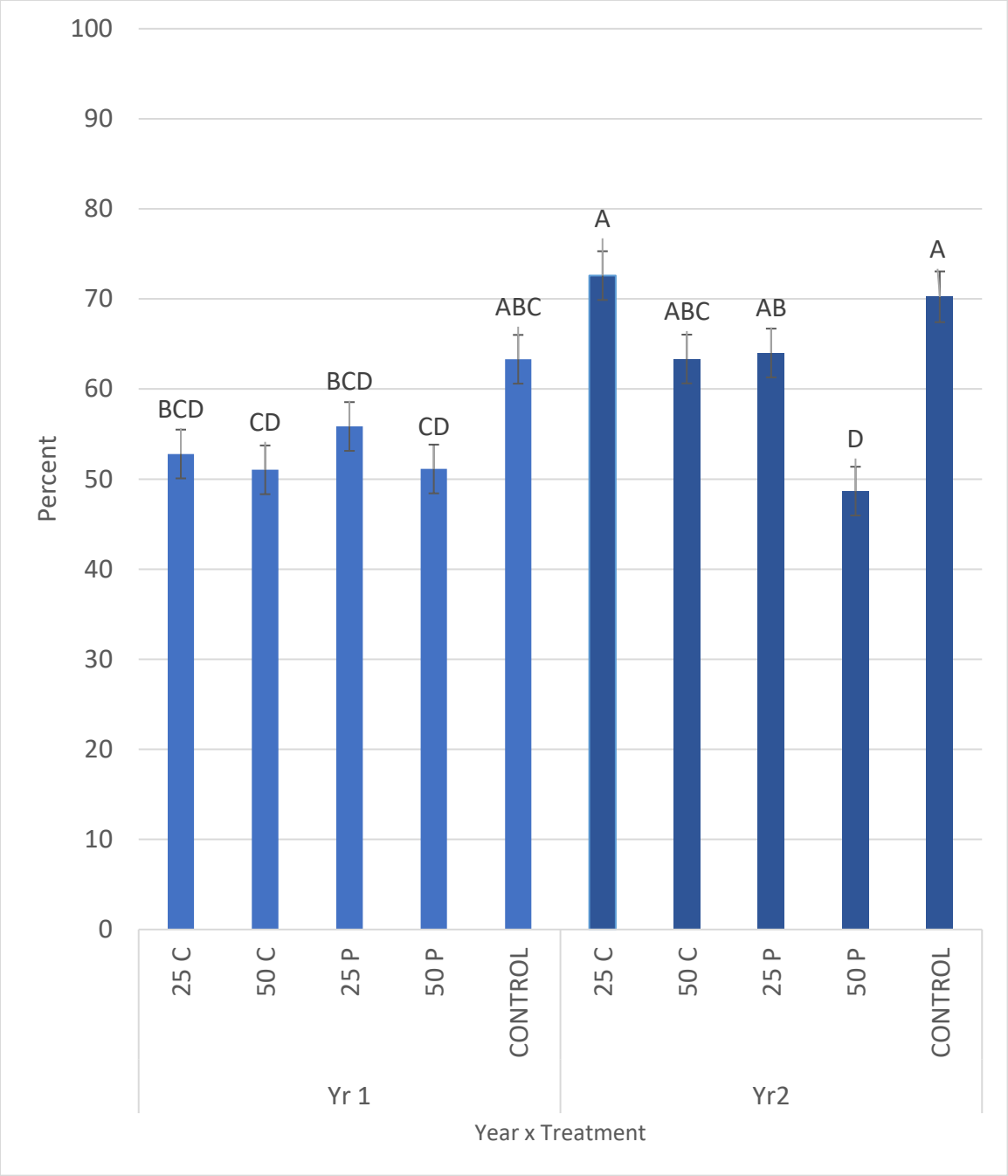

Figure 3.2. Germination percent within treatments in year 1 and 2 on day 4 of the bioassay (p=0.0023). Data denoted with different letters are statistically significantly different at p<0.05. Tukey's HSD was used for mean separation.

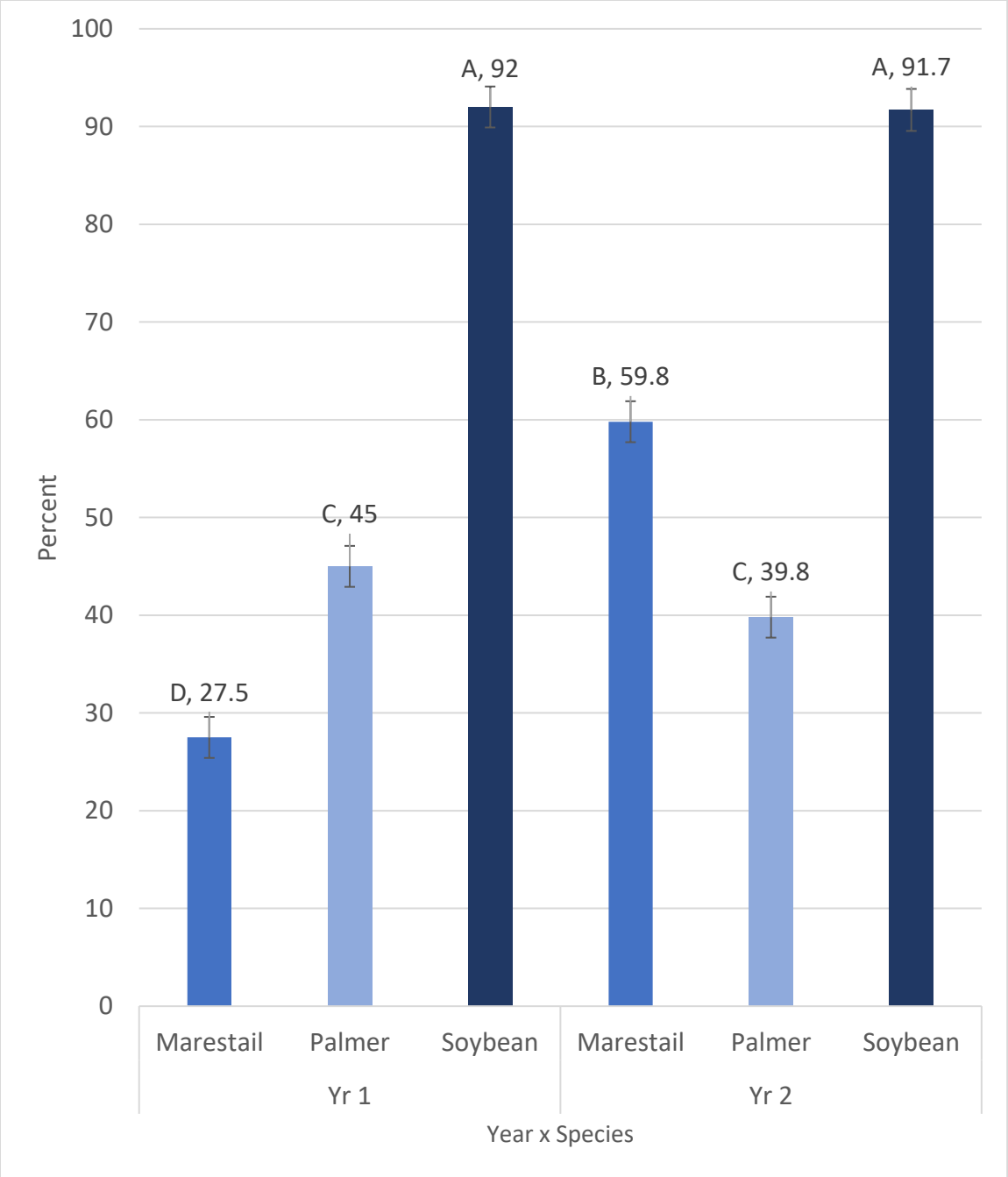

Figure 3.3. Germination percent within species in year 1 and 2 on day 4 of the bioassay ($p<0.0001$). Data denoted with different letters are statistically significantly different at $p<0.05$. Tukey's HSD was used for mean separation.

