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Evaluation of strip tillage and precision planters in irrigated and rainfed canola production systems in southern Alberta

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Abstract

Conservation tillage practices, including no tillage (NT) and reduced tillage, are widely adopted in the Canadian prairies. However, managing crop residues in NT canola (*Brassica napus* L.) systems can be challenging. This study evaluated strip tillage (ST) and precision planting (PP) in handling crop residues and improving canola emergence, growth, and yield. ST was compared to NT and conventional tillage (CT), while PP was compared to disc hoe (DH), narrow knife, and spreader openers for their effect on crop emergence and seed yield under both irrigated and rainfed conditions. The results indicated that PP was effective in improving uniformity with increased stand establishment (13%–17%). This was particularly evident in the irrigated CT systems, where 83% of sites showed a higher plant density. However, the DH opener outperformed the PP in improving seed yield (15%) due to its narrower row spacing, regardless of soil moisture regimes. Tillage practices did not influence canola growth parameters or yield in most cases; however, when ST is combined with the DH opener, a high and stable seed yield is guaranteed. Additionally, the NT practice was particularly beneficial under rainfed conditions, improving water conservation and helping mitigate yield losses in water-limited environments. The adoption of ST provides improved moisture retention, lower energy consumption, and a reduced carbon footprint compared to CT, making it a viable option for farmers seeking to balance yield stability and environmental impact. When adopting PP, sufficient nutrient supply is necessary to compensate for the inter-plant competition and maintain yield potential.

Key words: canola, conservation tillage, strip tillage, precision planting, moisture regimes, uniformity

Introduction

Canola (*Brassica napus* L.) is a major oilseed crop in the Canadian prairies due to its low erucic acid (<2%) and low glucosinolate (<30 μg mL^{-1}) content in the seed. Because of its growing consumption and demand, canola production in the Canadian prairies has increased from 1.8 million tonnes (MT) in 1981 to 17.8 MT in 2024 (Canola Council 2024). The projected canola production in 2030 is 24.7 MT, representing a 32% increase from 2020 levels (Antony et al. 2024). To achieve this target, the average canola yield must increase by approximately 15%, while the harvested area will need to expand by 32% by 2030 (Antony et al. 2024). An increase in canola yield can be achieved by a combination of optimal agronomic management practices and appropriate genetic selection of high-yielding varieties (Chapagain and Good 2015; Assefa et al. 2018).

Higher crop emergence contributes to higher seed yield (Angadi et al. 2003), promotes earlier flowering and maturity, reduces the risk of fall frost, and decreases the occurrence of green seed (Harker et al. 2012). The rapid emergence of a uniform canola stand is crucial for enhancing crop competitiveness against weeds, thereby reducing the need for herbicide applications. Despite the availability of high-quality seeds with more than 95% germination in the laboratory conditions, seedling emergence in canola can be highly variable and low, with less than 50% of planted canola seeds emerging under field conditions (Harker et al. 2003). Harker et al. (2012) observed that under moist conditions, as seeding depth decreased from 4 to 1 cm, canola seed emergence rate improved from 37% to 62%, suggesting the importance of seed placement.

Uniform and higher seedling emergence in canola can be achieved through shallow, precise sowing and consistent germination conditions for the seeds. These conditions can be ensured by adopting appropriate tillage practices for seedbed preparation and using efficient sowing methods. Different sowing methods can influence seed placement and the conditions under which seedlings grow. Precision planters (row crop planters) are increasingly used to seed canola, particularly in regions where they have already been used for seeding corn, soybeans, dry beans, and sugar beets (Dhillon et al. 2022). Compared to conventional seeders, precision planters offer superior depth control and precise seed placement along the row, which has the potential to improve seedling emergence in terms of proportion, uniformity, and speed. Yang et al. (2014) observed a 20%–32% increase in seed yield with spatially uniform canola plant establishment compared to non-uniform stands in a study carried out in western Canada. Despite these potential advantages, there is a lack of studies evaluating the effectiveness of using precision planters for small-seeded crops like canola.

Canola requires a moist, firm seedbed free of large soil clods for optimal seedling germination and establishment. Conventional tillage (CT) practices typically provide a better seedbed for canola emergence. However, CT is often associated with increased soil degradation, reduced organic matter, and lower water retention in the surface soil layer (Khakbazan and Hamilton 2012). Additionally, CT practices lead to higher fuel, machinery, labor costs, and energy consumption (Kusek et al. 2016). As a result, there has been a significant shift among farmers in the Canadian prairies towards conservation tillage practices, including no tillage (NT) and reduced tillage, over the past five decades. Conservation tillage leaves a crop residue layer covering at least 30% of the soil surface (Reicosky and Allmaras 2003). Soils under conservation tillage tend to have higher soil organic matter content, which improves soil aggregation and enhances water-holding capacity. Cutforth et al. (2002) observed higher water use efficiency (WUE) for canola seeded directly into wheat stubble compared to CT in the semiarid Canadian prairies.

Managing previous crop residues is a key consideration for farmers adopting conservation tillage practices for canola. Excessive crop residue on the soil surface can delay soil warming, leading to reduced germination and delayed plant establishment due to low soil temperatures. Additionally, heavy surface residues can hinder seed-to-soil contact, resulting in poor root penetration (Morris et al. 2010). One way to mitigate these negative effects is by moving heavy residues away from the seed row during planting. This can be achieved through creating a residue-free strip over the seeding row, ensuring better seed-to-soil contact while conserving moisture in the inter-row areas. This technique, known as strip tillage (ST), combines the benefits of CT and NT.

Licht and Al-Kaisi (2005) found that strip-tilled soils had soil temperatures 1.2–1.4 °C higher than NT soils, contributing to an improved plant emergence rate under ST compared to NT practices. Strickland et al. (2015) showed that ST increased soil carbon by an average of 20 Mg ha^{-1} and nitrogen by 2 Mg ha^{-1} compared to CT, enhancing water-holding capacity and leading to a 189% increase in corn yield on sandy soils in the southeastern coastal plains of the United States. Due to these benefits, ST has been widely adopted, particularly for planting crops with wider row spacings, such as corn and sugar beets. However, there has been limited research on the application of ST for narrowly spaced crops like canola, primarily due to challenges in creating residue-free planting rows for such crops.

The objective of this study was to determine the effect of different tillage practices (ST, NT, and CT), and different sowing methods (precision planting (PP) vs. disc hoe (DH), narrow knife (NK) and spreader (SP) furrow openers) on canola emergence, growth, and yield in the irrigated and rainfed production systems of Alberta.

Materials and methods

Experiments were conducted at four locations in southern Alberta: Lethbridge, Bow Island, Brooks, and Stirling. The locations were under both rainfed and irrigated conditions from 2021 to 2023, with a new location established each year. Location and agronomic details are summarized in Tables 1–3.

The experimental treatments included four sowing methods: PP and three types of air drill openers, Pillar Laser disc-hoe (DH), 1 in. Barton Narrow Knife (NK), and 3 in. Barton Spreader (SP). These were combined with three tillage practices: ST, NT, and CT, with ST and CT being performed before planting. Seed bed utilization rates were 13% for PP, 25% for the SP, 16% for the DH, and 8% for the NK opener.

In 2021 and 2022, the canola cultivar used was Pioneer RR DKTF96SC. In 2023, Pioneer RR DKTF96SC was used in Lethbridge, while Pioneer LL DKLL83SC was selected for Stirling. The Liberty Link variety was chosen for Stirling to avoid potential chemical drift and crop damage, as this field location was surrounded by a Liberty Link canola crop.

A split-plot randomized complete block design was used, with tillage practices as the main plots (8 m by 16 m) and seeding methods as subplots (1.2 m by 16 m, excl. borders). A Monosem vacuum planter (Monosem Inc., Edwardsville, Kansas, USA) was utilized for PP, with a row spacing of 38.1 cm, while the DH, NK, and SP treatments used an air drill with removeable toolbar and had a row spacing of 30.5 cm, targeting a seeding rate of 60 seeds m^{-2}. The seeding depth was set at 1.3 cm. Soil samples were collected before sowing and analyzed for nutrient content (Table 1) to determine fertilizer requirements for each location. Fertilizers N, P, K, and S were supplemented based on the recommendations. Herbicides were chosen based on the weed species present and their abundance and were applied at the recommended label rates. Insecticide and fungicide were applied at the pod fill stage to control flea beetles, cabbage seed pod weevil, and Sclerotinia stem rot. Harvest aid was used at maturity. Details of the pesticides used are provided in Table A1.

Data collection

Canola plant counts were taken at both establishment and maturity to determine plant density. Stand density was initially assessed approximately 2 weeks after sowing (early-season plant density) and again at the end of the growing season through stubble counts following harvest (plant density at maturity). This involved counting plants in two side-by-side 1 m rows at two representative locations within each plot. Early- (4–5 weeks after planting) and late-season (6–8 weeks after planting) canopy cover was measured using the

Table 1. Soil properties of all sites (combination of location and year, depth 0–15.2 cm); EC and SOM represent electrical conductivity and soil organic matter, respectively.

