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Carinata growth, yield, and chemical composition responses to nitrogen fertilizer management

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Abstract

Production of carinata (*Brassica carinata* A. Braun) as a winter crop in the Southeast United States presents a unique opportunity for growers to produce significant amounts of biofuel feedstock to meet domestic energy needs. Field experiments were conducted to quantify the effects of N application rates (0, 45, 90, and 135 kg N ha^{-1}) and split management (single, two-way split, or three-way split of 90 kg N ha^{-1} applied at planting, bolting, and flowering) on carinata growth, yield, and chemical composition. In Study 1, plant height, mainstem node numbers, primary and secondary branches, pod length, pods numbers, and seeds per pod increased quadratically with N application rate. Averaged over the 5 yr, seed yield response to N application rate was quadratic and ranged from 1,245 kg ha^{-1} with 0 kg N ha^{-1} to 2,444 kg ha^{-1} with 117 kg N ha^{-1}. The economic optimum nitrogen rate (EONR) occurred at 103 kg N ha^{-1}, which produced 2,427 kg seed ha^{-1} representing a US$386 ha^{-1} profit margin. Except for protein, N application rate did not have an effect on glucosinolates and fatty acid composition. In Study 2, a split application of N had variable effects on carinata growth; however, seed yield did not vary with split management or timing of N averaging 3,905 kg ha^{-1}. Split management and N source did not have an effect on seed chemical composition. These results suggest that carinata grown at the EONR of 103 kg N ha^{-1} can maximize seed and oil production in the Southeast.

1 | INTRODUCTION

The Renewable Fuel Standard (RFS) is a federal biofuel policy in the United States that emerged in response to concerns over energy independence, agricultural surpluses, and climate change (Perlack & Stokes, 2011). The RFS was created under the Energy Policy Act of 2005 and amended by the Energy Independence and Security Act of 2007 (Schnepf & Yacobucci, 2012). The RFS2 targets the production of 136 billion liters of renewable biofuels by 2022, mandating 58% be comprised of advanced biofuels derived from non-food feedstocks that achieve at least 50% reductions in greenhouse gas emissions (Schnepf & Yacobucci, 2012). Second-generation or advanced biofuels can be produced from a variety of non-food feedstock, including non-edible energy crops {camelina [*Camelina sativa* (L.) Crantz], field pennycress [*Thlaspi arvense* L.], pongamia [*Millettia pinnata* (L.) Panigrahi], jatropha [*Jatropha*

Abbreviations: AE, agronomic efficiency; EONR, economic optimum nitrogen rate; ESN, environmentally smart nitrogen; PFP, partial factor productivity; PNB, partial nutrient balance.

curcas L.]} cultivated non-edible oils (cottonseed [*Gossypium arboretum* L.), agricultural and municipal wastes, waste oils, and algae.

Carinata (*Brassica carinata* A. Braun) is a second-generation non-food oilseed feedstock used to produce an alternative "drop-in" aviation fuel that is functionally equivalent in thermochemical properties and performance to petroleum-derived fuels (Cardone et al., 2003, Cardone et al., 2002). Carinata oil can be transesterified/methanolyzed to produce biodiesel (Cardone et al., 2003), hydrotreated to produce jet fuel (Gesch et al., 2015), or subjected to catalytic hydrothermolysis to produce naptha, jet, and diesel fuels (McVetty et al., 2016). Carinata is a C3 herbaceous annual with desirable agronomic traits (drought and heat tolerance [Malik, 1990], pod shatter resistance [Banga, Kaur, Grewal, Salisbury, & Banga, 2011], non-dormancy, and non-invasiveness [USDA, 2014]). Commercial winter carinata production occurred on 4,000 ha in the tristate region of Florida, Georgia, and Alabama during the winter–spring growing seasons from 2015 to 2018 (Seepaul, Marois, Small, George, & Wright, 2018). Scaling up production requires fitting carinata into existing and diverse crop rotations in the Southeast (Seepaul et al., 2018) as well as the identification of agronomic cultural management practices (Mulvaney, Leon, Seepaul, Wright, & Hoffman, 2019).

Nitrogen application accounts for the largest energy input and production cost in oilseed production (Gan, Malhi, Brandt, Katepa-Mupondwa, & Stevenson, 2008). Therefore optimizing the N application rate and timing for optimum productivity, economic feasibility, and environmental stewardship is critical for the commercial success of this relatively new bioenergy crop. Brassicas are highly responsive to N application (Hocking, Kirkegaard, Angus, Gibson, & Koetz, 1997) and require relatively high rates of mineral N fertilizers for optimal seed yield (Malagoli, Laine, Rossato, & Ourry, 2005; Rathke, Behrens, & Diepenbrock, 2006). Maximum seed yield (2,204 kg ha^{-1}) of spring-planted carinata was produced at 150 kg N ha^{-1} in the Canadian prairies (Pan, Caldwell, Falk, & Lada, 2012). In Italy, the application of 100 kg N ha^{-1} produced 1,770 kg seed ha^{-1}, 29% greater than the 0 N control (Montemurro et al., 2016). Nitrogen application increased field-grown winter mustard [*Brassica juncea* (L.) Czern.] seed yield by 10–347% in southern Alberta (McKenzie, Middleton, & Bremer, 2006) and 19–60% in Mississippi (Zheljazkov, Vick, Ebelhar, Buehring, & Astatkie, 2012) over nontreated controls. Limiting N during carinata reproductive development resulted in a 62% yield penalty indicating that carinata is sensitive to N limitation, although this sensitivity was less than in canola (*Brassica napus* L.). Under non-limiting conditions, carinata produced 164% greater seed yield when compared to limited N (Seepaul et al., 2019).

Core Ideas

- Optimizing N management can improve carinata growth and yield in North Florida.
- Optimum seed yield (2,444 kg ha^{-1}) was produced at 117 kg N ha^{-1}.
- The economic optimum N rate occurred at 103 kg N ha^{-1} yielding 2,427 kg seed ha^{-1}.
- Split management or N source did not have an effect on crop growth or seed yield.
- Synchronizing N supply with crop uptake and utilization enhances N use efficiency.

Nitrogen availability alters the early season and post-bolting physiology, morphology, and biomass distribution patterns in carinata. Carinata grown with limited N produced 47% more photosynthates (21.2 µmol m^{-2}s^{-1}) than plants grown with supraoptimal N (31.0 µmol m^{-2}s^{-1}) (Seepaul, George, & Wright, 2016). Suboptimal N availability modified carinata canopy architecture through a reduction in leaf size, early abscission and senescence, and vertical distribution of leaves on the main stem. Modification in canopy architecture in response to N deficiency adversely affected canopy photosynthesis and the production of structures involved in sexual reproduction (Seepaul et al., 2016) (Seepaul, Marois, Small, George, & Wright, 2019a). Relative to canola, optimizing N application for carinata resulted in increased reproductive branches, number of racemes, and pods per plant, each having a positive correlation with seed yield (Seepaul et al., 2019a).

In addition to restricting plant growth and reproductive performance, N deficiency may also modify seed chemical composition, particularly protein concentration (Seepaul et al., 2019). Industrial oilseeds are grown primarily to produce industrial oils; however, the presscake is a valuable co-product and a source of protein in animal feeds. Although oil and protein concentration are inversely related (Seepaul et al., 2019), N application needs to be optimized for maximum crop productivity and seed quality.