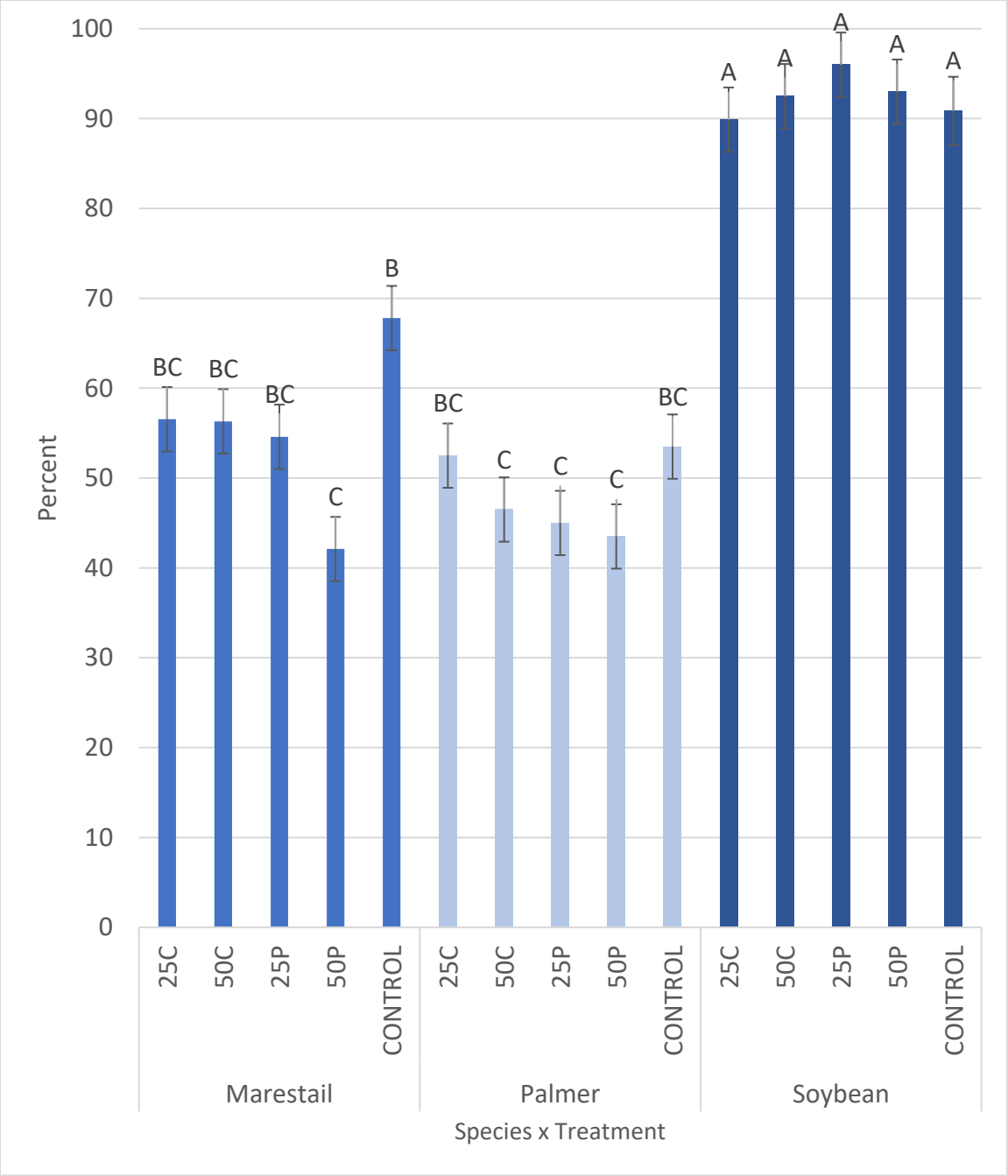

Figure 3.4. Germination percent within plates on day 8 of the bioassay (p=0.0223). Bars denoted with a different letter are statistically significant different at p<0.05. Tukey's HSD was used for mean separation.

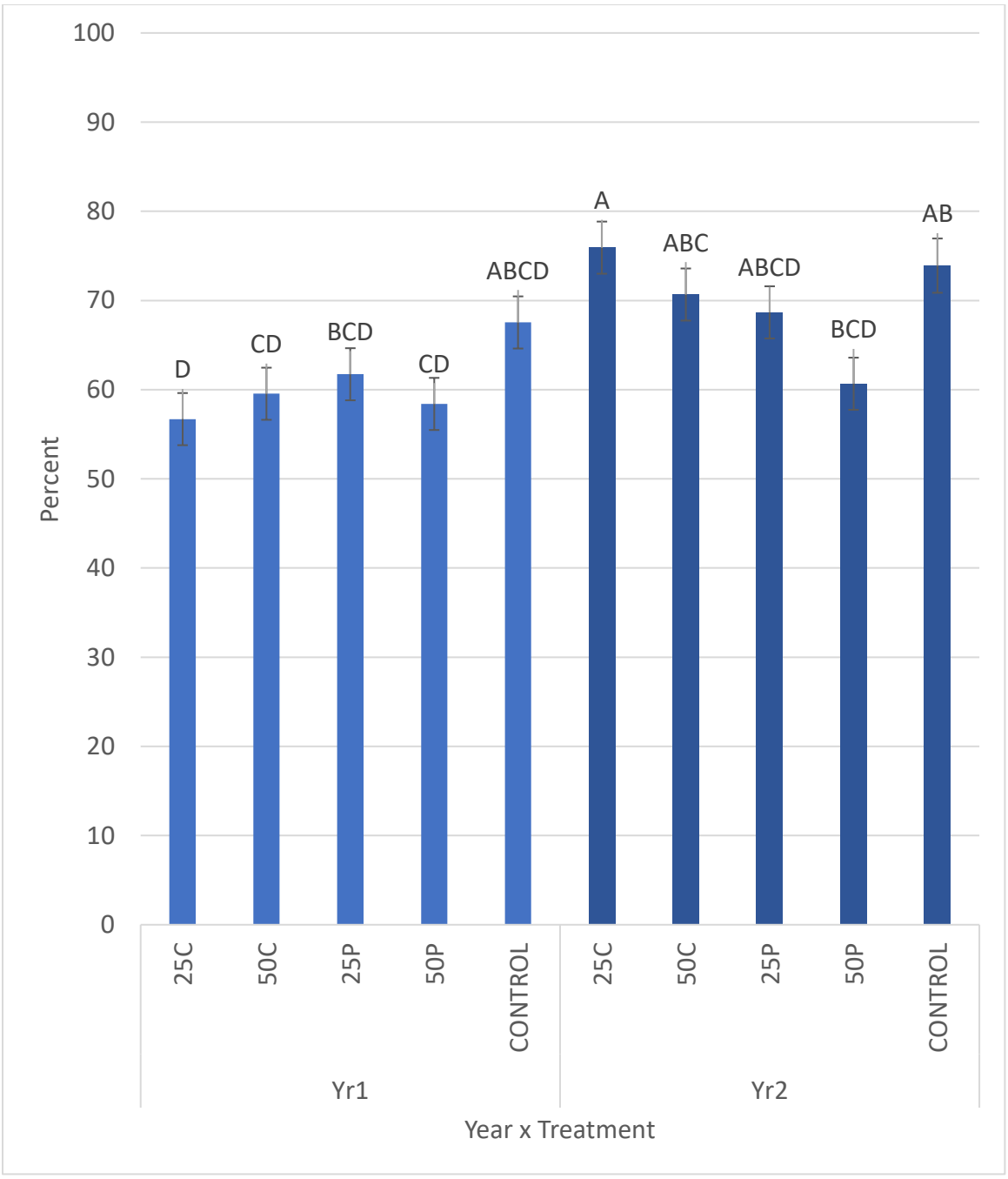

Figure 3.5. Germination percent within treatments in year 1 and 2 on day 8 of the bioassay (p=0.0525). Data denoted with different letters are significantly different at p<0.05. Tukey's HSD was used for mean separation.