Location	Year		Coordinate	Soil classification	Soil texture classification	Sand (%)	Clay (%)	EC (dS m^{-1})	SOM (%)	Soil pH	Soil NO_3-N (kg ha^{-1})
Lethbridge	2021	Rainfed	49°42′00.9″N 112°44′30.6″W	Orthic Dark Brown Chernozem	Clay loam	32	31	0.7	4.2	7.6	72.8
	2021	Irrigated	49°41′29.7″N 112°44′24.6″W		Sandy clay loam	54	28	0.5	3.1	7.6	17.9
	2022	Rainfed	49°41′55.8″N 112°44′19.1″W		Clay loam	32	31	0.7	4	7.6	22.4
	2022	Irrigated	49°41′30.2″N 112°44′18.8″W		Sandy clay loam	54	28	0.5	3	7.6	39.1
	2023	Rainfed	49°42′02.0″N 112°44′13.6″W		Clay loam	32	31	0.4	4.1	7.4	10.1
	2023	Irrigated	49°41′49.3″N 112°44′23.6″W		Sandy clay loam	54	28	0.3	3.1	7.5	16.8
Bow Island	2022	Rainfed	49°43′56.7″N 111°27′09.8″W	Orthic Brown Chernozem	Clay loam	40	27	0.5	2.4	6.7	20.2
	2022	Irrigated	49°43′56.7″N 111°27′09.8″W		Clay loam			0.5	2.4	6.7	20.2
Brooks	2022	Rainfed	50°32′49.3″N 111°50′46.7″W	Orthic Brown Chernozem	Loam	46	12	0.2	2	7	22.4
	2022	Irrigated	50°32′49.3″N 111°50′46.7″W					0.2	2	7	22.4
Stirling	2023	Rainfed	49°27′55.1″N 112°26′22.1″W	Orthic Dark Brown Chernozem	Clay loam*	35*	29*	0.2	3.4	7.3	16.8
	2023	Irrigated	49°27′58.0″N 112°26′27.9”W					0.2	3.4	7.3	16.8

Note: The Stirling soil texture information (∗) is based on data from AGRASID 4.1 (2025).

Table 2. Agronomic management of all sites.

Location	Year		Coordinate	Preceding crop	Tillage date	Planting date	Harvest date	Irrigation received (mm)
Lethbridge	2021	Rainfed	49°42′00.9″N 112°44′30.6″W	Durum	1 May 2021	12 May 2021	23 August 2021	
	2021	Irrigated	49°41′29.7″N 112°44′24.6″W	Durum	1 May 2021	13 May 2021	10 September 2021	190
	2022	Rainfed	49°41′55.8″N 112°44′19.1″W	Durum	19 October 2021	13 May 2022	14 September 2022	
	2022	Irrigated	49°41′30.2″N 112°44′18.8″W	Durum	19 October 2021	13 May 2022	14 September 2022	200
	2023	Rainfed	49°42′02.0″N 112°44′13.6″W	Durum	23 April 2023	11 May 2023	24 August 2023	90
	2023	Irrigated	49°41′49.3″N 112°44′23.6″W	Durum	24 April 2023	11 May 2023	30 August 2023	235
Bow Island	2022	Rainfed	49°43′56.7″N 111°27′09.8″W	Wheat	20 October 2021	24 May 2022	23 September 2022	
	2022	Irrigated	49°43′56.7″N 111°27′09.8″W	Wheat	20 October 2021	24 May 2022	23 September 2022	175
Brooks	2022	Rainfed	50°32′49.3″N 111°50′46.7″W	Fall rye	30 April 2022	13 May 2022	14 September 2022	
	2022	Irrigated	50°32′49.3″N 111°50′46.7″W	Fall rye	30 April 2022	13 May 2022	14 September 2022	100
Stirling	2023	Rainfed	49°27′55.1″N 112°26′22.1″W	Barley	27 April 2023	11 May 2023	1 September 2023	
	2023	Irrigated	49°27′58.0″N 112°26′27.9″W	Barley	27 April 2023	11 May 2023	11 September 2023	304

Table 3. Weather station and growing season weather data of all sites; GGD represents growing degree days.

Location	Year		Coordinate	Weather station	Weather station coordinate	Growing season precipitation (mm)	Growing season GGD (°C)	Average growing season temperature (°C)
Lethbridge	2021	Rainfed	49°42′00.9″N 112°44′30.6″W	IMCIN Lethbridge Demo Farm	49°41′12.1″N 112°44′41.6″W	82.7	1310.6	17.8
	2021	Irrigated	49°41′29.7″N 112°44′24.6″W			85.4	1497.9	17.6
	2022	Rainfed	49°41′55.8″N 112°44′19.1″W			238.7	1504	17.3
	2022	Irrigated	49°41′30.2″N 112°44′18.8″W			238.7	1504	17.3
	2023	Rainfed	49°42′02.0″N 112°44′13.6″W			78.9	1371.4	18.3
	2023	Irrigated	49°41′49.3″N 112°44′23.6″W			79.2	1458.2	18.3
Bow Island	2022	Rainfed	49°43′56.7″N 111°27′09.8″W	ACIS Bow Island	49°43′59.9″N 111°27′00.0″W	169.7	1620.6	18.2
	2022	Irrigated	49°43′56.7″N 111°27′09.8″W			169.7	1620.6	18.2
Brooks	2022	Rainfed	50°32′49.3″N 111°50′46.7″W	ACIS Brooks	50°32′60.0″N 111°50′60.0″W	194.7	1560.4	17.7
	2022	Irrigated	50°32′49.3″N 111°50′46.7″W			194.7	1560.4	17.7
Stirling	2023	Rainfed	49°27′55.1″N 112°26′22.1″W	IMCIN Raymond	49°29′13.6″N 112°40′31.4″W	84.2	1455.3	18.3
	2023	Irrigated	49°27′58.0″N 112°26′27.9″W			84.2	1563.4	18.1

fractional green canopy cover (FGCC) with the Canapeo Android app.

Canola seed yield was determined using a plot combine Harvest Master system. At maturity, five randomly sampled plants per plot were analyzed for yield components, including the number of branch plant^{-1}, pod plant^{-1}, seed pod^{-1}, and 1000-seed weight (TSW). The method developed by Canola Council of Canada (2020) was used to determine TSW. The oil content was measured by a FOSS Infratec 1241 Grain Analyzer (Foss Analytical, Hillerød, Denmark).

Soil moisture was measured using a neutron moisture probe (503 Elite Hydroprobe, InstroTek, Denver, Colorado, USA) to a depth of 90 cm, with readings taken at 15 (from 7.5 to 52.5 cm depth) to 20 (from 70 to 90 cm depth) cm increments from the surface. Soil temperature was recorded using Thermochron iButton temperature loggers (iButtonLink Technology, Whitewater, Wisconsin, USA) installed at a depth of 2.5 cm in each plot of one replication. The average temperature from deployment until seeding was used as the pre-seed soil temperature, while the average temperature from sowing to emergence was used as the post-seed soil temperature. Rainfall and air temperature data were obtained from nearby weather stations (Table 3).

Statistical analysis

Univariate mixed model analyses for all variables were conducted using the MIXED and GLIMMIX procedures of SAS (Littell et al. 2006; SAS Institute 2023). The replicate effect was treated as random, while site (combinations of location and year), irrigation, sowing method, and tillage practices were considered fixed effects. The irrigation and site by interaction effects are included in analysis but were not valid for interpretation because sowing method and tillage system were randomized within irrigation system at each site.

To assess residual variance, PROC GLIMMIX residual panels were used, revealing heterogeneous residual variances among sites for response variables. To address this, a preliminary PROC MIXED analysis was conducted with heterogeneous residual variances modeled to estimate starting covariance parameter values. These estimates were then utilized in a subsequent PROC GLIMMIX analysis via the PARMS statement (SAS Institute 2023). The model fit criterion, corrected Akaike's information, confirmed the benefit of modeling residual variance heterogeneity among sites. Heterogeneity was addressed using the REPEATED statement for PROC MIXED and the RANDOM statement for PROC GLIMMIX. A Gaussian error distribution was used for the PROC GLIMMIX analyses. The treatment and site by treatment effects were considered significant if the associated p-value was ≤ 0.05. Following a significant ANOVA, protected Fisher's least significant difference tests were performed.

A grouping methodology was used to explore system responses and variability of canola seed yield and oil content (Francis and Kannenberg 1978). This methodology has been employed in numerous agronomic studies (Beres et al. 2011, 2016; Turkington et al. 2016; Wang et al. 2023). The means and coefficient of variation (CV) were estimated for each treatment combination across sites and replicates. Means were plotted against CV and used to categorize the biplot data into four quadrants, which included high mean and high stability (Group I), high mean and low stability (Group II), low mean and low stability (Group III), and low mean and high stability (Group IV).