In addition to the right rate and timing of N application, controlled-release fertilizers have emerged as a tool to bolster the right source aspect of nutrient management (Rajkovich, Osmond, & Weisz, 2017). The right source of N needs to be available in a form that is readily available for plant uptake without restricting plant growth and development. Environmentally smart nitrogen (ESN, Agrium, Inc) is a commercially available controlled-release fertilizer with a polymer coating to release N at predictable rates that are temperature dependent (Golden, Slaton, & Norman, 2011). The agronomic performance of ESN compared with conventional fertilizers is negative, neutral, or positive. For example, relative to urea, canola grown with ESN reduced yields in 4 of 20 site-years, similar in 14 of 20 site-years and increased in 1 of 20 site-years (Blackshaw et al., 2011). Similar occasional benefits were found with field-grown wheat (*Triticum aestivum* L), barley (*Hordeum vulgare* L.), and canola with ESN or ESN blended with urea; however, the yield gain did not offset the cost of the product (Khakbazan et al., 2013).

In the soils of the southeastern United States, where the leaching potential is high, judicious nutrient applications informed by the 4R Nutrient Stewardship Framework is key to achieving cropping system goals such as increased production, increased farmer profitability, enhanced environmental protection, and improved sustainability. Nitrogen optimization must take into consideration application rates and timing that are synchronous with critical phenostages corresponding to maximum N uptake (Seepaul et al., 2016; Seepaul et al., 2019a). Optimizing N rate, split management, and timing of application in soils with high leaching potential will reduce the potential for environmental pollution and improve seed yield and N use efficiency. Therefore, the objective of these two studies was to determine the optimal N application rate and split management and determine its effect on carinata growth, yield, and chemical composition.

2 | MATERIALS AND METHODS

2.1 | Site characterization, management, and experimental design

Two field trials were conducted during the winter–spring growing seasons at the University of Florida North Florida Research and Education Center (30°32′44" N, 84°35′40.7′′ W) in Quincy, FL.

Study 1: The response of carinata to the N application rate was evaluated in a 5-yr field study. Carinata was planted on a Norfolk loamy fine sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with 0–2%slopes (2014–2015 and 2018–2019) and an Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults), 2–5%slopes (2015–2016, 2016–2017, 2017–2018). For clarity, 2014–2015, 2015–2016, 2016–2017, 2017–2018, and 2018–2019 will be referred to as Years 1, 2, 3, 4, and 5, respectively. The experimental design was a randomized complete block with four replications. Treatments were four N application rates (0, 45, 90, and 135 kg N ha^{-1}).

Study 2: The response of carinata to split management and timing was evaluated in a 2-yr study during the winter–spring seasons of 2014–2015 and 2015–2016 on a Norfolk loamy fine sand with 0–2% slopes in Year 1 and on an Orangeburg loamy sand, 2–5%slopes in Year 2. The experimental design was a randomized complete block with four replications. Treatments were split management: single, two-way split, or three-way split of 90 kg N ha^{-1} applied at planting, bolting, and flowering. The ESN was applied at similar rates to a single application of 90 kg N ha^{-1} at planting, bolting and flowering to determine the response of carinata to N source.

The agronomic management of both studies was similar. Plots were 1.5 by 10 m with 1.8 m between plots. Alleys were planted with carinata and mowed at physiological maturity to reduce border and alley effects. The soil was prepared by a single disk cultivator pass to a 15-cm depth followed by a cultipacker to create a firm and smooth seedbed. Carinata variety 110994EM (Years 1 and 2) and Avanza 641 (Years 3, 4, and 5) sourced from Nuseed (previously Agrisoma Biosciences Inc.) were planted using either a Hege 1000 series cone planter (Wintersteiger Inc.) in 17.8 cm rows in Years 1 and 2 or a JT-5DN cone planter (R-Tech Industries Ltd.) in 30.5-cm rows in Years 3, 4, and 5 at a rate of 6.1 kg ha^{-1} (129 seeds m^{-2}). Row spacing changes from 17.8 to 30.5 were not expected to change yield or oil quality characteristics based on previous research (Mulvaney et al., 2018). Carinata was planted once every 3 yr in the same field since rotation is recommended (Seepaul et al., 2019).

Pre-emergence herbicide pendimethalin (N-[1-ethylpropyl]-3,4-dimethyl-2,6-dinitrobenzenamine) (Prowl) (Leon, Ferrell, & Mulvaney, 2017) and burndown herbicide paraquat dichloride (N, N′-dimethyl-4,4′-bipyridinium dichloride) (Gramoxzone 3SL) were tank mixed and applied at planting at the rate of 0.73 L ha^{-1} (a.i.) and 0.63 L ha^{-1} (a.i.), respectively, in all years. Diflubenzuron [1-(4-chlorophenyl)-3-(2,6-difluorobenzoyl)urea] (Dimilin 2L) applied at 0.05 L ha^{-1} (a.i.) was tank mixed with Spinosad (Tracer) at 0.10 L ha^{-1} (a.i.) to control diamondback moth (*Plutella xylostella*). Bifenthrin {2 methyl[1,1–biphenyl]-3-yl)methyl 3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethyl-cyclopropanecarboxylate} (Bifenture) was applied at rates of 0.05 L ha^{-1} (a.i.) to control aphids (*Myzus persicae*) and diamondback moth.

The plots were fertilized according to soil test recommendations for canola in all years. Pre-plant soil chemical characteristics were relatively comparable in the 5 yr of the study (Table 1). Potassium (K_2O) and phosphorus (P_2O_5) were pre-plant incorporated at 42 and 84 kg ha^{-1}, respectively. Sulfur was applied 10 kg ha^{-1}, 50% at bolting, and 50% at flowering. Ammonium nitrate (NH_4NO_3) (34—0—0)

TABLE 1 Soil chemical characteristics of fields planted with carinata during five winter–spring growing seasons at Quincy, FL. Soils were sampled to 15-cm depth

Year[a]	Soil texture	pH	CEC	P_2O_5	K_2O	Mg	Ca	S	B	Zn	Mn	Fe	Cu
			$\text{cmol}_c\ \text{kg}^{-1}$	kg ha^{-1}									
1	Norfolk loamy fine sand	6.7	5.7	32	185	147	603	45	0.45	4	11	31	0.45
2	Orangeburg loamy sand	6.6	4.7	96	155	111	753	46	0.45	5	13	38	1.01
3	Orangeburg loamy sand	6.1	4.2	49	105	195	794	3	0.3	3	11	30	0.6
4	Orangeburg loamy sand	6.2	4.5	117	345	120	761	8	0.5	8	20	29	1.9
5	Norfolk loamy fine sand	5.9	4.5	49	178	126	817	33	0.4	6	15	30	0.3

[a] Years 1, 2, 3, 4, and 5 correspond to the winter–spring growing seasons of 2014–2015, 2015–2016, 2016–2017, 2017–2018, and 2018–2019, respectively.