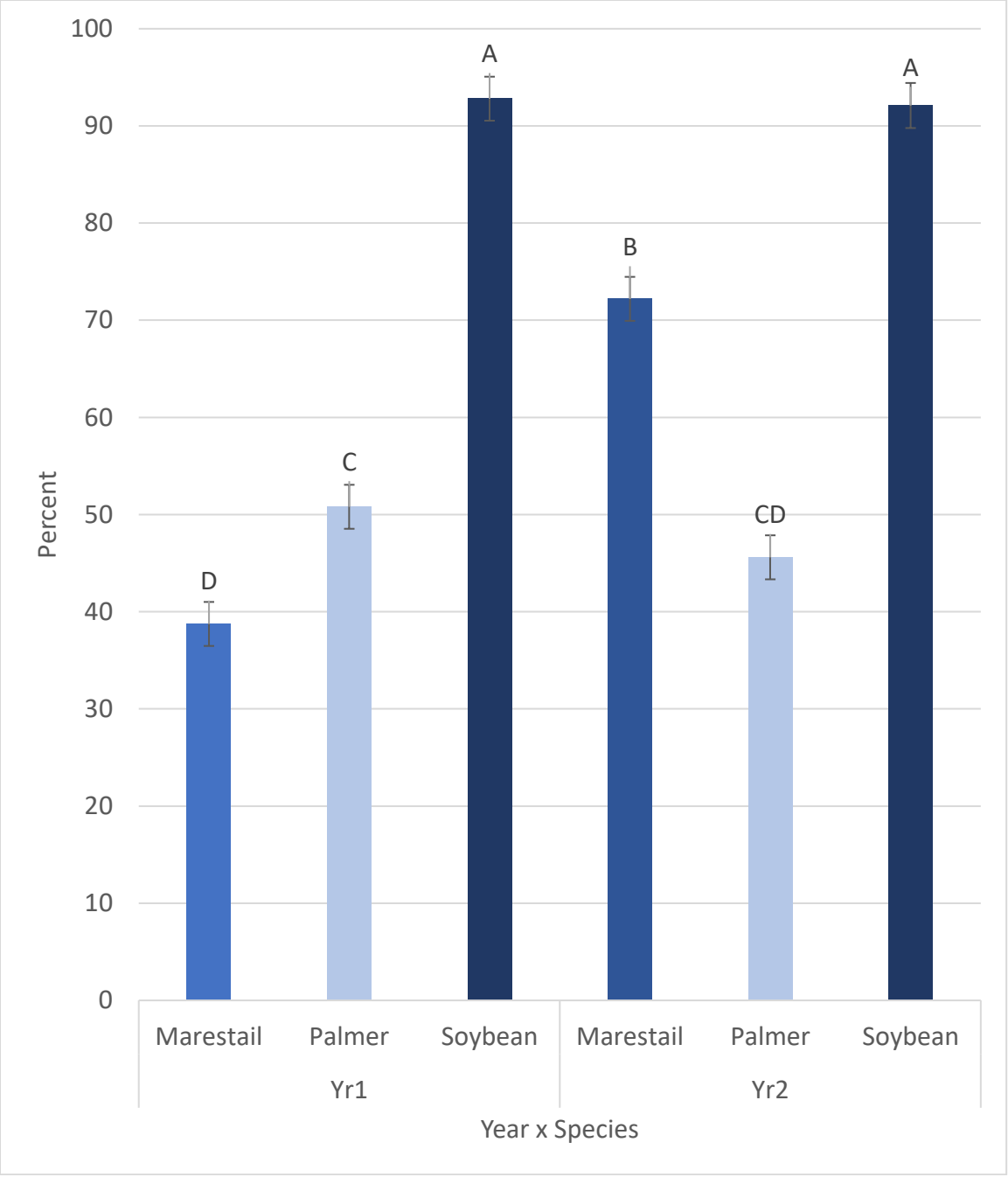

Figure 3.6. Germination percent within species in year 1 and 2 on day 8 of the bioassay ($p<0.0001$). Data denoted with different letters are statistically significantly different at $p<0.05$. Tukey's HSD was used for mean separation.

26. Root Growth

Radicle length differed significantly by species*treatment*year (Figure 3.7). Within mare's tail and palmer amaranth, all plates irrigated with any dilution of winter oilseed extract had significantly shorter radicles compared to the control of the same species (Figure 3.7). No significant differences were observed within soybean (Figure 3.7). Within all species, no significant differences existed across years (Figure 3.7).

27. Shoot Growth

Hypocotyl length differed significantly by species*treatment (Figure 3.8) and species*year (Figure 3.9). Treatment interactions were non-significant within soybean or mare's tail (Figure 3.8). Within palmer amaranth, plates irrigated with 25C, 25P, and 50P had longer hypocotyls than control plates irrigated with DI water (Figure 3.8). When looking at differences between years, mare's tail and palmer amaranth plates in year 2 had shorter overall hypocotyl length than in year 1 (Figure 3.9).

28. Glucosinolate Content

Specific glucosinolate compounds found within the root may explain some of the interactions observed between extracts and seeds. Table 3.1 lists three specific glucosinolates present within the ground root material of canola and pennycress. Pennycress had a high concentration of glucosinigrin in 2021 (year 1), which is often used as a soil fumigant (Table 3.1). In 2022 (year 2), pennycress did not have any detectable glucosinolates (Table 3.1). Canola had gluconasturtiin present each year (Table 3.1). The samples came from a homogeneous sample of each field; compounds present in year one may be present but below detection levels in year two.

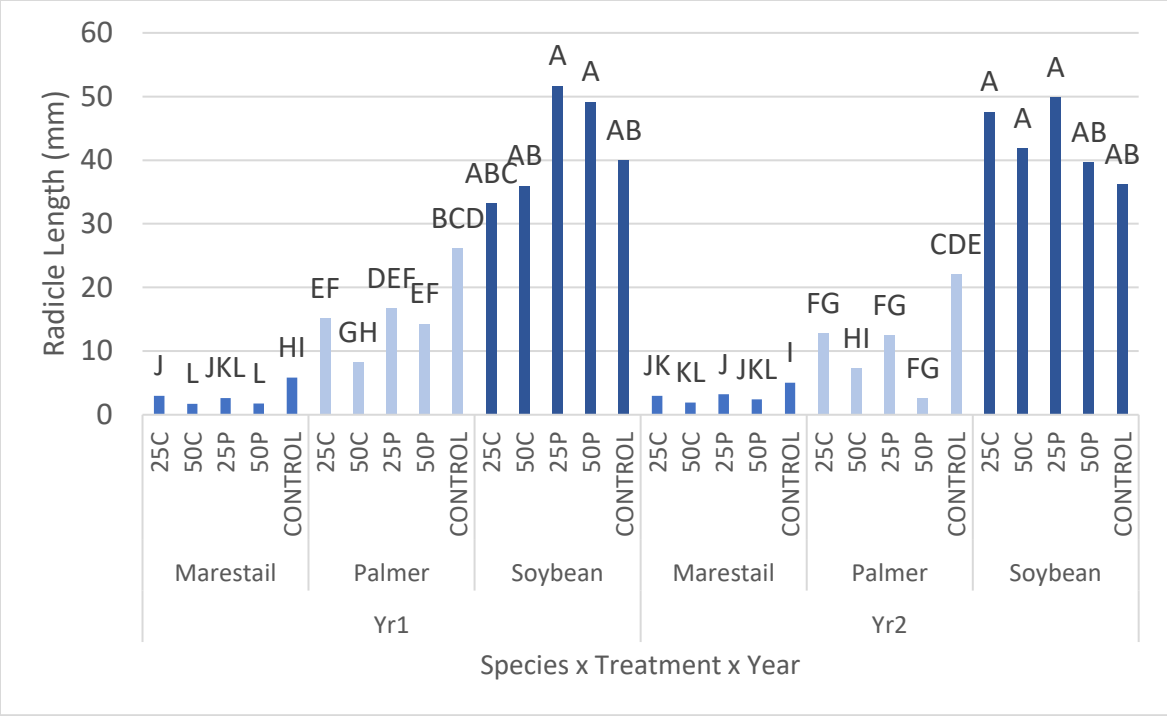

Figure 3.7. Average radicle length (mm) within plates (p=0.0059). Differing letters above bars indicate significant differences at p<0.05. Tukey's HSD was used for mean separation.