Results and discussion

Agronomic variables

In this study, PP generally improved seed germination by increasing early-season plant density. This was particularly evident in Bow Island 2022, Brooks 2022, and Stirling 2023 under irrigated conditions, as well as in Lethbridge 2021 and 2022, Brooks 2022, and Stirling 2023 under rainfed conditions (Table 4). Under irrigated conditions, PP improved canola stand establishment by 23%, 9%, and 9% compared to the DH opener, NK opener, and SP opener, respectively, across all sites. Similarly, PP improved stand establishment by 12%–25% compared to other sowing methods on rainfed sites. In terms of stand density at maturity, PP significantly improved density in half of the irrigated sites and four out of six rainfed sites (Table 4). Specifically, stand density at maturity improved by 15%–17% across irrigated sites and by 13%–16% across rainfed sites with PP compared to other sowing methods.

Sowing methods also influenced early-season FGCC at all four irrigated sites and at three out of five rainfed sites with data collected (Table 5). Under irrigated conditions, PP exhibited the highest early-season FGCC at three out of four sites, while DH showed the highest early-season FGCC at three out of five rainfed sites. Late-season FGCC was influenced by sowing methods at all sites with data collected, except Bow Island 2022. Linde et al. (2001) observed that quicker canopy closure in canola resulted in greater biomass, higher seed yield, and improved competitiveness with volunteer barley (*Hordeum vulgare* L.). Rapid emergence of a uniform canola stand is crucial for increasing crop competitiveness against weeds, which reduces the need for herbicide application. Moreover, suppressing weed growth is essential for reducing the replenishment of the weed seedbank, with implications for subsequent growing seasons (Martin et al. 2001). The highest late-season FGCC resulted from PP at four out of six irrigated sites and at three out of five rainfed sites.

The superior performance of PP in this study can be attributed to its ability to provide consistent seed placement at specific intervals along the seed row, enhanced depth control, and better seed-to-soil contact compared to other sowing methods. These attributes directly contributed to improved stand establishment.

Similar findings were reported by Dhillon et al. (2022), who compared PP to air seeders for canola production under NT practices. The uniform plant distribution achieved through PP optimizes the use of resources such as sunlight, water, and nutrients, leading to improved growth and yield. In a study by Yang et al. (2014), uniform plant establishment through PP resulted in a 20%–32% increase in seed yield compared to non-uniform stands, primarily due to an increased number of fertile pods. Angadi et al. (2003) also observed that canola's ability to adapt and compensate for poor crop establishment was lower in non-uniform stands. Moreover, uniformly distributed stands can promote rapid crop growth, enabling quicker canopy closure compared to other sowing methods. In this study, PP led to faster canopy closure than other sowing methods. Other research has shown that uniform plant distribution is essential for yield stability (Diepenbrock 2000).

Regarding tillage practices, no significant differences in early-season plant density were observed among ST, CT, and NT practices, except at Bow Island 2022 (Table 4). Stand density at maturity varied across sites, with significant differences observed at Lethbridge 2021 and 2022 rainfed sites. Tillage practices influenced early-season FGCC at two out of five irrigated sites and one out of five rainfed sites (Table 5). CT exhibited the highest early-season FGCC at Lethbridge 2021 irrigated and rainfed sites, while NT resulted in the highest early-season FGCC at the Stirling 2023 irrigated site. Late-season FGCC was affected by tillage practices at four out of six irrigated sites and two out of five rainfed sites. The highest late-season FGCC was produced by NT at the Brooks 2022 and Stirling 2023 irrigated sites, and at Brooks 2022 and Stirling 2023 rainfed sites, while CT resulted in the highest late-season FGCC at Lethbridge 2021 and Bow Island 2022 irrigated sites. Jaskulska et al. (2018) found that during a year with significant rainfall shortages at seeding, ST resulted in considerably higher plant density compared to CT practices. However, ST did not outperform CT or NT in either irrigated or rainfed environments in this study. Under irrigated conditions, PP consistently produced the highest early-season plant density and late-season plant stand across ST, CT, and NT tillage systems.

The use of PP outperformed DH opener, NK opener, and SP opener. This advantage was most evident in the CT system, where early-season plant density and late-season plant stand were significantly higher than 10 out of 12 and 8 out of 12 sowing method by tillage system combinations, respectively (Table 7). In contrast, DH opener consistently resulted in the lowest early-season plant density across all three tillage systems. A similar trend was observed under rainfed conditions (Table 7). PP again led to the highest early-season plant density and late-season plant stand across all tillage systems. Specifically, PP in the CT system outperformed 6 out of 12 sowing method and tillage system combinations for early-season plant density, while PP in the ST system resulted in a significantly higher late-season plant stand than 7 out of 12 combinations.

Seed yield

Overall, the sowing method altered canola yield in both irrigated and rainfed conditions (Table 6). Despite being effective in growth performance, PP did not increase canola yield compared to other sowing methods. Under irrigated conditions, the DH, NK, and SP openers produced 15%, 7%, and 8% higher yields than PP, respectively (Table 6). The SP opener yielded the highest seed yield among all sowing methods at Lethbridge 2021. In contrast, at Brooks 2022, PP, and DH outperformed the NK and SP openers, while PP yielded

Table 4. Early-season and at maturity plant density responses to sowing method and tillage practice.

	Irrigated							Rainfed						
	LB21	LB22	BI22	BR22	LB23	STL23	All site	LB21	LB22	BI22	BR22	LB23	STL23	All site
Early-season plant density														
PP	45.4b	30.0	45.1a	16.6a	41.9	33.1a	35.3a	47.6a	35.2a	44.1	20.2a	37.7ab	12.4a	32.9a
DH	42.8b	33.2	32.4b	7.2b	35.4	21.3b	28.7c	34.6b	30.9ab	39.0	10.9b	43.7a	10.0a	28.2bc
NK	52.1a	32.3	39.2ab	6.3b	39.2	24.5b	32.3b	43.3a	29.9b	35.0	8.9b	32.1b	9.4a	26.4c
SP	47.8ab	33.8	41.1a	5.9b	40.3	24.7b	32.3b	49.9a	35.5a	39.1	7.7b	37.3ab	6.0b	29.3b
$\text{LSD}_{0.05}$	6.7	ns	7.0	3.9	ns	4.1	2.3	6.7	5.0	ns	3.9	6.7	4.1	2.3
p-value	**0.048***	0.441	**0.006****	**<0.001*****	0.273	**<0.001*****	**<0.001*****	**<0.001*****	**0.051***	0.093	**<0.001*****	**0.011****	**0.028***	**<0.001*****
ST	47.0	32.5	37.2b	7.7	38.6	28.0	31.8	38.9	34.0	37.5	11.6	40.1	9.0	28.5
CT	47.7	32.3	45.2a	8.8	39.9	25.6	33.2	47.5	31.2	40.6	13.1	35.5	8.0	29.3
NT	46.4	32.1	36.0b	10.5	39.1	24.2	31.4	45.1	33.5	39.8	11.0	37.6	11.3	29.7
$\text{LSD}_{0.05}$	ns	ns	6.3	ns	ns	ns	ns	6.0	ns	ns	ns	ns	ns	ns
p-value	0.910	0.986	**0.009****	0.309	0.905	0.154	0.196	0.017	0.443	0.609	0.502	0.311	0.234	0.531
At maturity plant density														
PP	40.0	37.9	38.1	15.2a	39.5a	31.3a	33.7a	36.7ab	43.3a	26.7b	19.5a	41.4	18.4a	31.0a
DH	38.8	32.9	39.8	8.6b	33.6b	19.8b	28.9b	27.5c	35.0b	35.7a	10.9b	38.5	13.0b	26.8b
NK	44.8	31.7	36.1	7.4b	29.7b	23.6b	28.9b	32.7bc	34.0b	34.4a	10.3b	34.9	18.2a	27.4b
SP	39.4	32.9	38.8	9.0b	31.0b	23.8b	29.2b	38.7a	34.6b	32.1ab	9.2b	37.6	12.3b	27.4b
$\text{LSD}_{0.05}$	ns	ns	ns	2.9	5.1	4.1	2.1	5.7	6.1	6.5	2.9	ns	4.1	2.1
p-value	0.147	0.190	0.715	**<0.001*****	**0.001*****	**<0.001*****	**<0.001*****	**0.001*****	**0.009****	**0.038***	**<0.001*****	0.084	**0.003****	**<0.001*****
ST	42.8	36.1	34.9	9.4	34.4	25.5	30.5	30.7b	38.2a	30.9	11.0	41.2	15.3	27.9
CT	39.6	31.4	39.1	9.2	34.3	23.9	29.6	38.0a	32.5b	33.2	12.8	37.0	15.8	28.2
NT	39.9	34.2	40.6	11.6	31.6	24.5	30.4	33.0ab	39.5a	32.6	13.5	36.1	15.3	28.3
$\text{LSD}_{0.05}$	ns	ns	ns	ns	ns	ns	ns	6.0	4.6	ns	ns	ns	ns	ns
p-value	0.381	0.212	0.116	0.105	0.367	0.656	0.562	**0.013****	**0.023***	0.695	0.128	0.056	0.938	0.866

Note: LB, BI, BR, and STL represent Lethbridge, Bow Island, Brooks, and Stirling, respectively. LSD = least significant difference. ns = not significant. *, **, and *** denote significance at $p \leq 0.05$, 0.01, and 0.001, respectively. PP, DH, NK, and SP represent precision planter, disc hoe opener, narrow knife, and spreader opener, respectively. ST, CT, and NT represent strip tillage, conventional tillage, and no tillage, respectively.