TABLE 2 Cropping history, planting dates, fertilizer application dates, and harvest dates of carinata grown during five winter-spring growing seasons at Quincy, FL

Management	Year 1	Year 2	Year 3	Year 4	Year 5
Cropping history					
Previous spring	Fallow	Fallow	Fallow	Fallow	Fallow
Previous winter	Fallow	Oat	Small grains	Small grains	Fallow
Planting date	21 Nov. 2014	31 Oct. 2015	14 Nov. 2016	28 Nov. 2017	9 Jan. 2019
Growing season mean historic GDD[a]	3,709	4,595	2,966	3,786	3,029
GDD	3,288	5,176	3,689	3,994	3,288
Fertilizer application	K_2O (0–0–60) and P_2O_5 (0–46–0) was pre-plant incorporated at 42 and 84 kg ha^{-1}				
(NH_4NO_3) (34–0–0)-25%	15 Dec. 2014	4 Nov. 2015	15 Nov. 2016	21 Dec. 2017	14 Jan. 2019
(NH_4NO_3) (34–0–0)-50%	17 Feb. 2015	1 Feb. 2016	17 Feb. 2017	23 Feb. 2018	12 Mar. 2019
(NH_4NO_3) (34–0–0)-25%	30 Mar. 2015	22 Feb. 2016	28 Feb. 2017	23 Mar. 2018	3 Apr. 2019
Irrigation (quantity applied)	18 Dec. 2014 (15 mm)		17 Nov. 2016 (15 mm)	20 Mar. 2019 (15 mm)	
			23 Nov. 2016 (15 mm)		
			28 Nov. 2016 (15 mm)		
Harvest date	29 May 2015	18 May 2016	19 May 2017	4 June 2018	30 May 2019

[a] Growing degree days (GDD) were calculated using a 4.4 °C base temperature with AgroClimate web-based GDD calculator (http://www.agroclimate.org).

was applied with a First Products Dry Fertilizer Applicator (1st Products Inc.,) as per N rate treatments for Study 1, with 25% pre-plant incorporated, 50% topdressed at bolting and 25% topdressed at flowering. For Study 2, 90 kg N ha^{-1} was applied as a single, two-way split or three-way split at planting, bolting and flowering. In Year 1of Study 2, 90 kg N of ESNpolymer coated urea or ESN (44–0–0) (Agrium Inc.) was applied at planting while in Year 2, 90 kg N of ESN was applied at planting, bolting, and flowering.

Details on the cropping history, planting date, fertilizer application, and harvest dates are provided in Table 2. Insect pests and diseases were managed according to production recommendations (Seepaul et al., 2019). In both studies, supplemental irrigation was applied in Years 1 and 3 at planting to aid stand establishment while in Year 4, the crop was irrigated during flowering.

2.2 | Data Collection

Plants from both studies were phenotyped in Years 1 and 2 only. At physiological maturity, 10 plants from each treatment were clipped at soil level and measured for growth characteristics, seed yield, and yield components (reproductive branches, raceme length, raceme numbers, pod number, pod length, and seeds per pod). Plant height, number of nodes, and primary and secondary branches were measured on 10 plants in only Years 1 and 2 of both studies. Pod length and seeds per pod were determined as the average of measurements from all pods on the terminal raceme.

All plots were trimmed to 7.62 m on either end before harvest. All rows of naturally desiccated carinata were harvested with a Wintersteiger Delta plot combine in all years

(Wintersteiger Inc.,). Seeds were oven-dried at 45 °C for 48 h, and yields were corrected to 8% moisture. Seed moisture content and test weights were measured with a Steinlite Sl95 moisture meter (Steinlite,) using ∼0.75 kg seeds. A 1,000 seed weight was measured on two subsamples. The number of plants per square meter was counted at harvest.

Total glucosinolates, protein concentration, oil concentration, and fatty acid composition were estimated using near-infrared reflectance spectroscopy (NIRS). Samples were analyzed using a FOSS XDSTM Rapid Content Analyzer (FOSS Inc.). Sample spectra were evaluated using the ISIscan program (FOSS Analytical) using a proprietary carinata calibration (Nuseed, previously Agrisoma Biosciences, Inc.), including numerous calibration and validation samples. Oil yield was calculated by multiplying seed yield (corrected to 8% moisture content) by the oil concentration and then dividing by the density of carinata oil (0.92 kg L^{-1}).

The economic optimum nitrogen rate (EONR), defined as the point where the last increment of N returns a yield increase large enough to pay for the additional N, was calculated by equating the first derivatives of the quadratic response equation to N fertilizer price ratio and solving for N (Kyveryga, Blackmer, & Morris, 2007) (data not shown). The baseline cost of production used in the calculation was US$675 ha^{-1} taking into consideration $0.68 kg^{-1} as the cost of N. Revenue was calculated using a price of $8.50 bu^{-1} (22.7 kg^{-1}) of carinata seed.

Agronomic efficiency (AE), partial nutrient balance (PNB), and partial factor productivity (PFP) were calculated using equations described by Fixen et al. (2015).

$$AE = (Y - Y0)/F \tag{1}$$

$$PNB = UH/F \tag{2}$$

$$PFP = Y/F \tag{3}$$

where Y = seed yield with nutrient applied; $Y0$ = seed yield with no nutrient applied; F = amount of nutrient applied; UH = nutrient content of the seed.

2.3 | Statistical analysis

Fatty acids, glucosinolates, and protein percent values were arcsine transformed before data analysis and back-transformed for reporting. The dataset was tested for normality of the residuals by Shapiro–Wilk W statistics (PROC UNIVARIATE) in SAS 9.4 (SAS Institute Inc.) and for homogeneity of variances among treatments with Levene's test (PROC GLM) before proceeding with the ANOVA. When these assumptions were not satisfied, the data were transformed with the natural logarithm ($\log_e$) to improve the normality of the data.

Study 1: To test the main effects of N application rate on growth, yield, and chemical composition, a one way ANOVA was performed using PROC MIXED. The N application rate was considered a fixed effect, while replication and year were considered random effects. Responses were tested with orthogonal polynomial contrasts. When linear, quadratic, and/or cubic functions were detected, the functional form of the regression relation was determined by starting with the linear function, then adding successively higher-order polynomials in conjunction with plotting data and making visual assessments. If it was determined that the higher-order polynomial did not substantially improve the explanation of the response curve (based on r^2 values), then those higher-order polynomials were discarded. Correlations among growth parameters, seed chemical composition, and yield were determined by correlation analysis (PROC CORR). When correlations were detected, regressions were performed using PROC REG to quantify the relationship.

Study 2: To test the main effects of N split management and N source (a subset of Study 2) on growth, yield, and chemical composition, a one way ANOVA was performed using PROC MIXED. Split management was considered the fixed effect, while replication and year were considered random effects. Comparisons among split management treatments were tested with contrast statements in PROC MIXED. Within split management, comparisons of N application timing least-squares means were analyzed by the PDIFF option of PROC MIXED. The source of N in Treatments 2 and 11, 3 and 12, and 4 and 13 were different; hence comparison between sources was tested with a contrast statement in PROC MIXED. Comparisons of N application timing within N source were analyzed by the PDIFF option of PROC MIXED.