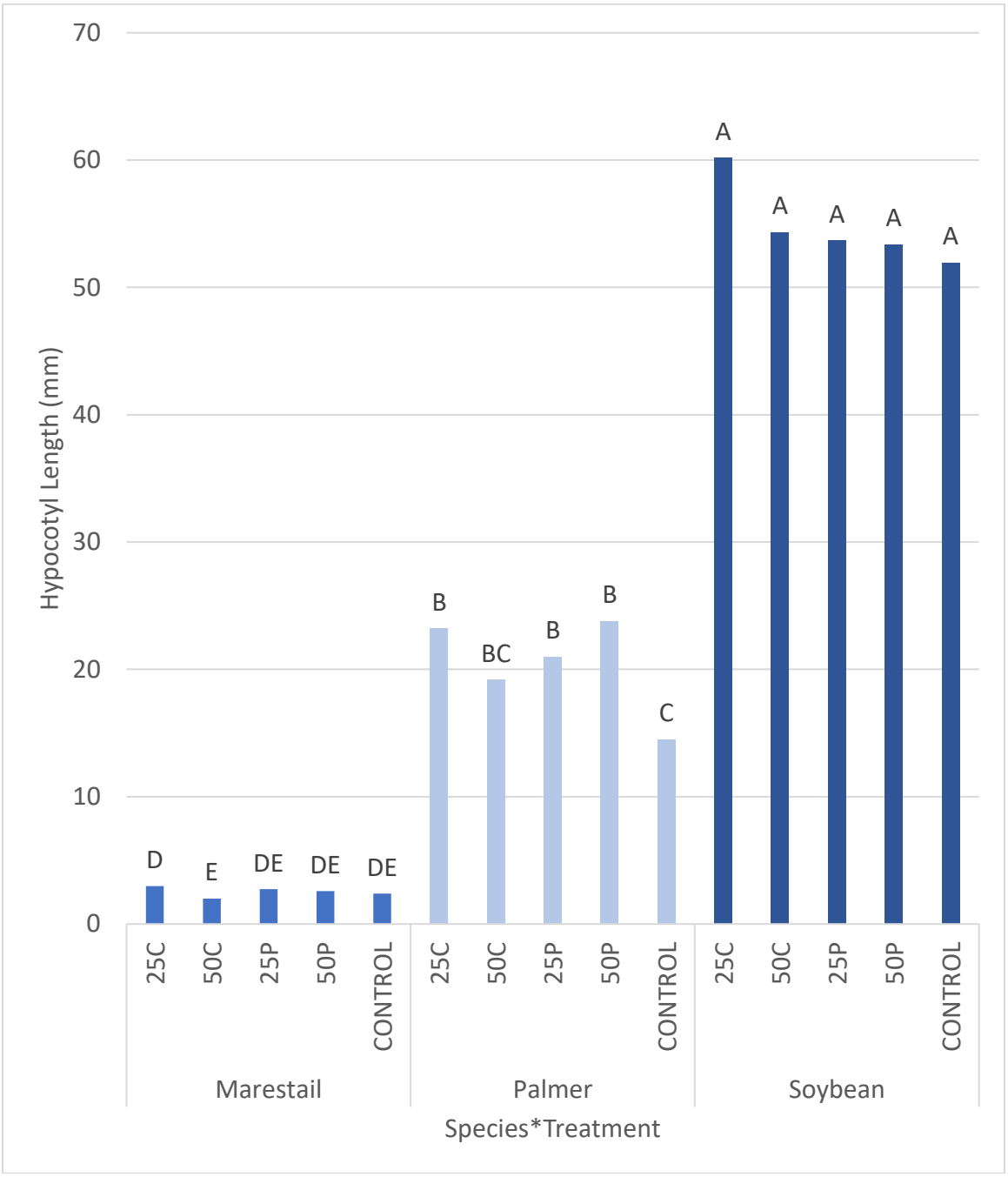

Figure 3.8. Average hypocotyl length (mm) within plates (p=0.005). Different letters above the bars signify statistically significant differences at p<0.05. Tukey's HSD was used for mean separation.

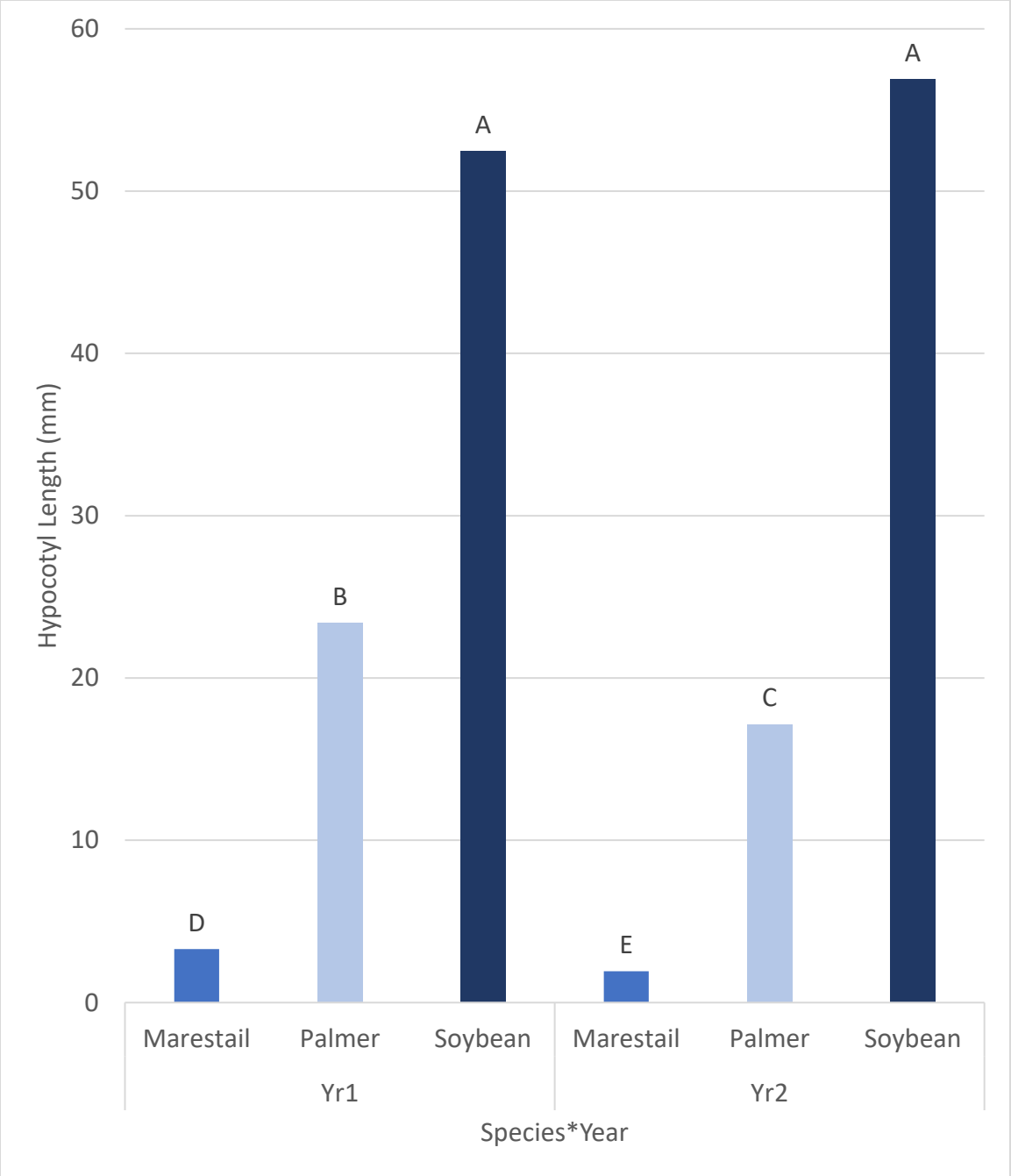

Figure 3.9. Average hypocotyl length (mm) within species by year ($p<0.0001$). Different letters above the bars signify statistically significant differences at $p<0.05$. Tukey's HSD was used for mean separation.

Table 3.1. Average glucosinolates present (mg g^{-1}) within dried root material from pennycress and canola samples used to create the extract treatments within the bioassay.

Species	Year Collected	Glucosinigrin mg g^{-1}	Glucoraphanin mg g^{-1}	Gluconasturtiin mg g^{-1}	Total mg g^{-1}
Canola	2021 (Yr1)	0	0	0.073	0.073
Pennycress	2021 (Yr1)	0.024	0.031	0.018	0.073
Canola	2022 (Yr2)	0	0	0.100	0.100
Pennycress	2022 (Yr2)	0	0	0	0

Discussion and Conclusion

Overall, this bioassay suggests that the water extractable compounds within winter oilseed root material that will be left in the field following harvest can have allelopathic interactions with herbicide resistant weed species likely to be present in the field after winter oilseed production. Currently no literature explores the control of herbicide-resistant weeds from winter oilseed post-harvest allelochemicals. Further investigation is warranted to determine to what degree these interactions translate to field conditions throughout the summer growing season and how they will impact the decision to plant winter oilseeds for the growers.

Herbicide-resistant mare's tail is likely to be less competitive in the field compared to soybean if the results indicated by this bioassay translate to the field. Lowered or delayed germination will allow the soybean seedlings a head start to close canopy before the weeds can begin to compete for light. The shorter roots of mare's tail in the presence of winter oilseed extracts will make the weeds less competitive in the field as well, with the soybean seedlings able to outcompete for water and nutrients.

Herbicide-resistant palmer amaranth is likely to be less competitive in the field compared to soybean seedlings as well if results directly translate to the field. Palmer with short roots and longer than normal shoots is more likely to lodge or break during weather events in the field, is less competitive in drought, and will struggle more with nutrient uptake.

None of the extracts showed any significant effects on the germination or early growth of soybean. A review from Koehler-Cole et al. (2020) found no current research available on allelopathic effects of winter Brassica crops on soybean. Findings from this study support that the presence of winter oilseed stubble in the field will not affect the growth and production of soybeans grown immediately following winter oilseed harvest through allelopathy. Corn>winter

oilseed>soybean rotations are currently recommended as an economically viable rotation for winter oilseed production. Further research is needed to determine season-long effects of winter oilseed stubble on soybean yield.

As herbicide-resistant weeds become a larger problem for growers, novel ways to control weeds will become imperative. Field studies are necessary to determine allelopathic impacts of growing winter oilseeds in rotation with corn and soybean. If studies show that similar results as this bioassay translate to the field, growers could potentially include winter oilseeds as a weed management tool, making them a dual-use double crop. A lower need for spring herbicide could also be included in the economic analysis of growing winter oilseeds, making the crops more likely to be profitable. Continued research of this type is needed to determine if winter oilseeds are worthwhile crops to promote to growers.