Table 5. Fractional green canopy cover (FGCC) responses to sowing method and tillage practice.

	Irrigated							Rainfed						
	LB21	LB22	BI22	BR22	LB23	STL23	All site	LB21	LB22	BI22	BR22	LB23	STL23	All site
							Early-season FGCC							
PP	13.42b	8.38a	NA	NA	33.09a	34.67a	NA	7.69b	14.75a	9.16b	NA	23.30	5.50	12.08
DH	12.71b	6.75ab	NA	NA	24.23b	25.62b	NA	6.81b	11.91bc	12.16a	NA	26.27	5.67	12.56
NK	17.02a	6.02b	NA	NA	15.99c	20.17c	NA	10.93a	9.84c	11.97a	NA	24.62	2.42	11.96
SP	18.54a	4.82b	NA	NA	9.79d	15.21d	NA	13.18a	12.49b	11.66a	NA	24.38	3.17	12.98
LSD$_{0.05}$	2.88	2.10	NA	NA	3.92	3.65	NA	2.88	2.10	1.99	NA	ns	ns	ns
p-value	**<0.001*****	**0.011****	NA	NA	**<0.001*****	**<0.001*****	NA	**<0.001*****	**<0.001*****	**0.013****	NA	0.510	0.196	0.411
ST	14.36b	6.77	NA	NA	22.74	25.22b	NA	6.50b	13.37	11.42	NA	25.99	3.50	12.16
CT	18.46a	5.54	NA	NA	21.24	17.21c	NA	13.03a	10.11	11.99	NA	23.30	3.00	12.29
NT	13.45b	7.16	NA	NA	18.34	29.31a	NA	9.44b	13.27	10.31	NA	24.64	6.06	12.74
LSD$_{0.05}$	3.45	ns	NA	NA	ns	3.95	NA	3.45	ns	ns	NA	ns	ns	ns
p-value	**0.012****	0.536	NA	NA	0.104	**<0.001*****	NA	**0.002****	0.060	0.511	NA	0.436	0.259	0.738
							Late-season FGCC							
PP	50.8c	22.0a	44.1	61.7a	75.9a	86.8a	56.9a	25.9b	32.3a	NA	48.6a	63.7b	25.4a	NA
DH	64.7b	20.6ab	42.1	42.1b	73.9a	70.5b	52.3b	31.9a	26.8b	NA	40.3b	72.3a	24.7a	NA
NK	69.3ab	14.1c	37.9	27.3c	65.6b	71.9b	47.7c	36.6a	22.5c	NA	32.9c	69.4ab	12.9b	NA
SP	70.9a	17.6bc	34.9	22.0c	58.4c	67.1b	45.1d	36.5a	24.7bc	NA	29.4c	75.3a	14.3b	NA
LSD$_{0.05}$	5.6	4.0	ns	6.4	6.4	6.8	2.5	5.6	4.0	NA	6.4	6.4	6.8	NA
p-value	**<0.001*****	**<0.001*****	0.071	**<0.001*****	**<0.001*****	**<0.001*****	**<0.001*****	**<0.001*****	**<0.001*****	NA	**<0.001*****	**0.004****	**<0.001*****	NA
ST	62.3b	18.9	37.0	34.1b	71.3	78.9a	50.4	30.9	27.2	NA	33.0b	71.9	19.3ab	NA
CT	69.8a	20.7	46.4	37.9ab	68.3	64.1b	51.2	35.8	25.0	NA	40.2a	70.0	14.6b	NA
NT	59.7b	16.0	35.7	42.9a	65.9	79.2a	49.9	31.6	27.5	NA	40.3a	68.6	24.1a	NA
LSD$_{0.05}$	5.7	ns	7.1	6.3	ns	6.7	ns	ns	ns	NA	6.3	ns	6.7	NA
p-value	**0.002****	0.143	**0.007****	**0.027***	0.245	**<0.001*****	0.696	0.191	0.505	NA	**0.037***	0.569	**0.021***	NA

Note: LB, BI, BR, and STL represent Lethbridge, Bow Island, Brooks, and Stirling, respectively. LSD = least significant difference. ns = not significant. *, **, and *** denote significance at $p \le 0.05$, 0.01, and 0.001, respectively. PP, DH, NK, and SP represent precision planter, disc hoe opener, narrow knife, and spreader opener, respectively. ST, CT, and NT represent strip tillage, conventional tillage, and no tillage, respectively. NA = not available.

Table 6. Seed yield and oil content response to sowing method and tillage practice.

	Irrigated							Rainfed						
	LB21	LB22	BI22	BR22	LB23	STL23	All site	LB21	LB22	BI22	BR22	LB23	STL23	All site
Seed yield (Mg ha^{-1})														
PP	3.07c	3.35	1.42	3.18a	4.13b	7.30c	3.74c	0.40	2.41a	0.42b	1.85b	1.87c	1.04b	1.33b
DH	4.18b	3.53	1.48	3.12a	5.45a	8.11a	4.31a	0.50	2.25ab	0.69a	2.09a	3.06a	1.34a	1.65a
NK	4.28b	3.18	1.41	2.03b	5.33a	7.78b	4.00b	0.51	1.94b	0.65a	1.75b	2.33b	0.99b	1.36b
SP	4.56a	3.26	1.39	1.89b	5.27a	7.89b	4.04b	0.55	2.29a	0.61a	1.71b	2.25bc	1.01b	1.40b
$LSD_{0.05}$	0.14	ns	ns	0.17	0.41	0.17	0.10	ns	0.31	0.09	0.17	0.41	0.17	0.10
p-value	**<0.001*****	0.142	0.331	**<0.001*****	**<0.001*****	**<0.001*****	**<0.001*****	0.147	**0.024***	**<0.001*****	**<0.001*****	**<0.001*****	**<0.001*****	**<0.001*****
ST	3.91b	3.30	1.41	2.52	4.91b	7.78b	3.97	0.45	2.19	0.62	1.88	2.33	1.03b	1.42b
CT	4.23a	3.50	1.53	2.42	5.35a	7.30c	4.05	0.42	2.19	0.66	1.80	2.26	0.84b	1.36b
NT	3.93b	3.19	1.34	2.73	4.87b	8.23a	4.05	0.61	2.28	0.51	1.88	2.54	1.41a	1.54a
$LSD_{0.05}$	0.25	ns	ns	ns	0.41	0.26	ns	ns	ns	ns	ns	ns	0.26	0.12
p-value	**0.021***	0.183	0.237	0.062	**0.041***	**<0.001*****	0.327	0.275	0.817	0.421	0.777	0.366	**<0.001*****	**0.014****
Oil content (%)														
PP	45.3b	47.6	41.1	45.7a	48.1	48.8	46.1a	38.7b	48.0	38.1	46.9	46.4	43.6	43.6b
DH	46.1a	47.4	40.9	44.5b	48.1	48.4	45.9b	39.2ab	47.4	39.3	46.6	46.4	44.4	43.9a
NK	46.1a	47.3	40.7	43.0c	47.6	48.5	45.5c	38.6b	47.1	38.8	45.5	46.5	43.5	43.3c
SP	46.0a	47.3	40.8	42.6c	47.5	48.4	45.4c	39.2a	47.4	38.9	44.7	46.0	43.5	43.3c
$LSD_{0.05}$	0.5	ns	ns	0.9	ns	ns	0.2	0.5	ns	ns	ns	ns	ns	0.2
p-value	**0.002****	0.217	0.788	**<0.001*****	0.076	0.312	**<0.001*****	**0.007****	0.790	0.131	0.798	0.932	0.199	**<0.001*****
ST	45.9	47.3	41.1	43.8	47.9	48.5	45.7	38.9	47.5	39.4a	46.1	46.5a	43.6b	43.7
CT	45.7	47.6	40.8	43.9	47.9	48.5	45.7	38.8	47.6	39.0a	46.1	45.7b	43.4b	43.4
NT	46.1	47.2	40.8	44.2	47.8	48.5	45.8	39.1	47.3	38.0b	45.6	46.8a	44.3a	43.5
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.7	ns	0.6	0.6	ns
p-value	0.344	0.308	0.674	0.588	0.979	0.965	0.911	0.518	0.466	**<0.001*****	0.373	**0.004****	**0.009****	0.166

Note: LB, BI, BR, and STL represent Lethbridge, Bow Island, Brooks, and Stirling, respectively. LSD = least significant difference. ns = not significant. *, **, and *** denote significance at $p \leq 0.05$, 0.01, and 0.001, respectively. PP, DH, NK, and SP represent precision planter, disc hoe opener, narrow knife, and spreader opener, respectively. ST, CT, and NT represent strip tillage, conventional tillage, and no tillage, respectively.

significantly lower than all other methods in Lethbridge 2023. At Stirling 2023, DH produced the highest seed yield.