3 | RESULTS AND DISCUSSION

3.1 | Growing season conditions

Precipitation during the carinata growing season (November to June) varied in the 5 yr of the study (Table 3). Early growing season precipitation (November to January) in Years 1, 2, 3, and 5 were 245, 188, 74 and 270 mm greater than the long-term average for the similar period, respectively while Year 4 was 164 mm less than the long-term average for the first 3 mo of the growing season. Mid-season precipitation (February to March) was less than the long-term average for 4 out of the 5 yr. End-of-season

TABLE 3 Monthly and total seasonal precipitation and mean monthly temperature during five winter–spring growing seasons and 30-yr long-term monthly average (LTA) precipitation and temperature at Quincy, FL

	Precipitation						Temperature					
Month	Year 1	Year 2	Year 3	Year 4	Year 5	LTA	Year 1	Year 2	Year 3	Year 4	Year 5	LTA
	mm						°C					
Nov.	144.5	171.2	10.2	11.2	196.3	85.9	11.1	18.3	16.1	15.4	14.0	14.5
Dec.	270.8	175.0	134.4	80.8	263.9	130.7	12.6	16.6	14.5	12.1	12.7	11.9
Jan.	137.9	149.9	237.5	52.3	117.6	91.4	10.1	9.4	13.7	8.1	11.1	10.3
Feb.	87.9	73.4	74.7	133.9	29.0	122.3	9.2	11.8	16.0	17.4	16.5	12.4
Mar.	59.7	73.2	31.5	137.7	70.9	101.3	17.4	17.3	16.6	14.6	15.2	15.6
Apr.	152.7	479.8	86.9	67.6	155.4	140.4	21.1	18.9	20.2	18.0	19.0	18.8
May	75.2	50.3	151.1	206.0	61.5	82.0	23.3	22.4	22.7	23.6	24.5	23.0
June	143.3	156.7	246.4	91.7	117.3	139.8	25.6	25.8	24.5	25.9	26.3	25.7
Total	1,071.9	1,329.4	972.6	781.1	1,011.9	898.8						

precipitation (April to June) fluctuated over the 5-yr test period with April 2016 (Year 2) and May 2018 (Year 4) recording 339- and 124-mm greater precipitation than the long-term average, respectively. Growing season precipitation was 178, 436, 79, and 118 mm greater than the 30-yr long-term average in Years 1, 2, 3, and 5, respectively, whereas, in Year 4, growing season rainfall was 113 mm less than the long-term average.

Growing season temperatures were warmer than the long-term average in all years except in Year 1 (Table 3). Early season mean temperature (November to January) in Years 2, 3, and 5 were 7.5, 7.6, and 1.1 °C warmer than the long-term average for a similar period while Year 1 and 4 were 3.0 and 1.2 °C cooler than the long-term average for the similar period. Mid-season temperatures (February to March) were warmer in all years except in Year 1, where it was 0.7 °C cooler while the end of the season (April to -June) was warmer or slightly cooler in all years. The number of freezing hours that lasted for 4 or more hours differed significantly across years with 14, 10, 3, 0, and 6 events recorded in Years 1, 2, 3, 4, and 5, respectively. This influenced the number of growing degree days (GDD) accumulated across the growing season: 3,288; 5,176; 3,689; 3,994;, and 3,288 in Years 1, 2, 3, 4, and 5, respectively. In Year 1, the cumulative growing season GDD was 11.4% less than the long-term average for a similar period, while in Years 2 through 5, the GDD was 13, 24, 5, and 9% greater than the long-term average for a similar period, respectively. During flowering and pod set on 16 Mar. 2017 (Year 3), 9 consecutive hours of <0 °C resulted in freeze damage of flowers and developing pods. There was no other freeze event during the reproductive stage in the other 4 yr of the study.

3.2 | Study 1: Nitrogen application rate

3.2.1 | Plant stand and growth

Plant stand did not significantly differ among the various N rates ($P > .05$), averaging 33 plants m^{-2} across the 5 yr of the study. Plant growth was responsive to N application rate (Table 4). Plant height, mainstem node numbers, primary and secondary branches, pod length, pods numbers, and seeds per pod increased quadratically with N application rate (Table 4). Height, node numbers, primary branches, secondary branches, pod numbers, and seeds per pod increased by 38.3, 6.7, 146.1, 128.2% from 0 to 135 kg N ha^{-1}, respectively (Table 4). In contrast, pod length and seeds per pod did not respond to N application averaging 4.3 cm and 11.8, respectively.

Nitrogen is an integral structural component of amino acids and chlorophyll and a constituent of all enzymes; therefore suboptimal availability induces a cascade of biochemical, physiological, and morphological changes in carinata growth, resource allocation, and productivity regardless of growth stage (Seepaul et al., 2016; Seepaul et al., 2019a and 2019b). In the current study, carinata mainstem height and branching patterns were regulated by N supply supporting previous findings by Alberti et al. (2019) and Pan et al. (2012). Plant height correlated positively with node numbers ($r = .63$, $P = .0003$), primary branches ($r = .65$, $P = .0002$), secondary branches ($r = 0.51$, $P = 0.0059$), and number of pods per plant ($r = .71$, $P < .0001$). Pods per plant was strongly correlated with node numbers ($r = .88$, $P < .0001$), primary branches ($r = 0$ .88, $P < .0001$), and secondary branches ($r = .64$, $P = .0003$). Oilseed yield is dependent on the number of branches, the

TABLE 4 Nitrogen main effects on plant growth and pod characteristics of carinata grown during 2014–2015 and 2015–2016 winter–spring growing season at Quincy, FL

N rate	Height	Nodes	Primary branches	Secondary braches	Pod length	Pod numbers	Seeds per pod	1,000 seed weight	Test weight	Protein concentration
kg N ha^{-1}	cm	no.			cm	no.		g	kg hl^{-1}	%
0	87.9	27.0	9.3	8.9	4.0	111.8	11.0	3.8	63.2	22.4
45	111.1	27.9	11.3	13.7	4.3	182.8	12.0	3.9	63.5	23.0
90	121.6	30.1	16.0	24.6	4.6	280.5	13.0	4.0	64.0	23.3
135	121.6	28.8	15.3	21.9	4.2	255.1	11.2	4.2	63.9	24.7
Mean					4.3		11.8		63.6	
P-value	.0302	.0467	.0428	.0144	.9827	.0354	.0756	.0462	.3001	.0478
OPC	Q**	Q*	Q**	Q**	ns	Q***	ns	L**	ns	L**

Note. OPC = Orthogonal polynomial contrasts, L = linear, Q = quadratic, ns = not significant ($P > .05$).
*Significant at the .05 level. **Significant at the .01 level. ***Significant at the .001 level.

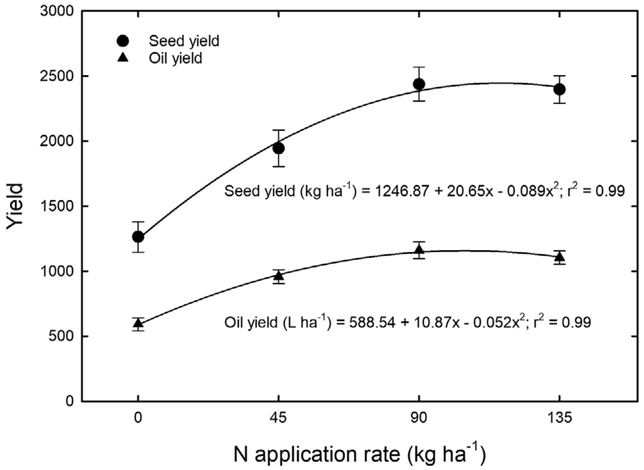

FIGURE 1 Nitrogen rate main effect on seed and oil yield of carinata grown during five winter–spring growing seasons at Quincy, FL

number of pods per plant, and the number of seeds per pod (Öztürk, 2010). Nutrient management strategies that promote high numbers of primary and secondary branching enhance the productivity of carinata (Seepaul et al., 2016).