Acknowledgements

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CHAPTER FOUR: BUDGET AND BREAKEVEN PRICES OF WINTER CANOLA AND PENNYCRESS PRODUCTION IN TENNESSEE

Core Ideas:

1. Canola and pennycress are potential new energy crops for the Mid-South.
2. Average canola yields and projected oilseed prices are likely profitable.
3. Average pennycress yields and projected oilseed prices are not profitable currently.
4. Further research on BMP's, plant breeding for higher yields, and the creation of a market are needed before promoting adoption in the Mid-South.

Budget and Breakeven Prices of Winter Canola and Pennycress Production in Tennessee

Abstract

Canola (*Brassica napus*) and pennycress (*Thlaspi arvense* L.) are winter oilseed crops that can be used to create sustainable aviation fuel. They have been grown successfully in the Upper Midwest and Great Plains and are garnering interest in the Mid-South. A field study was conducted in Tennessee to determine management practices and average yields expected for the region. From this study, a budget and breakeven analysis was conducted. Budgets were created for tilled and no-till canola and pennycress systems. Based on average yields obtained and projected oilseeds prices, canola systems are potentially profitable while pennycress systems are not. However, breakeven prices were highly variable between years, locations, oilseed species, and tillage type. Canola has been relatively established in the region and can be promoted to growers as a profitable crop. Presently, the adoption of pennycress in the Mid-South is not recommended without further research on best management practices (BMP's), breeding efforts for higher yielding varieties, and the creation of a viable market for sale.

Introduction

Winter oilseeds are annual cool season Brassica crops that produce oil rich seeds which can be used for many purposes (Cubins et al., 2019; Myers, 2018). The driving force of recent interest is their use within biofuel, biodiesel, and sustainable aviation fuel (SAF) creation (Fan et al., 2013; Gholami et al., 2021; Keske et al., 2013). In 2019, the United States aviation industry emitted 5% of all total domestic CO_2 energy related emissions (Karami et al., 2022). Studies of various SAF feedstocks show that the use of SAF can decrease CO_2 emissions by 80 % of current rates (Karami et al., 2022). Specific species of interest are canola (*Brassica napus*), pennycress (*Thlaspi arvense* L.), and camelina (*Camelina sativa*). Each species has winter biotypes which can be planted in the fall, function as a winter cover, supply extra income to growers in spring after harvest, create sustainable fuel sources, and do not interfere with current summer food production.

Canola has undergone more extensive breeding efforts in the Mid-South, while pennycress and camelina are still novel crops in the region. Currently, no publications exist with field data of pennycress and camelina being grown in the Mid-South. A significant amount of literature has been published within recent years discussing best management practices for winter oilseed production (Allen et al., 2014; Altendorf, 2017; Assefa et al., 2018; Bronson et al., 2019; Cecchin et al., 2021; Chopra et al., 2020; Cubins et al., 2019; Does et al., 2017; Fan et al., 2013; Hoerning et al., 2022; McGeary et al., 2022; Moore et al., 2020; Sainju et al., 2020), as well as information on the economics of winter oilseed production (Dangol et al., 2017; Gholami et al., 2021; Markel et al., 2018; Mousavi-Avval & Shah, 2021; Ott et al., 2019; Shila et al., 2021; Trejo-Pech et al., 2019). However, the majority of this information is specific to the Upper Midwest or Great Plains. A large literature gap exists for winter oilseed economic viability

within the Mid-South, as well as for no-till winter oilseed production. Studies by Markel et al. (2018) and Trejo-Pech et al. (2019) have analyzed the potential economic viability of winter oilseed sustainable aviation fuel production in the Mid-South; however, all data was generated using assumed yields. Studies using experimental yields of winter oilseeds from the Mid-South do not currently exist. To bridge this information gap, a study was designed to determine the cost of production, net returns, breakeven prices, and profitability of winter oilseed production in the Mid-South.

Materials and Methods

An in-field variety trial including canola, pennycress, and camelina was conducted in Tennessee in the growing seasons 2020-21 and 2021-22. Both tilled and no-till systems were evaluated. The crops were grown at two locations: Springfield, TN at the Highland Rim Research and Education Center (HRREC) (36.476648, -86.821195; soil type Sango Silt Loam) and Milan, TN at the Research and Education Center at Milan (RECM) (35.934679, -88.715231; soil type Loring). Plots were arranged in a randomized complete block design with three replications for each till and no-till field at each location. Three varieties of each species were nested within species blocks, along with a fallow control block to create 10 total treatments. Canola varieties included ‘HeKip’, ‘Inspiration’, and ‘Phoenix CL’. Pennycress varieties included ‘Beecher’, ‘MN 106’, and ‘Spring Type’ in year one which was replaced with ‘GE Golden’ in year two. Camelina varieties included ‘Joelle’, ‘Suneson’, and ‘Blaine Creek’. Each year of study, the oilseeds were planted in a corn/winter oilseed/soybean rotation. Fields were rotated each year to maintain this rotation across the study.

Prior to planting, no-till fields had cornstalks chopped while tilled fields were worked two weeks prior to planting with a chisel plow and disk. Sulfur, nitrogen, and boron were applied one

week pre-planting, and amounts were based on soil tests for each field. Soil test recommendations were based on canola needs in Tennessee. Winter oilseeds were planted in late September to mid-October each year. In year one, planting occurred on 29 September 2020 in Milan and 19 September 2020 in Springfield. In year two, planting occurred on 12 October 2021 in Milan and on 1 October 2021 in Springfield. All winter oilseed species were planted at the same time using a Hege 1000 Cone Plot Drill (Colwich, Kansas) following corn harvest at a depth of 1 cm. Camelina and pennycress seeds were planted at a rate of 5.6 kg ha^{-1} (5 lbs ac^{-1}), while canola was planted at a rate of 543,631 seeds ha^{-1} (220,000 seeds ac^{-1}). In March, sulfur, boron, and nitrogen were applied based on soil testing per field. At Springfield, phosphorous and potassium was applied as well in March 2022.

In the spring, all plots were harvested by hand using two randomly selected squares (53 by 53 cm) to determine yield. Pennycress was harvested in late May and canola was harvested in early to mid-June.

29. Budget Creation

Oilseed budgets created by Markel et al. (2018) and Trejo-Pech et al. (2019) were modified to represent tilled and no-till canola systems and tilled and no-till pennycress systems using the field operations, inputs, and yields obtained from the field study. Unfortunately, camelina failed in both years of the study and therefore did not warrant an economic analysis.

Inputs for each system were determined by the field study. Notable inputs for each system include the cost of seed, planting, 156 kg urea ha^{-1}, 44 kg sulfur ha^{-1}, 2.2 kg zinc ha^{-1}, 1.1 kg boron ha^{-1}, harvest equipment, and transport of oilseeds from the farm to the crushing facility. Each system differed in inputs during establishment. Tilled system establishment operations included a chisel plow and tandem disk, while no till system establishment operations included

chopping corn stalks. Prices of urea, sulfur, zinc, and boron fertilizers and diesel fuel from the last 12 years (2009-2021) were gathered from archived UT Extension crop budgets (McKinley & Gerloff, 2009; McKinley & Gerloff, 2010; McKinley & Gerloff, 2011; McKinley & Gerloff, 2012; McKinley & Gerloff, 2013; Smith et al., 2014; Smith et al., 2015; Smith et al., 2016; Smith et al., 2017; Smith et al., 2018; Smith et al., 2019; Smith et al., 2020; Smith & Bowling, 2021). Prices were adjusted for inflation using the Gross Domestic Product Implicit Price Deflator Index (Kansas City Federal Reserve). The average price across years in 2021 equivalent dollars was then entered into the corresponding budget. This process was repeated for the inputs of boron, canola seed, capital recovery, chisel plow, diesel, fuel oil, labor, repairs and maintenance, sulfur, and urea. These budgets were used to determine the total cost of production for each system: tilled canola, no-till canola, tilled pennycress, and no-till pennycress.

Within the budgets, assumed price for oilseeds is from Trejo-Pech et al. (2019) and represents what a crushing facility could pay if the assumed end use is a biofuel for pennycress. Canola prices are based on prices received by growers from 2012 to 2021 reported by the USDA.

30. Breakeven Analysis

Based on the budgets created, breakeven prices were determined for each yield sample collected in the field study across two years. The following equation was used to determine breakeven prices:

$$Breakeven\ Price\ (\$\ kg^{-1}) = \frac{Total\ Production\ Cost\ Including\ Transportation\ (\$\ kg^{-1})}{Oilseed\ Yield\ (kg\ ha^{-1})}$$

Breakeven prices were analyzed in SAS (vs. 9.4, Cary, NC) using the glimmix procedure to perform an ANOVA. Tukey's HSD was used for mean separation. Breakeven values had to be transformed using a natural log to meet variance and normality requirements for analysis. Results have been transformed back for ease of discussion in the following section. Fixed effects were

year, location, crop species, and tillage. All possible interactions of these effects were tested. $P < 0.05$ was considered significant. Tukey's HSD was used to determine mean separations.