Under rainfed conditions, the DH opener consistently outperformed other methods, improving yield by 18%–24% compared to the other sowing methods (Table 6). Specifically, DH produced the highest seed yield at Bow Island 2022, Brooks 2022, Lethbridge 2023, and Stirling 2023. In Bow Island 2022, NK and SP openers yielded similarly to DH. In Lethbridge 2022, PP produced the highest seed yield, while DH and SP yielded comparable amounts to PP. The inferior yield with PP in both irrigated and rainfed conditions may be attributed to its wider row spacing (38.1 cm), which increases inter-plant competition and reduces seed yield, as reported by Lithourgidis et al. (2011) and Yang et al. (2014). Previous studies have also suggested that PP is less effective than air seeding under water-limited conditions (Dhillon et al. 2022). In contrast, disc openers are designed to handle more residue by cutting through it at an angle, minimizing the effects on seed emergence (Swanepoel et al. 2019). Tessier et al. (1991) also reported that disc openers cause less superficial soil disturbance, which helps preserve soil structure and biological activity, ultimately supporting better yield. Therefore, the DH opener resulted in a higher yield relative to the PP. To offset inter-plant competition and sustain canola's yield potential, it is essential to ensure appropriate seeding rate and an adequate nutrient supply at sowing time when using a PP. In retrospect, our results could suggest that a lower seeding rate might have benefitted yield in PP systems, but our aim at the start of the project was to test the same seeding rate as the other seeding systems. The grower would need to adjust the vacuum meters to ensure proper seed singulation, preventing skips and doubles.

Tillage method generally had no significant impact on canola yield under irrigated conditions, although some variations were observed (Table 6). Under irrigated conditions, CT provided the highest seed yield at Lethbridge 2021 and 2023, while NT produced the best yields at Stirling 2023. Some studies have shown that CT can improve yield, but it is often associated with soil degradation and lower organic matter and water content in the surface soil layer (Khakbazan and Hamilton 2012). Under rainfed conditions, significant seed yield differences were only observed at Stirling 2023, although NT produced numerically higher yields than ST and CT at Lethbridge 2021, 2022, and 2023. Reduced tillage is known to conserve soil moisture and reduce surface runoff and soil loss and ST is offering a promising anti-erosion benefit compared to intensive tillage (Laufer et al. 2016). The lack of significant yield differences among tillage practices suggests that farmers can adopt ST without sacrificing yield. This is supported by Rogalsky et al. (2024), who found no yield difference between ST and CT in corn, as both practices resulted in similar soil disturbance near the seed row. Kusek et al. (2016) also noted that CT is often associated with higher costs for fuel, machinery, labor, and energy consumption. In contrast, ST demonstrated higher seeding efficiency and 54% and 80% lower energy consumption than shallow and deep rotary tillage, respectively (Li et al. 2024), making it a more sustainable option with a lower carbon footprint. When canola was planted using a DH opener, significantly higher seed yields were observed in both the CT and NT systems compared to 9 out of 12 sowing method and tillage system combinations in an irrigated environment (Table 7). Similarly, in the ST system, the DH opener resulted in significantly higher yields than 7 out of 12 sowing method and tillage system combinations. In the rainfed environment, DH in the NT system produced significantly higher yields than all other sowing method and tillage system combinations (Table 7).

The yield mean–CV biplot indicated that DH combined with all three tillage practices and NK combined with CT produced higher than average and stable seed yield under irrigated conditions (Fig. 1). The combination of NT with SP opener also yielded higher-than-average seed yields but with lower stability. All other sowing method and tillage system combinations provided lower-than-average yields. Under rainfed conditions, DH combined with CT and NK combined with NT resulted in higher-than-average and stable yields (Fig. 1). Other combinations, such as DH with NT and ST, SP opener with ST, and PP with NT, also produced higher-than-average yields but with low stability. These results suggest that when DH is used in CT high and stable seed yield is warranted under either irrigated or rainfed conditions. In rainfed conditions CT does have a lower yield compared to the other tillage practices combined with DH and some of the variability in rainfed systems could come from higher crop performance during high rainfall years. The additional risk of much higher wind erosion comes with CT so overall it cannot be recommended. Although ST alone did not perform as well as other practices, it yielded better than 11 out of 16 sowing and tillage combinations when paired with DH. This is because ST kept residue in the field, but less residue was left in seed row. The soil temperature in the seed row could be improved at the early stage, which benefited seed germination. Due to these reasons, there has been a significant shift of farmers in the Canadian prairies from CT practices to NT and reduced tillage in the last five decades.

When soil moisture is a limit factor, the uncovered seed row accelerated soil moisture loses, like that in the CT scenario. The abiotic stress had a negative effect on canola development and then resulted in low seed yield. Crop residues help reduce soil water evaporation by covering the surface, creating a favorable microclimate for water conservation and crop emergence by dampening wind speed and reducing solar radiation (Horton et al. 1996; Klocke et al. 2009). For example, Klocke et al. (2009) found that covering the soil with corn stover and wheat stubble reduced evaporation by nearly 50% compared to bare soil.

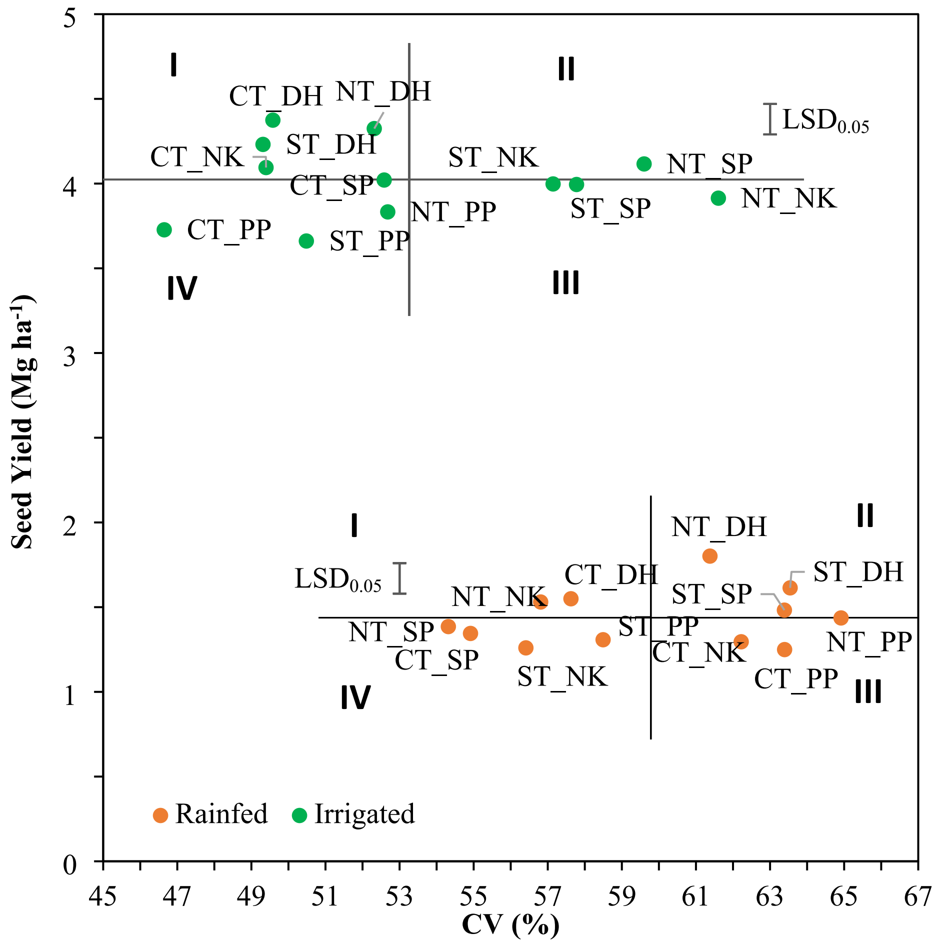
However, excess residues can delay soil warming and hinder seedling emergence, particularly in regions like the Canadian prairies, where cold and wet soil conditions are common. Delayed plant establishment is particularly detrimental in these areas due to the short growing season, leaving crops with insufficient time to adapt and compensate for poor establishment. Improved soil water conservation and WUE are critical in semiarid regions where moisture deficits typically increase as the season progresses. When ST combined with DH, wet and cold soil conditions owing to surface residue are mitigated and seed row soil temperature is enhanced. Under rainfed conditions, three NT-based sowing method and tillage

Table 7. Canola seed yield, oil content, and seed yield components response to the interaction of sowing method and tillage practice.