3.2.2 | Seed yield, oil concentration, and oil yield

Seed yield varied with N application rate ($P < .0001$). The yield response to N application rate (averaged over 5 yr) followed a quadratic model ($y = 1246.87 + 20.65x - 0.089x^2$; $r^2 = .99$) (Figure 1). The yield was 1,264 kg ha^{-1} at 0 kg N ha^{-1} and 2,444 kg ha^{-1} at 117 kg N ha^{-1}, the agronomic optimum N rate. When the N rate surpassed 117 kg N ha^{-1}, yield declined (Figure 1). The EONR, which is the rate of N that maximizes profitability, was 103 kg N ha^{-1}, which produced 2,427 kg seed ha^{-1} representing a $386 ha^{-1} profit. In all years of the study, plant stand did not correlate with seed yield ($P = .1921$). Seed yield correlated positively with plant height ($r = .72$, $P < .0001$), node numbers ($r = .91$, $P < .0001$), primary branches ($r = .81$, $P < .0001$), secondary branches ($r = .62$, $P < .0001$), pods per plant ($r = .94$, $P < .0001$), and seeds per plant ($r = .75$, $P < .0001$).

Oil concentration did not respond to N application rate ($P = .4155$) averaging 48.6%. Similar to seed yield, oil yield varied with N application rate ($P < .0001$) following a similar quadratic model ($y = 588.54 + 10.87x - 0.052x^2$; $r^2 = .99$) as the seed yield response to N rate where the mean minimum oil yield was 5,93 l ha^{-1} at 0 kg N ha^{-1}, and the estimated maximum oil yield was 11,56 L ha^{-1} at 102 kg N ha^{-1} (Figure 1). Seed and oil yield did not have a relationship with oil concentration; however, seed yield correlated positively with oil yield ($r = .97$, $P < .0001$).

Oilseed brassicas are generally very responsive to the N application rate Gan et al., 2008; Johnson, Malhi, Hall, & Phelps, 2013; Seepaul et al., 2019a) with agronomic optimum N rate being species specific (Gan et al., 2008). In the current study, the mean 5-yr maximum yield (2,444 kg ha^{-1}) occurred at 117 kg N ha^{-1}. The agronomic optimum N rate in the current study is within the range previously reported for spring-planted carinata in South Dakota (Alberti et al., 2019) and Canada (Hossain et al., 2018) and winter planted carinata in Florida (84^{-}150 kg N ha^{-1}) Seepaul et al., 2019a).

3.2.3 | Seed weight

Thousand seed weight was responsive to N ($P = .0301$) increasing linearly with N application rate ($y = 3.78 + 0.0029x$) (Table 4). Test weight, a measure of seed density, did not vary with N rate ($P = .8056$), averaging 63.6 kg hl^{-1}

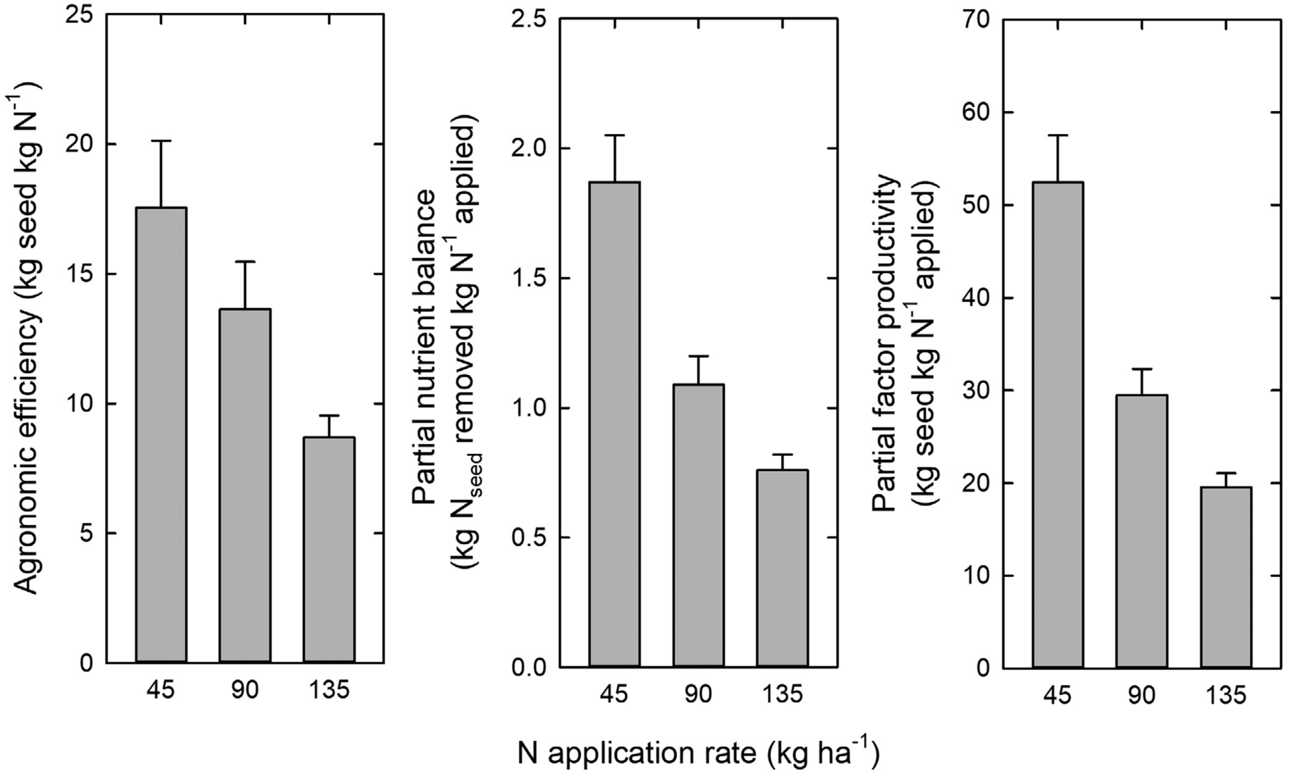

FIGURE 2 Nitrogen rate main effect on agronomic efficiency, partial nutrient balance, and partial factor productivity of carinata grown during five winter–spring growing seasons at Quincy, FL

(Table 4). Thousand seed weight positively correlated with protein concentration ($r = .86$; $P < .0001$) but negatively correlated with oil concentration ($r = -.82$; $P < .0001$). Plants with access to a non-liming N supply assimilate greater quantities of N resulting in increased protein concentration (Pan et al., 2012) and increased seed weight and consequently increased seed value (Getinet, Rakow, & Downey, 1996).

3.3 | Nitrogen use metrics

Agronomic efficiency ($P = .0015$), partial nutrient balance (PNB) ($P = .0019$), and partial factor productivity (PFP) ($P < .0001$) varied with N application rate. Agronomic efficiency was greatest at 45 kg N ha^{-1} and decreased as the N rate increased (Figure 2). Partial nutrient balance and PFP decreased as N input increased. Improving the uptake, assimilation, and utilization of N is crucial to the agronomic, environmental, and economic competitiveness and commercial success of carinata. Although temporal variation in rainfall and temperature during critical growth stages exists and may reduce N use efficiency, a combination of N management strategies informed by the 4R framework of nutrient stewardship, conservation tillage, soil, and crop testing, precision application of N and irrigation management can enhance carinata N utilization efficiency.