31. Sensitivity Analysis

A one-way sensitivity analysis was also conducted for each system budget on the farm breakeven oilseed price per pound. The base scenario represents practices used in the field study as well as average prices according to UT Extension budgets for canola. Sensitivity analysis was accomplished by changing each variable to 150% above the base value to achieve the upper bound, and to 50% below the base value to achieve the lower bound while holding the other variables at their base value. Tornado diagrams were used to present the one-way sensitivity analysis effects of each variable on breakeven price for each species and management combination. The variables represented by the horizontal bars of the tornado diagram were ordered such that the largest bar was at the top, indicating that the variable had the largest effect on breakeven price, while the smallest bar at the bottom had the least impact.

Results

32. Budgets

Budget summaries for each of the four systems analyzed are listed below in Tables 4.1 to 4.4. Differences can be observed between species (canola or pennycress), between management type (till or no-till), and between management type within species. In this study, no yield differences were observed by varieties within species. Further information regarding specific results of the field study can be found in Chapter 2. Based on average experimental yields, canola produced positive returns while pennycress produced negative returns (Tables 4.1 to 4.4). Canola was a much higher yielder than pennycress, on average, in Tennessee. At an average yield of 2,802 kg ha^{-1}, tilled canola had a return above total expenses of \$752.38 ha^{-1} (Table 4.1)

Table 4.1. Budget summary for conventional-tillage canola production in the Mid-South.

		Unit	Quantity	Price	Total
Revenue ($/ha)					
	Canola oilseed	kg/ha	2,802	$0.46*	$1,297.47
			Total Revenue		**$1,297.47**
Variable Expenses ($/ha)					
	Seed	kg/ha	2.8	$16.35	$45.78
	Fertilizer	hectare	1	$273.26	$273.26
	Chemical	hectare	1	$0	$0
	Repair & Maintenance	hectare	1	$57.25	$57.25
	Fuel, Oil, & Filter	hectare	1	$44.68	$44.68
	Operator Labor	hectare	1	$28.18	$28.18
	Crop Insurance	hectare	1	$0	$0
	Operating Interest	hectare	$449.15	6.0%	$13.47
			Total Variable Expense		**$462.62**
			Return Above Variable Expenses		**$834.85**
Fixed Expenses ($/ha)					
	Machinery Capital Recovery	hectare	1	$69.70	$69.70
	Taxes, Housing, & Insurance	hectare	1	$12.77	$12.77
			Total Fixed Expenses		**$82.47**
			Total Variable & Fixed Expenses		**$545.09**
			Return Above Total Expenses		**$752.38**

* Price based on average price received by growers for canola seed as reported by the USDA from 2012-2021 reported in 2021 dollars.

Table 4.2. Budget summary of no-till canola production in the Mid-South.

		Unit	Quantity	Price	Total
Revenue ($/ha)					
	Canola oilseed	kg/ha	2,802	$0.46*	$1,297.47
			Total Revenue		**$1,297.47**
Variable Expenses ($/ha)					
	Seed	kg/ha	2.8	$16.35	$45.78
	Fertilizer	hectare	1	$273.26	$273.26
	Chemical	hectare	1	$0	$0
	Repair & Maintenance	hectare	1	$59.06	$59.06
	Fuel, Oil, & Filter	hectare	1	$40.83	$40.83
	Operator Labor	hectare	1	$25.54	$25.54
	Crop Insurance	hectare	1	$0	$0
	Operating Interest	hectare	$444.47	6.0%	$13.33
			Total Variable Expense		**$457.80**
			Return Above Variable Expenses		**$839.67**
Fixed Expenses ($/ha)					
	Machinery Capital Recovery	hectare	1	$68.61	$68.61
	Taxes, Housing, & Insurance	hectare	1	$12.52	$12.52
			Total Fixed Expenses		**$81.13**
			Total Variable & Fixed Expenses		**$538.93**
			Return Above Total Expenses		**$758.54**

* Price based on average price received by growers for canola seed as reported by the USDA from 2012-2021 reported in 2021 dollars.

Table 4.3. Budget summary of conventional-tillage pennycress production in the Mid-South.

		Unit	Quantity	Price	Total
Revenue ($/ha)					
	Pennycress oilseed	kg/ha	673	$0.25*	$166.23
			Total Revenue		**$166.23**
Variable Expenses ($/ha)					
	Seed	kg/ha	5.6	$5.51	$30.70
	Fertilizer	hectare	1	$44.77	$273.26
	Chemical	hectare	1	$0	$0
	Repair & Maintenance	hectare	1	$57.25	$57.25
	Fuel, Oil, & Filter	hectare	1	$44.68	$44.68
	Operator Labor	hectare	1	$28.18	$28.18
	Crop Insurance	hectare	1	$0	$0
	Operating Interest	hectare	$434.07	6.0%	$13.02
			Total Variable Expense		**$447.09**
			Return Above Variable Expenses		**-$280.86**
Fixed Expenses ($/ha)					
	Machinery Capital Recovery	hectare	1	$69.70	$69.70
	Taxes, Housing, & Insurance	hectare	1	$12.77	$12.77
			Total Fixed Expenses		**$82.47**
			Total Variable & Fixed Expenses		**$529.56**
			Return Above Total Expenses		**-$363.33**

*Price estimated using Trejo-Pech et al., 2019 crushing facility model.

Table 4.4. Budget summary of no-till pennycress production in the Mid-South.

		Unit	Quantity	Price	Total
Revenue ($/ha)					
	Pennycress oilseed	kg/ha	673	$0.25*	$166.23
			Total Revenue		**$166.23**
Variable Expenses ($/ha)					
	Seed	kg/ha	5.6	$5.51	$30.70
	Fertilizer	hectare	1	$273.26	$273.26
	Chemical	hectare	1	$0	$0
	Repair & Maintenance	hectare	1	$59.06	$59.06
	Fuel, Oil, & Filter	hectare	1	$40.83	$40.83
	Operator Labor	hectare	1	$25.54	$25.54
	Crop Insurance	hectare	1	$0	$0
	Operating Interest	hectare	$429.39	6.0%	$12.88
			Total Variable Expense		**$442.27**
			Return Above Variable Expenses		**-$276.04**
Fixed Expenses ($/ha)					
	Machinery Capital Recovery	hectare	1	$68.62	$68.62
	Taxes, Housing, & Insurance	hectare	1	$12.52	$12.52
			Total Fixed Expenses		**$81.14**
			Total Variable & Fixed Expenses		**$523.41**
			Return Above Total Expenses		**-$357.18**

*Price estimated using Trejo-Pech et al., 2019 crushing facility model.

and no-till canola had $758.54 ha^{-1} (Table 4.2). Pennycress had a lower average yield of 673 kg ha^{-1} and subsequently lower returns above total expenses compared to canola. Tilled pennycress had a return above total expenses of -$363.33 ha^{-1} (Table 4.3) and no-till pennycress had -$357.18 ha^{-1} (Table 4.4). Based on average yields obtained, practices used in the field study in Chapter 2, costs of inputs in 2021 dollars, and expected oilseed prices, canola is a profitable crop while pennycress is not.

33. Breakeven Prices

The interaction of all fixed effects within the model (year*location*species*tillage) was significant ($p<0.0001$). Overall, canola had a lower breakeven price than pennycress in all years, locations, and tillage systems, except for pennycress grown in tilled plots at HRREC in 2021 (Figures 4.1 & 4.2). Within just canola plots, breakeven prices were lower in 2021 compared to 2022 regardless of tillage type or location (Figure 4.1). Within years, no differences were observed by location or tillage type in canola (Figure 4.1). Pennycress had more variability within and across years and locations. At the RECM location, no-till plots in 2022 had a $10.05 kg^{-1} higher breakeven price than in 2021 for pennycress (Figure 4.2). Differences by tillage were observed at RECM in 2022, with no-till pennycress ($11.64 kg^{-1}) having a higher breakeven price than tilled pennycress ($3.90 kg^{-1}). At the HRREC location, tilled plots in 2022 had a $1.34 kg^{-1} higher breakeven price than in 2021 in pennycress (Figure 4.2). Differences between locations occurred within tilled plots in 2021, with RECM ($1.93 kg^{-1}) having a higher breakeven price than HRREC ($0.66 kg^{-1}) (Figure 4.2).

For canola production, the breakeven oilseed price at a yield of 2,802 kg ha^{-1} was determined to be $0.210 kg^{-1} for conventional tillage and $0.148 kg^{-1} for no-till production. The breakeven yield at a price of $0.46 kg^{-1} is 1,276 kg ha^{-1} for conventional tillage and 899 kg ha^{-1}



Figure 4.1. Breakeven prices obtained for canola grown in two years (2021 & 2022), two locations (HRREC & RECM), and two different tillage types (no-till and till) in dollars per hectare ($p<0.0001$). Bars with different letters above denote significant differences at $p<0.05$.

