

Variety screening trial of *Brassica carinata* as a summer intermediate crop in Northern Italy

Maria Giovanna Sessa^a, Federica Zanetti^{a,*}, Rick Bennett^b, Agustina Sans^b,
Micah Gartenberg^c, Andrea Monti^a

^a Dept. of Agricultural and Food Sciences (DISTAL), University of Bologna, Italy

^b Nuseed Canada, 1-110 Wheeler St., Saskatoon, SK S7P 0A9, Canada

^c Department of Plant Sciences, North Dakota State University, Fargo, ND, USA

ARTICLE INFO

Keywords:

Cover crop
Brassicaceae
Fallow replacement
Oilseed crop
Seed yield

ABSTRACT

Intermediate oilseed crops serve a dual purpose by providing feedstock for the biofuel industry while also offering ecosystem services and additional income to farmers. Winter intermediate crops, such as camelina (*Camelina sativa* L.), have been identified as a suitable strategy for northern Italy, meanwhile, there remains a complete lack of possible alternatives for summer intermediate crops. Nonetheless, winter cereals continue to spread across a larger growing area. This study aimed to evaluate the agronomic performance of 13 different varieties of *carinata* (*Brassica carinata* A. Braun) provided by Nuseed (Canada), and grown as an intermediate summer crop in 2021 and 2022 in northern Italy. *Carinata* was planted in early June and harvested by the end of September. Key meteorological parameters were also recorded. In 2021, limited precipitation led to early maturity of *carinata*, reaching 2130 Growing Degree Days (GDD) in 101 days, from sowing to harvest. In contrast, in 2022, a wetter growing season resulted in seed maturity at 2885 GDD over 147 days. *Carinata* seed yield varied greatly across varieties, between 0.24 Mg ha⁻¹ up to 1.92 Mg ha⁻¹, a range likely influenced by genetic factors. This study demonstrates that *carinata* presents a promising intermediate summer crop, particularly when seed yield exceeds 0.96 Mg ha⁻¹, which represents the break-even yield to fully compensate for cultivation costs. To enhance *carinata* productivity, selection of the most suitable variety for each pedo-climatic area can help to overcome damages caused by abiotic (i.e., heat and drought) and biotic (i.e., *Altica oleracea*, *Nysius cymoides*) stresses.

1. Introduction

Intermediate crops are defined as crops cultivated between the growth cycles of main staple crops (Pieters, McKee, 1938; Brady and Weil, 1999). In recent years, the potential of intermediate crops and cover crops has reemerged due to the rising costs of agricultural inputs, increasing soil degradation, and the need to embrace sustainable management practices. In addition, intermediate crops can play an important role as they are cultivated as a replacement for fallow, thus they can provide extra income for farmers. Additional beneficial functions of intermediate cover crops are the ecosystem services they provide, which include weed control, increase of soil organic matter and nutrients, protection against soil erosion, and improvement of soil structure (Sarrantonio and Gallandt, 2003). In the European Union, the percentage of utilization of cover crops increased from 6.5 % in 2010 to 8.9 % in

2016 across all arable land. In the future, this percentage is expected to grow further because intermediate crops and cover crops are considered valid strategies to mitigate greenhouse gas (GHG) emissions (Fendrich et al., 2023). Currently, most intermediate crops and cover crops are harvested to produce hay or silage, or are otherwise terminated with herbicides or mechanical tillage to prepare the soil for the sowing of the main crop. Nevertheless, intermediate oilseed crops, managed as cover crops, can provide sustainable feedstocks (seeds and oil) for the biofuel industry, while also presenting an innovative strategy to pursue European Green Deal goals and related environmental benefits. The European Green Deal [Regulation (EU) 2021/1119] aims to reduce GHG emissions by at least 55 % by 2030 when compared to 1990 levels, with the overall goal of achieving carbon neutrality in the European Union by 2050. Moreover, the Renewable Energy Directive III [Directive (EU) 2023/2413] was established to help achieve a target of providing 42.5 %

* Corresponding author.