3.4 | Protein, glucosinolates, and fatty acid composition

Nitrogen application rate had a significant effect on protein ($P = .0478$) concentration but not glucosinolate ($P = .3343$) concentration. Protein concentration increased linearly with the N application rate ($y = 22.246 + 0.0152x$; rš = 0.82). Glucosinolate concentration averaged 72 mmol kg^{-1} dry weight. Oil concentration negatively correlated with glucosinolate (r = -.82, $P < .0001$) and protein ($r = -.96$, $P < .0001$) concentrations. This negative correlation may be due to C competition between the fatty acid and the amino acid biosynthetic pathways (Pan et al., 2012). Glucosinolate concentration was positively correlated with protein concentration ($r = .87$, $P < .0001$). Glucosinolates are biosynthesized from amino acids, hence may compete with protein synthesis. This result may indicate that higher N rates produce greater amino acids to meet protein synthesis and simultaneously produce glucosinolates, such that competition for protein amino acids is not a concern in carinata.

TABLE 5 Chemical characteristics of carinata seed grown during five winter–spring growing seasons at Quincy, FL. No statistical differences were observed among N application rates; therefore, only means and standard error of the mean (SEM) are presented

Parameter	*n*	Mean	SEM
Total seed glucosinolates, mmol kg^{-1}	80	79	14.9
Saturated fatty acids, %	80	6.2	0.0
Monounsaturated fatty acids, %	80	61.7	0.3
Polyunsaturated fatty acids, %	80	31.2	0.0
Long-chain fatty acids, % with chain length 14–18C	80	39.2	0.6
Very long-chain fatty acids, % with chain length >19C	80	60.8	0.3
C16:0, palmitic acid, %	48	3.1	0.0
C16:1, palmitoleic acid, %	32	0.1	0.0
C18:0, stearic acid, %	48	1.1	0.0
C18:1, oleic acid, %	80	10.3	0.3
C18:2,linoleic acid, %	80	15.4	0.2
C18:3, linolenic acid, %	80	12.9	0.1
C20:0, arachidic acid, %	32	1.4	0.0
C20:1, eicosenoic acid, %	80	8.8	0.1
C20:2, eicosadienoic acid, %	32	1.5	0.0
C22:0, behenic acid, %	32	0.4	0.0
C22:1, erucic acid, %	80	42.4	0.4
C22:2, docosadienoic acid, %	32	0.5	0.0
C24:0, lignoceric acid, %	32	0.2	0.0
C24:1, nervonic acid, %	32	1.7	0.0
Unknown fatty acids	32	0.5	0.0
Iodine value	32	111.3	0.2

Nitrogen application rate did not have an effect on fatty acid composition and distribution. Carinata has 39 and 61% long chain (C14–C18) and very long chain (>C19) fatty acids, respectively (Table 5). Of these, 6, 31, and 62% were saturated, polyunsaturated and monounsaturated fatty acids, respectively (Table 5). Mean fatty acid composition ranked in descending order of percent composition are C22:1 > C18:2 > C18:3 > C18:1 > C20:1 > C16:0 > C24:1 > C20:2 > C20:0 > C18:0 > C22:2 > C22:0 > C24:0 > C16:1 (Table 5).

3.5 | Study 2: Nitrogen split management and timing

3.5.1 | Plant stand and growth

Plant stand did not vary with N split management and timing ($P > .05$) treatments averaging 37 plants m^{-2}. Relative to the 0N control, the application of 90 kg N^{-1} increased plant height, node numbers, primary and secondary branches, and pod numbers by 26, 27, 79, 423, and 89%, respectively, but did not have an effect on pod length and seeds per pod (Table 6). A two-way split application increased plant height by 4% relative to a single and a three-way split application. Delaying the first application of N until bolting in a two-way split application decreased plant height by 11% relative to the first application at planting (Table 6). Node numbers did not vary with split management averaging 30 mainstem nodes per plant. A two- or three-way split of 90 kg N^{-1} increased primary branch numbers by 6% relative to a single application. Applying 25 and 50% of N at planting and bolting in a three-way split application produced the greatest number of primary branches. A two-way split of N increased secondary branches by 9% relative to a single or three-way split application. Applying N at planting and bolting maximized primary and secondary branches in both the two- and three-way split application. Pod numbers, pod length, and seeds per pod were similar across all split management averaging 220 pods per plant, 4 cm, and 12 seeds per pod, respectively (Table 6).

3.5.2 | Seed yield, oil concentration, oil yield, and seed weight

The application of 90 kg N^{-1} increased seed and oil yield by 36 and 29%, respectively, relative to the 0N control

TABLE 6 Carinata morphology and yield components in response to 90 kg N ha^{-1} applied in a single, two-way or three-way split application at planting (P), bolting (B), and flowering (F) during two winter–spring growing seasons at Quincy, FL

Treatment	Split management[a]	Timing of application[b]	Height	Nodes	Primary branches	Secondary branches	Pod numbers	Pod length	Seeds per pod
			cm	no.				cm	no.
1	0	Control	99.0	23.0	8.1	4.1	112.0	4.1	11.7
2	1	P (100)	140.2 a[c]	30.7 a	15.5 a	24.3 a	213.3 b	4.5 a	12.1 a
3		B (100)	121.6 b	28.6 a	15.3 a	29.8 a	243.8 a	4.4 a	11.6 a
4		F (100)	107.8 c	27.7 a	10.9 b	7.9 c	152.7 c	4.3 a	12.4 a
5	2	P (50)/B (50)	131.0 a	32.2 a	17.5 a	27.5 a	250.7 a	4.6 a	12.6 a
6		B (50)/F (50)	119.1 b	25.7 b	11.3 c	15.6 c	165.8 b	4.2 a	11.3 a
7		P (50)/F (50)	133.8 a	30.8 ab	15.2 b	24.8 b	234.2 a	4.5 a	12.8 a
8	3	P (50)/B (25)/F (25)	135.2 a	27.9 b	13.5 b	20.0 b	198.0 b	4.3 a	12.2 a
9		P (25)/B (50)/F (25)	118.1 b	31.3 a	17.2 a	25.1 a	249.6 a	4.6 a	12.2 a
10		P (25)/B (25)/F (25)	116.9 b	28.5 b	14.0 b	17.2 c	197.4 b	4.3 a	11.1 a
11	ESN	P (100)	122.2 a	27.9 a	14.1 a	22.2 b	200.5 c	4.3 a	11.7 a
12		B (100)	133.2 a	32.8 a	13.4 a	32.1 a	289.7 a	4.6 a	12.7 a
13		F (100)	125.2 a	30.8 a	12.6 a	21.0 b	240.0 b	4.3 a	15.2 a
Contrasts (split management)									
	0 vs. 1		***	**	*	**	*	ns	ns
	1 vs. 2		**	ns	**	*	ns	ns	ns
	1 vs. 3		ns	ns	ns	ns	ns	ns	ns
	2 vs. 3		ns	ns	ns	*	ns	ns	ns
Contrasts (source)									
	1 vs. ESN		ns	ns	ns	*	*	ns	ns

Note. ns: not significant.