	Irrigated						Rainfed					
	Yield (Mg ha^{-1})	Oil content (%)	Early-season plant density (plants m^{-2})	Late-season plant density (plants m^{-2})	Branch plant^{-1}	Seed pod^{-1}	Yield (Mg ha^{-1})	Oil content (%)	Early-season plant density (plants m^{-2})	Late-season plant density (plants m^{-2})	Branch plant^{-1}	Seed pod^{-1}
ST												
PP	3.66f	46.0ab	34.7ab	32.4ab	5.05abcd	24.5a	1.31def	43.7abcd	32.0ab	31.2a	5.00	23.6
DH	4.23ab	45.9abc	28.3de	30.4bcd	4.94bcd	25.3a	1.61b	44.0a	26.5 cd	26.8c	4.81	22.8
NK	4.00 cd	45.7bcd	31.2bcde	29.5bcde	4.99bcd	25.7a	1.26ef	43.2efg	27.7 cd	25.9c	4.70	22.3
SP	3.99 cd	45.4d	33.2bc	29.7bcde	5.05abcd	23.8ab	1.48bcd	43.8abc	28.0bcd	27.5bc	5.01	23.2
CT												
PP	3.73ef	46.1ab	37.9a	34.3a	4.86 cd	24.9a	1.25f	43.6bcde	33.4a	31.1ab	4.64	22.8
DH	4.37a	45.7bcd	30.6cde	29.3bcde	5.30abc	25.3a	1.55bc	43.7abcd	29.6abc	26.0c	4.84	23.5
NK	4.09bc	45.5 cd	32.5bc	28.4cde	5.47a	23.7ab	1.30ef	43.3defg	24.0d	27.1c	5.32	21.7
SP	4.02c	45.4d	32.0bcd	26.4e	5.04abcd	24.4a	1.34def	43.1fg	30.3abc	28.8abc	4.73	22.8
NT												
PP	3.83def	46.2a	33.5bc	34.3a	5.00bcd	23.7ab	1.44bcde	43.5bcdef	33.2a	30.7ab	4.87	22.6
DH	4.32a	46.0ab	27.3e	27.1de	5.37ab	25.6a	1.80a	43.9ab	28.5bc	27.5bc	5.03	23.9
NK	3.91 cd	45.4d	33.1bc	28.8bcde	5.14abc	24.1ab	1.53bc	43.5bcdef	27.7 cd	29.3abc	5.12	23.1
SP	4.12bc	45.4d	31.7bcd	31.4abc	4.67d	22.2b	1.39cdef	43.0 g	29.5abc	25.8c	5.06	22.4
p-values	**<0.001*****	**<0.001*****	**<0.001*****	**<0.001*****	**0.050***	**0.026***	**<0.001*****	**<0.001*****	**<0.001*****	**0.007****	0.145	0.721
LSD$_{0.05}$	0.18	0.44	4.03	3.65	0.46	1.99	0.18	0.44	4.03	3.65	ns	ns

Note: ST, CT, and NT represent strip tillage, conventional tillage, and no tillage, respectively. PP, DH, NK, and SP represent precision planter, disc hoe opener, narrow knife, and spreader opener, respectively. LSD = least significant difference. ns = not significant. *, **, and *** denote significance at $p \leq 0.05$, 0.01, and 0.001, respectively.

Fig. 1. Mean–coefficient of variation (CV) biplot shows seed yield response to sowing method and tillage practice. PP, DH, NK, and SP represent precision planter, disc hoe opener, narrow knife, and spreader opener, respectively. ST, CT, and NT represent strip tillage, conventional tillage, and no tillage, respectively. Group I: high mean and high stability; Group II: high mean and low stability; Group III: low mean and low stability; Group IV: low mean and high stability. LSD, least significant difference.



practice combinations produced higher than average yields and one resulted in close to average seed yield, indicating NT is a crucial tillage method under rainfed conditions.

Seed oil content

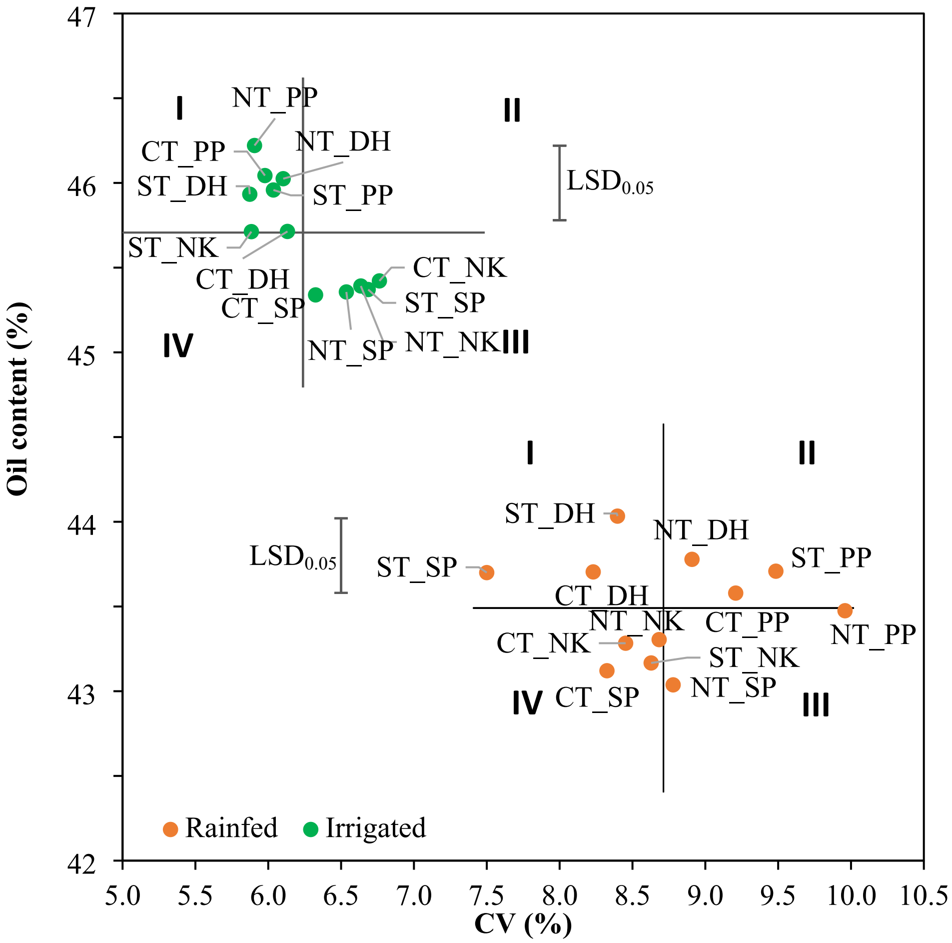
Oil content in canola was influenced by sowing methods, particularly in Lethbridge 2021 and Brooks 2022 under irrigated conditions, as well as in Lethbridge 2021 under rainfed conditions (Table 6). Similar to seed yield, the tillage method did not alter oil content, except in Bow Island 2022, Lethbridge 2023, and Stirling 2023 under rainfed conditions. The highest oil content was observed with PP in the NT system under irrigated conditions (Table 7). The PP in the ST and CT systems, as well as the DH opener in the ST and NT systems, produced oil content comparable to that of the PP in the NT system. In rainfed environments, the DH opener in the ST system resulted in the highest oil content, while the PP and SP in the ST system, PP and DH in the CT system, and DH in the NT system all produced oil content comparable to that of the DH in the ST system (Table 7).

Under irrigated conditions, both the PP and DH combined with all three tillage practices resulted in higher-than-average and stable oil content (Fig. 2). Additionally, the NK opener combined with ST also produced high and stable oil content. In contrast, all other sowing method and tillage practice combinations resulted in lower and more unstable oil content.

Under rainfed environments, DH combined with ST and CT, as well as SP combined with ST, provided high and stable oil content (Fig. 2). Additionally, DH combined with NT and PP combined with either ST or CT also produced high oil content, though with lower stability. All other sowing method and tillage practice combinations resulted in below-average oil content.

Overall, the DH opener combined with either ST or NT resulted in both higher and more stable seed yield and oil content under irrigated conditions (Figs. 1 and 2). In contrast, DH combined with CT produced high and stable seed yield and oil content under rainfed conditions. This suggests that the DH opener performed better than the other sowing methods regardless of soil moisture regimes. In terms of tillage

Fig. 2. Mean–coefficient of variation (CV) biplot shows oil content response to sowing method and tillage practice. PP, DH, NK, and SP represent precision planter, disc hoe opener, narrow knife, and spreader opener, respectively. ST, CT, and NT represent strip tillage, conventional tillage, and no tillage, respectively. Group I: high mean and high stability; Group II: high mean and low stability; Group III: low mean and low stability; Group IV: low mean and high stability. LSD, least significant difference.



practices, ST and NT outperformed CT in maintaining oil content when the abiotic stress is absent. Conversely, when soil moisture is a not a limiting factor, CT could benefit canola growth. Previous studies have indicated that CT enhances water retention in deeper soil layers compared to minimum tillage under rainfed environments (Bonari et al. 1995), which may explain its effectiveness under moisture-limited conditions in this study.