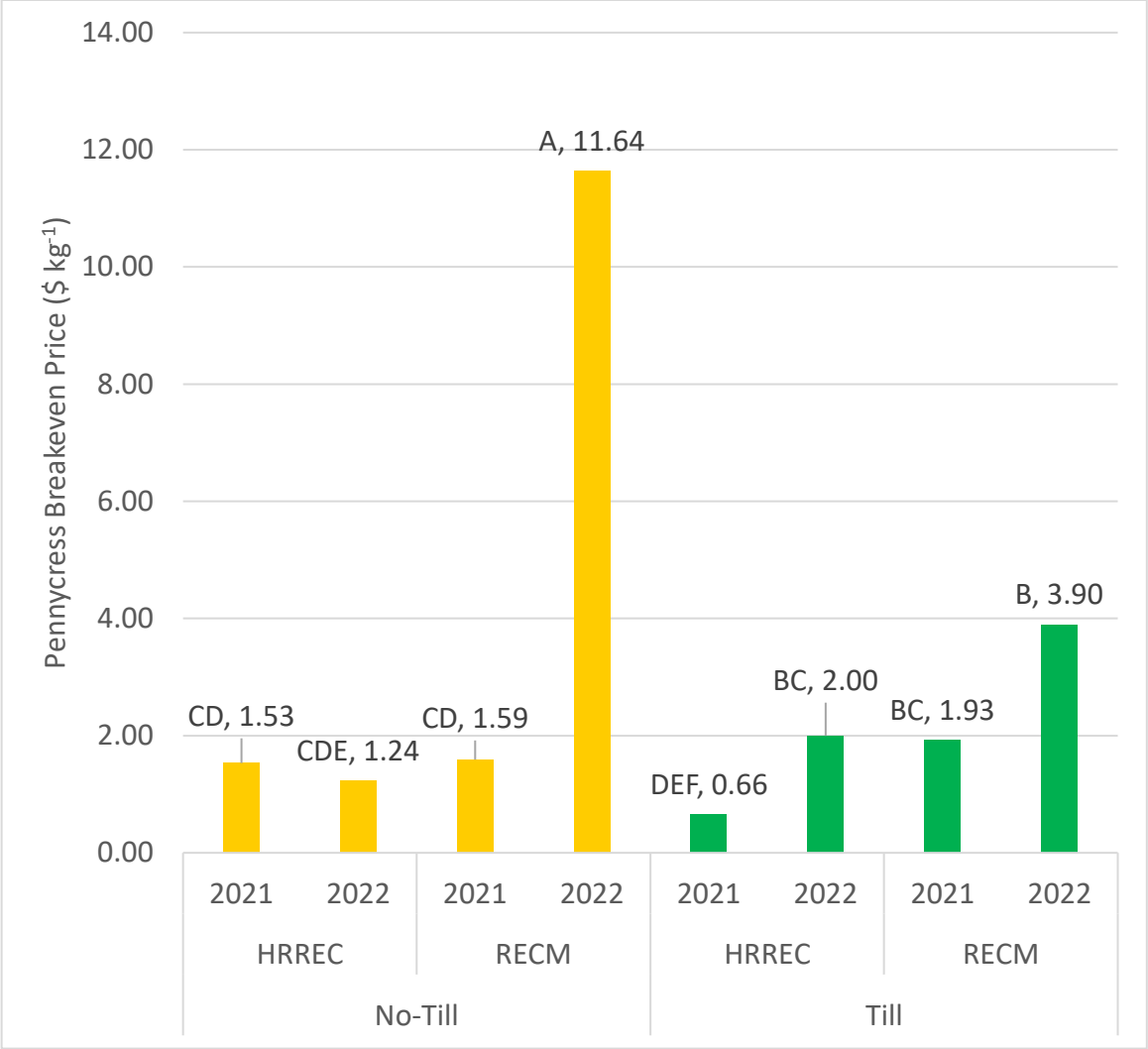

Figure 4.2. Breakeven prices obtained for pennycress grown in two years (2021 & 2022), two locations (HRREC & RECM), and two different tillage types (no-till and till) in dollars per hectare ($p<0.0001$). Bars with different letters above denote significant differences at $p<0.05$.

for no-till canola. For pennycress production, the breakeven oilseed price at a yield of 673 kg ha^{-1} was \$0.532 for conventional tillage and \$0.523 for no-till. The breakeven yield at a price of \$0.25 kg^{-1} is 1,432 kg ha^{-1} for conventional tillage and 1,407 kg ha^{-1} for no-till pennycress.

34. Sensitivity Analysis

Factors affecting profitability within the sensitivity analysis did not differ significantly within species by tillage management type. The factors affecting canola conventional tillage profitability impacted canola no-till profitability to the same degree. Pennycress profitability by conventional tillage or no-till had the same relationship.

At current average yields, canola breakeven price is \$0.15 kg^{-1} (Figure 4.3). In canola production, oilseed yield affects profitability the most (Figure 4.3). In years with lower yields, oilseed prices will need to be higher to meet the breakeven price, which at 50 % below the average yield becomes \$0.30 kg^{-1} (Figure 4.3). At 150 % above the average yield in the field study, oilseed breakeven price becomes \$0.10 kg^{-1} (Figure 4.3). Fertilizer costs have the second greatest effect on canola profitability (Figure 4.3).

Oilseed yield and fertilizer costs had the greatest impact on pennycress profitability as well (Figure 4.4). Compared to canola, pennycress must fetch a much higher price for seed to meet breakeven prices at current yields (\$0.52 kg^{-1}). Improving best management practices for pennycress and breeding for better adapted varieties will be necessary to improve profitability of this potential energy crop. Fertilizer costs per kilogram are also higher for pennycress production compared to canola (Figures 4.3, Figure 4.4). Lowering the cost of fertilizer for pennycress will make this crop more competitive with canola as well.

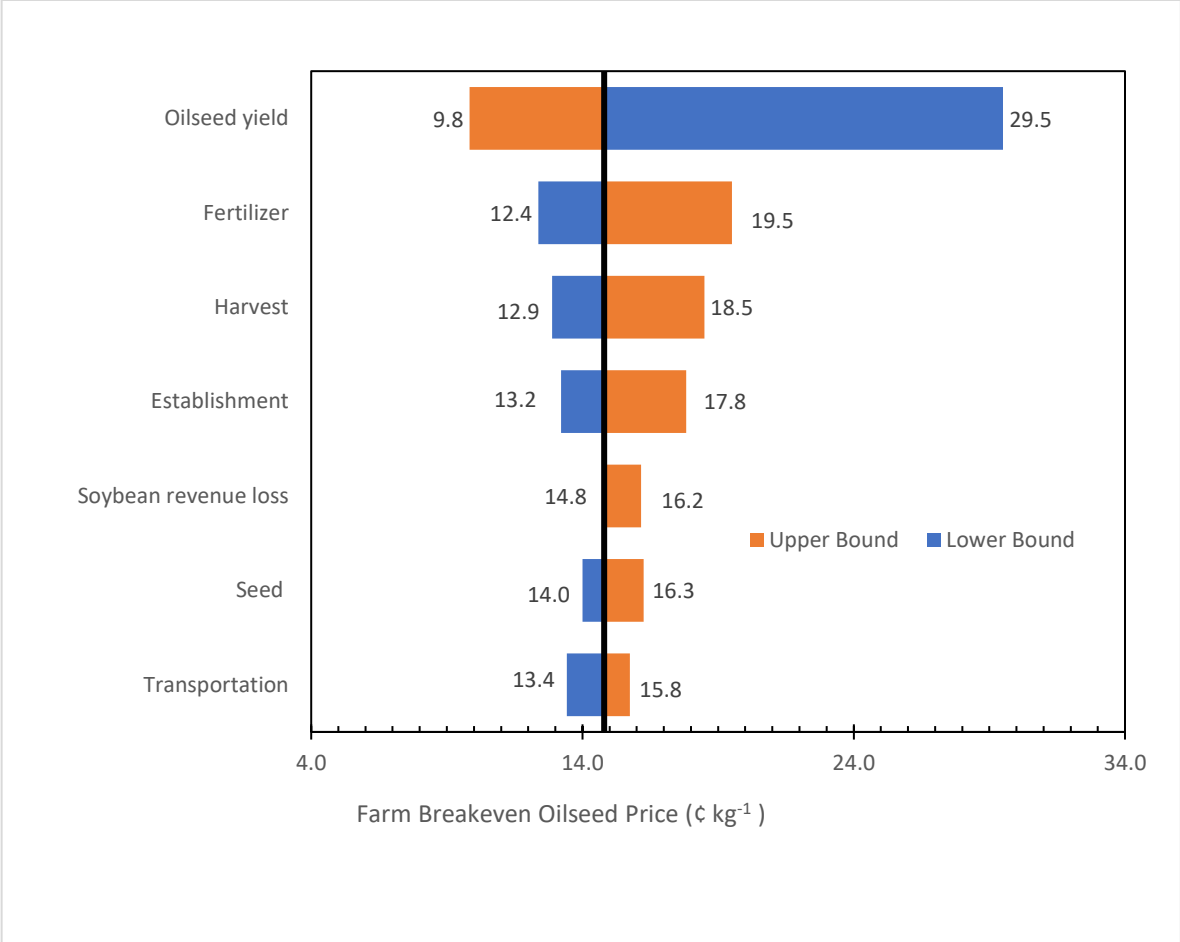

Figure 4.3. Canola no-till tornado diagram one-way sensitivity analysis of effects of no-tillage canola yields, production costs, and transportation costs on breakeven (net return=$0) oilseed prices for farmers to produce and transport oilseed feedstock from the field to the crushing facility. The upper bound represents a 150% increase from the base value, while the lower bound represents a 50% decrease from the base value for each variable while holding all other variables at their base value.