[a] N fertilizer was applied in a single, two-way, or three-way split application at planting, bolting, and/or flowering.

[b] The % N applied at planting (P), bolting (B), and flowering (F) in the single, two-way or three-way split management is in parenthesis.

[c] Means within split management followed by the same lowercase letter were not significantly different ($P > .05$) according to the pdiff option in PROC Mixed.

*Significant at the .05 level. **Significant at the .01 level. ***Significant at the .001 level.

(Table 7). Seed and oil yield did not vary with split management or timing of N averaging 3,905 kg ha^{-1} and 2,063 Lha^{-1} (Table 7). Oil concentration decreased by 4% with N application. Delaying 50% or greater of 90 kg N^{-1} to flowering generally reduced oil concentration (Table 7). The trend in oil yield responses to N timing was similar to that of seed yield in part due to the strong correlation between seed and oil yield ($r = .97$, $P < .0001$). Thousand seed weight and test weight were similar among all split management and timing averaging 4 g and 67 hl$^{-1,}$ respectively (Table 7).

3.5.3 | Protein, glucosinolates, and fatty acid composition

Glucosinolate and protein concentration increased with N application by 10% relative to the 0N control (Table 8). Split management did not have an effect on glucosinolate and protein concentration averaging 79 mmol kg^{-1} and 26% (Table 8). Nitrogen application, split management, and N timing did not have an effect on polyunsaturated, monosaturated, saturated fatty, long-chain, and very-long-chain fatty acids (Table 8). Fatty acids did not vary with N application, split management, or N timing. Palmitic, stearic, oleic, linoleic, linolenic, eicosenoic, and erucic acids averaged 3.2, 1.2, 13.0, 16.1, 13.2, 9.0, and 38.3%, respectively (Table 9).

Although carinata seed yield did not respond to splitting N in the current study, prudent management is required since N is very susceptible to loss from the soil profile through leaching, denitrification, erosion, and surface volatilization. Interannual weather variability may also reduce the availability and efficiency of N fertilizer applications. Nitrogen is more readily leached in sandy soils that are typical of the North Florida region than in fine-textured soils. Fine-textured soils, when exposed to high rainfall, may become saturated and increase N loss to denitrification. Leaching potential may increase with a single application in years with high rainfall leading to a

TABLE 7 Changes in carinata plant stand, seed yield, oil concentration, oil yield, 1,000-seed weight and test weight in response to 90 kg N ha^{-1} applied in a single, two-way or three-way split application at planting (P), bolting (B) and flowering (F) during two winter−spring growing seasons at Quincy, FL

Treatment	Split management[a]	Timing of application[b]	Plant stand	Seed yield	Oil concentration	Oil yield	1,000-seed weight	Test weight
			plants m^2	kg ha^{-1}	%	L ha^{-1}	g	kg hl^{-1}
1	0	Control	38.1	2,861.2	50.0	1,594.0	3.8	67.4
2	1	P (100)	31.5 a	3,792.9 a[c]	48.5 a	2,032.0 a	3.8 a	67.6 a
3		B (100)	33.0 a	4,083.8 a	48.7 a	2,171.2 a	3.7 a	67.2 a
4		F (100)	39.9 a	3,626.8 a	45.6 b	1,865.9 a	4.0 a	66.8 a
5	2	P (50)/B (50)	34.8 a	3,964.8 a	48.9 a	2,125.7 a	3.7 a	67.4 a
6		B (50)/F (50)	37.6 a	3,549.3 a	48.0 a	1,876.5 a	3.8 a	67.6 a
7		P (50)/F (50)	37.7 a	3,852.2 a	47.8 b	2,028.8 a	3.8 a	67.1 a
8	3	P (50)/B (25)/F (25)	34.6 a	4,217.4 a	48.3 a	2,234.5 a	3.8 a	67.7 a
9		P (25)/B (50)/F (25)	38.2 a	4,271.5 a	48.2 a	2,248.6 a	3.8 a	67.4 a
10		P (25)/B (25)/F (25)	37.5 a	3,783.5 a	47.6 b	1,979.6 a	3.8 a	67.0 a
11	ESN	P (100)	36.7 a	3,606.4 b	47.4 b	1,875.5 b	3.8 a	67.2 a
12		B (100)	38.0 a	4,405.5 a	51.4 a	2,455.8 a	3.6 a	67.5 a
13		F (100)	40.0 a	4,534.0 a	50.3 a	2,467.8 a	3.4 a	66.6 a
Contrasts (split management)								
	0 vs. 1		ns	*	*	**	ns	ns
	1 vs. 2		ns	ns	*	ns	ns	ns
	1 vs. 3		ns	ns	*	ns	ns	ns
	2 vs. 3		ns	ns	ns	ns	ns	ns
Contrasts (source)								
	1 vs. ESN		ns	ns	ns	ns	ns	ns

Note. ns: not significant.

[a] N fertilizer was applied in a single, two-way, or three-way split application at planting, bolting, and/or flowering.

[b] The % N applied at planting (P), bolting (B), and flowering (F) in the single, two-way or three-way split management is in parenthesis.

[c] Means within split management followed by the same lowercase letter were not significantly different ($P > .05$) according to the pdiff option in PROC Mixed.

*Significant at the .05 level. **Significant at the .01 level. ***Significant at the .001 level.

reduction in soil N and N deficiency. Conversely, dry conditions may limit the movement of applied N from the point of application to the root zone of the carinata plant. Optimal availability of N during the season can minimize the translocation of N from the vegetative to the reproductive tissues resulting in increased leaf duration, photosynthesis, carbohydrate production, and seed yield. Since carinata requires different nutrient rates at different growth stages (Seepaul et al., 2019b), N applications should be synchronized with maximum nutrient uptake, which occurs between 50% bolting and 50% flowering (Seepaul et al., 2019b) for optimum yields, therefore providing adequate N during this period should be a key goal of N management. Splitting and timing N to maximize uptake may minimize N loss, improve the N use efficiency, and may also minimize early-season susceptibility to frost damage. Excessive N applied at planting promotes luxuriant growth and denser canopies that are more sensitive to frost damage (Mulvaney et al., 2018).