Yield components

In general, sowing methods did not affect TSW under either irrigated or rainfed conditions. However, differences in TSW were observed at specific sites (Table 8): Brooks 2022 and Stirling 2023 under irrigated conditions, and Brooks 2022 and Lethbridge 2023 under rainfed conditions. In Brooks 2022, the PP resulted in the highest TSW under both irrigated and rainfed conditions. In contrast, the DH produced the highest TSW at Stirling 2023 under irrigated conditions and at Lethbridge 2023 under rainfed conditions.

Under irrigated conditions, sowing method affected the branch plant^{-1} and the seed pod^{-1} (Tables 7 and 8). Canola planted with the SP opener exhibited the lowest number of branch plant^{-1} and seed pod^{-1}. Under rainfed conditions, the PP resulted in the fewest pod plant^{-1}. This affirmed the high inter-plant competition for canola plant sown by the PP.

Tillage practices influenced TSW at irrigated sites, particularly at Bow Island 2022 and Stirling 2023, but had no effect at rainfed sites (Table 8). Furthermore, tillage practices did not affect branch plant^{-1}, pod plant^{-1} (except Lethbridge 2022 irrigated site), or seed pod^{-1} at any of the sites. Previous studies have reported higher branch numbers, greater main shoot length, and higher TSW in CT systems compared to NT systems (Gawęda and Haliniarz 2022). These differences were attributed to lower weed pressure and improved soil conditions, in CT systems, which enhanced root and shoot growth (Kaur et al. 2023).

The lack of significant differences in yield components among tillage practices in this study could be due to the absence of distinct soil moisture differences between treatments (Fig. 3). While other research has suggested that tillage can improve yield components by alleviating soil compaction and promoting deeper root growth (Seepaul et al. 2023), no

Table 8. Canola seed yield components response to sowing method and tillage practice.

	Irrigated							Rainfed						
	LB21	LB22	BI22	BR22	LB23	STL23	All site	LB21	LB22	BI22	BR22	LB23	STL23	All site
TSW														
PP	3.62	3.34	4.54	3.38a	3.66	4.62b	3.86	3.15	2.95	4.73	3.85a	3.05c	3.03	3.46
DH	3.69	3.34	4.52	3.12b	3.61	4.92a	3.87	3.13	2.83	4.84	3.60b	3.29a	2.98	3.45
NK	3.65	3.40	4.94	3.07b	3.59	4.73b	3.90	3.21	2.81	4.48	3.80a	3.18ab	2.95	3.40
SP	3.71	3.28	4.63	3.07b	3.48	4.65b	3.80	3.20	2.88	4.68	3.55b	3.14bc	2.93	3.40
LSD$_{0.05}$	ns	ns	ns	0.19	ns	0.13	ns	ns	ns	ns 1	0.20	0.15	ns	ns
p-value	0.512	0.606	0.489	**0.003****	0.087	**<0.001*****	0.427	0.484	0.317	0.702	**0.008****	**0.014****	0.457	0.639
ST	3.64	3.39	4.36b	3.18	3.56	4.78a	3.82b	3.08	2.87	4.61	3.63	3.16	2.96	3.39
CT	3.71	3.24	4.51b	3.09	3.67	4.61b	3.80b	3.25	2.83	4.88	3.68	3.18	2.90	3.45
NT	3.65	3.39	5.10a	3.21	3.53	4.80a	3.95a	3.18	2.90	4.55	3.79	3.16	3.06	3.44
LSD$_{0.05}$	ns	ns	0.54	ns	ns	0.15	0.11	ns	ns	ns	ns	ns	ns	ns
p-value	0.540	0.158	**0.017****	0.440	0.164	**0.022***	**0.019****	0.067	0.712	0.430	0.304	0.971	0.106	0.430
Branch plant^{-1}														
PP	6.12	4.72	4.72	5.03b	4.48	4.75	4.97ab	5.48a	4.10	4.55	5.08	4.72	5.07	4.83
DH	5.79	4.70	4.43	6.15a	5.27	4.87	5.20a	4.78b	4.72	4.97	5.00	5.25	4.63	4.89
NK	5.72	4.45	4.63	6.25a	5.28	4.87	5.20a	4.56b	4.47	5.10	5.60	5.30	5.25	5.05
SP	5.67	4.18	4.57	5.55ab	4.80	4.75	4.92b	4.51b	4.30	4.95	5.17	5.22	5.45	4.93
LSD$_{0.05}$	ns	ns	ns	0.76	ns	ns	0.26	0.60	ns	ns	ns	ns	ns	ns
p-value	0.454	0.111	0.802	**0.006****	0.071	0.973	**0.055***	**0.007****	0.090	0.277	0.410	0.318	0.114	0.429
ST	5.81	4.40	4.51	5.80	4.80	4.73	5.01	4.74	4.35	4.83	4.89	5.31	5.15	4.88
CT	5.59	4.81	4.55	6.08	5.08	4.90	5.17	4.76	4.45	4.80	5.35	5.21	4.73	4.88
NT	6.08	4.33	4.70	5.36	5.00	4.80	5.04	5.01	4.39	5.05	5.40	4.84	5.43	5.02
LSD$_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
p-value	0.235	0.093	0.768	0.121	0.675	0.855	0.391	0.563	0.912	0.603	0.294	0.299	0.087	0.426
Pod plant^{-1}														
PP	260.7	123.7	69.3	226.9b	190.6	281.5	192.1	72.5	75.3b	68.7	125.1	153.1b	161.9	109.4b
DH	252.2	133.4	83.4	255.5ab	225.0	331.0	213.4	63.8	105.8ab	82.2	144.9	193.4a	180.5	128.4a
NK	224.7	129.3	78.2	286.9a	204.3	314.4	206.3	72.8	114.3a	74.2	163.2	151.5b	178.1	125.7ab
SP	240.9	120.5	88.3	201.1b	217.5	342.7	201.8	66.7	87.5ab	68.5	196.0	167.1ab	206.2	132.0a
LSD$_{0.05}$	ns	ns	ns	58.3	ns	ns	ns	ns	30.7	ns	ns	32.3	ns	16.6
p-value	0.262	0.841	0.161	**0.030***	0.167	0.146	0.082	0.955	**0.057***	0.351	0.113	**0.043***	0.458	**0.040***
ST	238.5	122.1	78.6	253.7	210.0	304.1	201.2	64.3	81.9	65.5	173.4	166.3	184.8	122.7
CT	235.6	145.3	81.7	238.0	216.9	332.4	208.3	63.3	102.7	75.9	164.9	155.4	162.6	120.8
NT	259.8	112.8	79.2	236.0	201.2	315.8	200.8	79.3	102.5	78.8	133.6	177.1	197.7	128.2
LSD$_{0.05}$	ns	0.5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
p-value	0.282	0.053	0.912	0.754	0.544	0.502	0.514	0.555	0.216	0.219	0.263	0.316	0.342	0.578
Seed pod^{-1}														
PP	24.1a	24.0	18.0	26.1a	28.3	25.9b	24.4ab	17.7	21.2	16.9	23.2	28.4	30.5	23.0
DH	23.7a	23.6	18.7	26.0ab	29.4	31.0a	25.4a	16.3	21.9	18.5	25.3	29.3	28.9	23.4

Table 8. (*concluded*).

	Irrigated							Rainfed						
	LB21	LB22	BI22	BR22	LB23	STL23	All site	LB21	LB22	BI22	BR22	LB23	STL23	All site
NK	26.1a	22.9	18.2	27.7a	27.7	24.3b	24.5a	17.4	22.5	15.6	22.6	28.2	28.1	22.4
SP	20.1b	22.8	16.9	23.4b	29.2	28.2ab	23.4b	17.3	21.5	15.1	25.1	29.4	28.4	22.8
$LSD_{0.05}$	2.9	ns	ns	2.7	ns	4.1	1.1	ns	ns	ns	ns	ns	ns	ns
p-value	**0.001******	0.610	0.622	**0.018***	0.333	**0.012****	**0.011****	0.805	0.636	0.074	0.110	0.586	0.669	0.397
ST	23.0	23.8	19.4	27.3	28.3	27.1	24.8	17.2	21.3	17.5	24.5	28.9	28.5	23.0
CT	23.2	23.9	17.7	25.1	28.7	28.9	24.6	15.8	22.0	16.4	24.4	29.0	28.6	22.7
NT	24.3	22.2	16.7	25.0	28.9	26.1	23.9	18.5	22.0	15.8	23.2	28.6	29.8	23.0
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
p-value	0.528	0.117	0.083	0.096	0.787	0.290	0.162	0.112	0.605	0.362	0.483	0.916	0.713	0.793

Note: LB, BI, BR, and STL represent Lethbridge, Bow Island, Brooks, and Stirling, respectively. LSD = least significant difference. ns = not significant. *, **, and *** denote significance at $p \leq 0.05$, 0.01, and 0.001, respectively. PP, DH, NK, and SP represent precision planter, disc hoe opener, narrow knife, and spreader opener, respectively. ST, CT, and NT represent strip tillage, conventional tillage, and no tillage, respectively.

such effects were observed in this study. This may explain why no significant yield variation was found between tillage practices here.