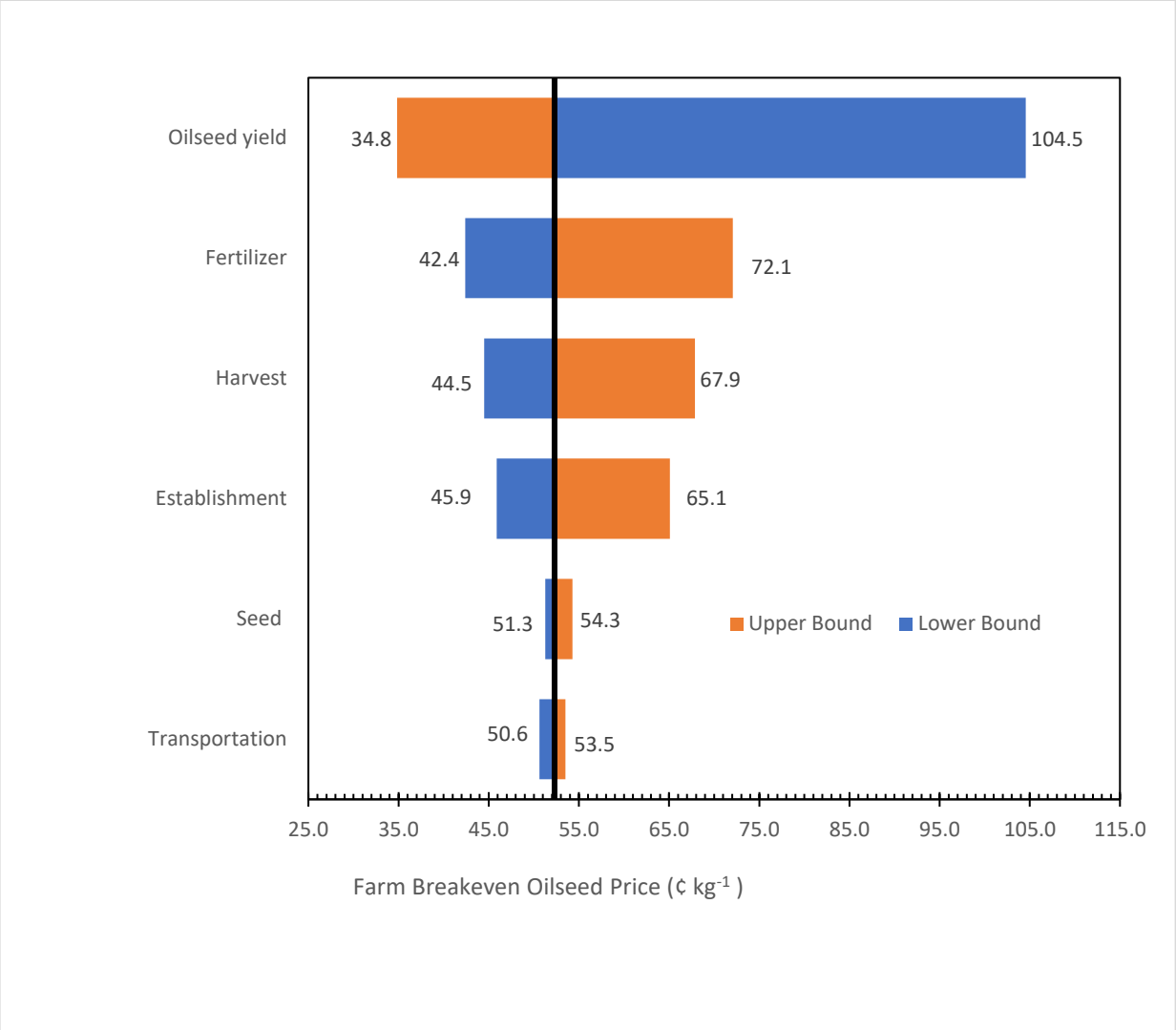

Figure 4.4. Pennycress no-till tornado diagram one-way sensitivity analysis of effects of no-tillage pennycress yields, production costs, and transportation costs on breakeven (net return=$0) oilseed prices for farmers to produce and transport oilseed feedstock from the field to the crushing facility. The upper bound represents a 150% increase from the base value, while the lower bound represents a 50% decrease from the base value for each variable while holding all other variables at their base value.

Discussion and Conclusion

The budgets developed show that average yields obtained in Tennessee and average projected oilseed prices will not be profitable for pennycress production using the practices described in the budget establishment, management, harvest, and transportation sections. Further research on best management practices for higher yield will be necessary before promoting adoption of pennycress in Tennessee. However, average canola yields obtained using the described management practices will produce roughly \$750 ha^{-1} profit for growers. For reference, average corn yields in Tennessee produce roughly \$307 ha^{-1} profit, average soybean yields produce \$207 ha^{-1}, and average yields from double cropped wheat and soybeans produce \$117 ha^{-1} profit. Canola is already a relatively established crop in Tennessee and can be promoted to growers for increased adoption.

Lower canola yields in 2022 contribute to the differing breakeven prices across years. Yields in 2021 averaged 3,922 kg ha^{-1} while yields in 2022 averaged 1,681 kg ha^{-1}. Pennycress yields on the other hand were consistent across years, averaging around 673 kg ha^{-1} in 2021 and 2022. However, plant stands varied greatly plot by plot, and likely contributed to the wide variability in breakeven prices across tillage types. Based on average yields and average breakeven prices observed in this study, canola is much more likely to be profitable for Tennessee growers who wish to produce winter oilseeds.

Pennycress has the potential to become more profitable with plant breeding efforts and further research on best management practices in the region is needed to improve yields. Equally as important to yield for profitability, many studies claim pennycress is a low input crop and stops responding to nitrogen inputs beyond 56 kg ha^{-1}. This value was far surpassed in this study, as recommended canola fertilizer rates were used. Many studies also suggest no nutrient

application is needed at all for pennycress production. If all fertilizer costs are removed from our current pennycress budget, the return above total expenses becomes -$81.87 ha^{-1} for tilled production and -$75.72 ha^{-1} for no-till production. Limiting the nutrient additions to pennycress fields can contribute to increasing the profitability of the crop in future studies along with improved yields. The creation of a large-scale market for sustainable aviation fuel in the region will improve the likelihood of crop adoption as well as increase the potential profitability of both crops.

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VITA

Brooke Keadle was born in Tacoma, Washington, then proceeded to move to Virginia, West Virginia, and North Carolina. She completed high school in North Carolina at West Rowan High School. She was very involved in the FFA, showed horses, and worked at Patterson Farm. She has always had a love of all things agriculture. After high school, she moved to Knoxville to attend the University of Tennessee, majoring in plant science with a concentration in organic production and a minor in international agriculture. She was an active member of the Zeta Tau Alpha fraternity, and she re-founded the undergraduate Plant Science Club, serving as the President for two years. She worked as a student assistant for Dr. Natalie Bumgarner throughout undergrad and was an extension summer intern in 2019 and 2020. She graduated number one in her class in the Herbert College of Agriculture in December 2020. In January 2021, she began as a Graduate Research Assistant working under Dr. Virginia Sykes. During graduate school, she was the Social Chair of the Plant Science Grad Student Association, presented at 3 Extension field days, 2 scientific conferences, and 3 departmental competitions, worked as a graduate teaching assistant, and co-authored 2 scientific publications and 13 extension publications. At the 2022 ASA/CSSA/SSSA conference in Baltimore, MD, she won first place in the biofuels oral competition. Brooke had a great time in graduate school, and to finish it out, she wrote this awesome thesis.