3.5.4 | Nitrogen source

The source of N did not have an effect on plant height, nodes, primary branches, pod length, and seeds per pod (Table 1). However, secondary branches and pod numbers increased by 21 and 20%, respectively, when 90 kg ha^{-1} ESN was applied in a single application (Table 1). The application of either ammonium nitrate or ESN at bolting resulted in maximum secondary branches and pod numbers. Nitrogen source did not have an effect on seed yield, oil concentration, oil yield, seed weight, protein concentration, polyunsaturated, monosaturated, saturated fatty, long-chain, very-long-chain fatty acids, or fatty acid composition (Tables 7 and 8). Glucosinolate concentration was 12% lesser with ESN application relative to ammonium nitrate. The ESN did increase grain yield, grain N uptake, or total crop N uptake in winter wheat in North Carolina (Rajkovich et al., 2017). However, ESN reduced nitrous oxide emissions by 34 and 9% relative to urea and urea

TABLE 8 Carinata chemical composition in response to 90 kg N ha^{-1} applied in a single, two-way or three-way split application at planting (P), bolting (B) and flowering (F) during two winter–spring growing seasons at Quincy, FL

Treatment	Split management[a]	Timing of application[b]	Glucosinolate concentration	Protein concentration	Polyunsaturated fatty acids	Monounsaturated fatty acids	Saturated fatty acids	Long-chain fatty acids	Very long chain fatty acids
			mmol kg^{-1}	%					
1	0	Control	71.5	23.6	60.3	33.4	6.2 a	43.7 a	54.6 a
2	1	P (100)	74.7 a[c]	25.0 a	59.9 a	33.5 a	6.2 a	44.0 a	56.0 a
3		B (100)	76.0 a	25.3 a	60.1 a	33.5 a	6.2 a	43.9 a	56.2 a
4		F (100)	79.1 a	26.0 a	59.9 a	33.5 a	6.1 a	44.4 a	55.7 a
5	2	P (50)/B (50)	83.8 a	27.3 a	59.2 a	34.1 a	6.2 a	44.0 a	56.0 a
6		B (50)/F (50)	81.3 a	26.3 a	59.3 a	33.9 b	6.1 a	44.5 a	55.6 a
7		P (50)/F (50)	82.3 a	26.6 a	59.7 a	33.8 b	6.2 a	44.3 a	55.8 a
8	3	P (50)/B (25)/F (25)	76.5 b	25.5 a	59.8 a	33.7 a	6.2 a	44.8 a	55.3 a
9		P (25)/B (50)/F (25)	76.8 b	25.6 a	60.0 a	33.4 a	6.1 a	43.7 a	56.4 a
10		P (25)/B (25)/F (25)	79.9 a	26.3 a	59.8 a	33.6 a	6.2 a	43.8 a	56.3 a
11	ESN	P (100)	73.9 a	25.4 a	60.0 a	33.5 a	6.3 a	43.4 a	56.6 a
12		B (100)	59.2 b	25.4 a	61.4 a	31.9 a	6.2 a	40.8 a	59.2 a
13		F (100)	68.7 a	26.3 a	60.5 a	32.8 a	5.9 a	42.7 a	57.3 a
Contrasts (split management)									
	0 vs. 1		*	***	ns	***	ns	*	*
	1 vs. 2		***	ns	ns	ns	ns	ns	ns
	1 vs. 3		ns	ns	ns	ns	ns	ns	ns
	2 vs. 3		ns	ns	ns	ns	ns	ns	ns
Contrasts (source)									
	1 vs. ESN		***	ns	ns	ns	ns	ns	ns

Note. ns: not significant.

[a] N fertilizer was applied in a single, two-way, or three-way split application at planting, bolting, and/or flowering.

[b] The % N applied at planting (P), bolting (B), and flowering (F) in the single, two-way or three-way split management is in parenthesis.

[c] Means within split management followed by the same lowercase letter were not significantly different ($P > .05$) according to the pdiff option in PROC Mixed.

[*] Significant at the .05 level. [**] Significant at the .01 level. [***] Significant at the .001 level.

TABLE 9 Carinata fatty acid composition in response to 90 kg N ha^{-1} applied in a single, two-way or three-way split application at planting (P), bolting (B), and flowering (F) during two winter–spring growing seasons at Quincy, FL

Treatment	Split management[a]	Timing of application[b]	Palmitic acid	Stearic acid	Oleic acid	Linoleic acid	Linolenic acid	Eicosenoic acid	Erucic acid
		%							
1	0	Control	3.2	1.3	14.3	16.3	12.7	9.5	36.8
2	1	P (100)	3.2 a[c]	1.2 a	13.1 a	16.1 a	13.1 a	9.1 a	38.0 a
3		B (100)	3.2 a	1.2 a	12.7 a	15.7 a	13.2 a	9.2 a	38.6 a
4		F (100)	3.2 a	1.2 a	12.6 a	15.8 a	13.4 a	9.0 a	39.0 a
5	2	P (50)/B (50)	3.2 a	1.3 a	13.8 a	16.8 a	12.9 a	8.9 a	37.1 a
6		B (50)/F (50)	3.2 a	1.2 a	12.5 a	15.9 a	13.4 a	9.1 a	38.7 a
7		P (50)/F (50)	3.2 a	1.2 a	13.2 a	16.2 a	13.2 a	8.8 a	38.4 a
8	3	P (50)/B (25)/F (25)	3.2 a	1.2 a	13.5 a	16.0 a	13.2 a	9.0 a	38.2 a
9		P (25)/B (50)/F (25)	3.2 a	1.2 a	12.7 a	15.9 a	13.2 a	9.2 a	38.9 a
10		P (25)/B (25)/F (25)	3.2 a	1.2 a	13.1 a	16.2 a	13.1 a	9.1 a	38.4 a
11	ESN	P (100)	3.2 a	1.3 a	13.6 a	16.1 a	12.9 a	9.2 a	38.2 a
12		B (100)	3.1 a	1.3 a	12.9 a	14.4 a	13.0 a	10.4 a	38.5 a
13		F (100)	3.2 a	1.2 a	11.2 a	14.4 a	14.0 a	9.7 a	38.3 a
Contrasts (split management)									
	0 vs. 1		ns	ns	ns	ns	ns	ns	*
	1 vs. 2		ns	ns	ns	ns	ns	ns	ns
	1 vs. 3		ns	ns	ns	ns	ns	ns	ns
	2 vs. 3		ns	ns	ns	ns	ns	ns	ns
Contrasts (source)									
	1 vs. 4		ns	ns	ns	ns	ns	ns	ns

Note. ns: not significant.

[a] N fertilizer was applied in a single, two-way, or three-way split application at planting, bolting, and/or flowering.

[b] The % N applied at planting (P), bolting (B), and flowering (F) in the single, two-way or three-way split application is in parenthesis.

[c] Means within split management followed by the same lowercase letter were not significantly different ($P > .05$) according to the pdiff option in PROC Mixed.

*Significant at the .05 level. **Significant at the .01 level. ***Significant at the .001 level.

ammonium nitrate (Halvorson, Del Grosso, & Francesco, 2010). Although ESN did not confer agronomic benefits to carinata, it may enhance the sustainability of production by reducing greenhouse gas emissions. Its use, however, may be restricted to the economics of ESN application.

These results demonstrated the effect of N application rate, split management, and source on carinata growth, seed yield, and chemical composition. Carinata growth, yield components, seed, and oil yield were more responsive to N application rate rather than split management or source. Our results demonstrate that agronomic variables such as optimizing N rate may lead to higher yield appear more controllable than those that lead to a concomitant increase in oil concentration. In developing an integrated N management strategy to improve seed yield and agronomic N use efficiency, especially in soils with high leaching potential, the optimum rate and split management of N may reduce the potential for environmental pollution and improve economic returns. Although the mean agronomic optimum yield of 2,444 kg ha^{-1} was produced at 117 kg N ha^{-1}, economic and environmental considerations suggest that carinata can be grown at the EONR of 103 kg N ha^{-1}, which produced 2,427 kg seed ha^{-1} representing a \$386 ha^{-1} profit margin. Carinata yield did not respond to split management of N or source. Synchronizing N supply with crop uptake and utilization will reduce N losses throughout the growing season and enhance N use efficiency and cropping system sustainability.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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