Soil properties

Tillage methods had minimal impact on soil properties, such as soil moisture and temperature. While soil moisture was numerically higher under NT compared to other tillage practices on certain dates, these differences were statistically insignificant (Fig. 3). The moisture retention observed under NT can be attributed to the presence of crop residues, which help maintain surface soil properties and reduce water evaporation (Horton et al. 1996; Klocke et al. 2009). As mentioned previously, crop residues cover the soil surface, decreasing water loss through evapotranspiration and creating a microclimate that conserves moisture, reduce wind speed, and limit solar radiation exposure.

In contrast, soil temperature was slightly higher under CT and ST compared to NT (Table 9). Pre-seed soil temperature under NT was 0.2 and 0.3 °C lower than under ST and CT, respectively. Similarly, post-seed soil temperature under NT was 0.3 and 0.4 °C lower compared to ST and CT, respectively. These findings are consistent with those of Licht and Al-Kaisi (2005), who reported that ST increased soil temperature by 1.2–1.4 °C over NT, which contributed to better canola emergence at seven out of 12 sites (Table 4). The improved soil temperature in the seed row under ST benefitted seed germination, leading to higher stand density at early growth stages at irrigated sites (Table 4). However, the enhanced soil temperature under CT did not significantly improve seed germination or stand establishment, likely due to the soil disturbance associated with this tillage practice, which may have led to increased surface soil moisture loss.

Conclusions

The adoption of innovative agronomic practices such as PP and conservation tillage practice plays a crucial role in improving canola production. In terms of stand establishment, canopy uniformity, and early-season canopy closure, PP demonstrated advantages under both irrigated and rainfed conditions, particularly in the CT system. These advantages are primarily due to the precision planter's ability to ensure consistent seed placement, better depth control, and improved seed-to-soil contact. However, despite these advantages in stand establishment, PP did not consistently lead to increased canola yield relative to other sowing methods. The higher row width typically associated with PP may have contributed to increased inter-plant competition, which negatively impacted yields. In contrast, the DH opener performed better in both irrigated and rainfed environments, producing higher and more stable yields.

Tillage practices had little direct impact on seed germination, stand establishment, or yield components, although conservational tillage systems like ST and NT showed benefits in soil moisture retention. However, when ST is combined with DH opener, higher and stable seed yield and oil con-

Fig. 3. Soil moisture response to tillage practice measured at multiple depths in irrigated fields in 2023 and 2021. Clockwise from top-left: 15 May (2023), 15 June (2023), 7 July (2021), and 15 August (2021). Cultivated represents conventional tillage.

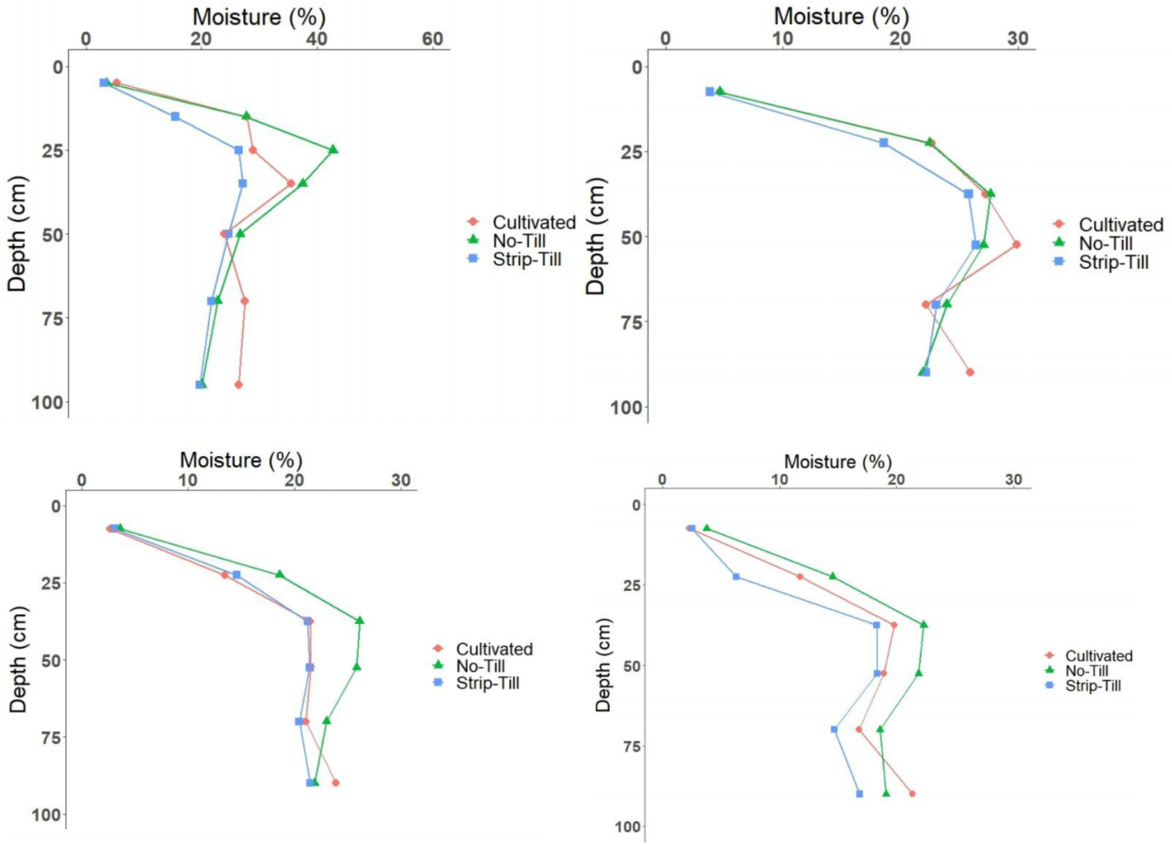


Table 9. Soil temperature (°C) responses to tillage practice.

	ST	CT	NT
Pre-seed	12.5	12.6	12.3
Post-seed	15.1	15.2	14.8

Note: ST, CT, and NT represent strip tillage, conventional tillage, and no tillage, respectively.

tent under irrigated conditions are warranted. Similarly, under rainfed conditions, a DH opener combined with CT improved plant stand establishment and yield maintenance. It does come at a high risk of soil losses due to wind erosion on the prairies. Furthermore, of all the DH treatments the CT had the lowest yield, so although CT has less variability in yield as indicated by the lower CV, it also has a lower potential yield. In rainfed agricultural systems on the Prairies it would be prudent for farmers to maximize their yield during wetter years, rather than aim for slightly higher crop yield during years of drought. Our paper would suggest that optimal canola production relies on a balance between uniformity in plant distribution and other factors, such as row spacing, tillage, and residue management. Future research is crucial to refining these practices for optimizing canola productivity, particularly regarding the impact of precision planter vacuum meter adjustments on reducing inter-plant competition.

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Data availability

Data generated or analyzed during this study may be available from the corresponding author upon reasonable request.

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Competing interests

The authors declare there are no competing interests.

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Appendix A

Table A1. Details of the pesticides applied in this study.

	Growth stage	Trade name	Common name	Rate	Manufacturer	Location applied
Herbicide	Pre-seed	Roundup WeatherMax®	Glyphosate	540 g a.e. L^{-1}	Bayer CropScience Canada, Calgary, Alberta	Lethbridge, Brooks, Bow Island, and Stirling
		Aim® EC	Carfentrazone-ethyl	240 g a.i. L^{-1}	FMC Corporation, Philadelphia, Pennsylvania, USA	Lethbridge, Brooks, Bow Island, and Stirling
		Avadex®	Trifluralin	480 g a.e. L^{-1}	Gowan Canada, Calgary, Alberta	Lethbridge rainfed
		Fortress®	Triallate and trifluralin	10% + 4% g a.e. L^{-1}	Gowan Canada, Calgary, Alberta	Lethbridge irrigated
Herbicide	2–4 leaf	Roundup WeatherMax®	Glyphosate	540 g a.e. L^{-1}	Bayer CropScience Canada, Calgary, Alberta	Lethbridge, Brooks, and Bow Island
		Liberty®	Glufosinate	150 g a.i. L^{-1}	BASF Canada, Calgary, Alberta	Stirling
Fungicide	Pod fill stage	Lance® AG	Pyraclostrobin	250 g a.e. L^{-1}	BASF Canada, Calgary, Alberta	Lethbridge, Brooks, Bow Island, and Stirling
Insecticide	Pod fill stage	Matador® 120 EC	Lambda-cyhalothrin	120 g a.i. L^{-1}	Syngenta Canada, Guelph, Ontario	Lethbridge, Brooks, Bow Island, and Stirling
Desiccant	Maturity	Reglone®	Diquat	240 g a.i. L^{-1}	Syngenta Canada, Guelph, Ontario	Lethbridge, Brooks, Bow Island, and Stirling