E-mail address: federica.zanetti5@unibo.it (F. Zanetti).

<https://doi.org/10.1016/j.indcrop.2025.121427>

Received 31 January 2025; Received in revised form 4 April 2025; Accepted 28 June 2025

0926-6690/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

of energy from renewable sources in the European Member States by 2030.

In order to avoid Land Use Change (LUC) effect, the production of biomass for bioenergy must derive from marginal land (Achten et al., 2012; Campbell et al., 2008). Another strategy to avoid competition for land and natural resources between non-food and food crops is the replacement of fallow periods with cultivation of intermediate oilseed crops, which allows for more efficient use of the limited availability of productive arable land. According to the definition provided by the RED II Article 2 (40), the use of intermediate oilseed crops, such as catch and cover crops, do require additional land and are considered sustainable sources for producing low-iLUC energy in the rail and road transport sectors [Directive (EU) 2018/2001]. Meanwhile, the aviation sector is urgently seeking new alternatives to fossil fuels, hence the European Commission launched the ReFuelEU Aviation proposal [Regulation (EU) 2023/2405] to achieve a 63 % share of Sustainable Aviation Fuels (SAF) by 2050. Under the Regulation (EU) 2023/2405, the definition of SAF includes aviation biofuels, synthetic aviation fuels, and recycled carbon aviation fuels. To ensure domestic production of biofuels, it is necessary to identify new, easy-to-grow oilseed crops.

This is the case of Ethiopian mustard (*Brassica carinata* A. Braun), a non-food oilseed crop that can contribute to a sustainable energy transition. Carinata oil is high in erucic acid (40–45 %) and has a low concentration of linoleic acid (14–17 %) and oleic acid (6–10 %) (George et al., 2021). Carinata oil is suitable for many purposes, such as the production of biofuel, especially SAF, (Seepaul et al., 2021, Del Gatto et al., 2015). Specifically, the use of carinata-based SAF reduces greenhouse gases emissions by at least 65 % compared to conventional aviation fuel (Liu et al., 2024; Alam et al., 2021). Moreover, the eco-efficiency of SAF production from carinata depends on obtaining government incentives and subsidies, as well as the commercialization of carinata co-products (Karami et al., 2024; Alam et al., 2021). In fact, carinata seed cake, with low fiber content and high protein content (18.7–28.3 % protein), could be a valuable ingredient for livestock feed (Schulmeister et al., 2019). Presumably native to the Ethiopian high plains, carinata is suited to the Mediterranean climate (Pan et al., 2012). As a result, the interest in carinata production has spread in southern European countries such as Italy, Spain, Greece, and the southern part of France (Seepaul et al., 2021). The increasing interest in carinata corresponds to its adaptability to unfavorable environmental conditions when compared with other *Brassicaceae* species such as *B. napus*. According to Seepaul et al. (2018), carinata is more tolerant to heat and drought stress and is resistant to seed shattering when compared with canola (*B. napus*). Carinata typically has low water demands and irrigation treatments can be limited to only reproductive stages to conserve water (George et al., 2021). As a result of its characteristics, carinata could be cultivated without affecting food production, confirming that carinata can be grown as an intermediate crop.

Carinata thrives in a broad spectrum of climatic conditions. In Italy, old studies identified carinata sown in fall (late October to early November) and harvested in summer (mid-June to early July) as the most feasible cropping system for this area when carinata is the main crop (Cardone et al., 2003, Del Gatto et al., 2015, Montemurro et al., 2016). Nevertheless, the actual legislation for SAF production and the consequent demand for new intermediate crops have paved the way for the present study, which is the first, as far as authors know, in which carinata is tested as a summer intermediate crop in Italy. The present work aims to evaluate the agronomic performance of different varieties of carinata grown as summer intermediate crops in Northern Italy, where summer is the typical fallow period after winter cereal harvest. So far, existing research has identified feasible fall/winter intermediate crops, such as camelina in southern Europe (Berzuini et al., 2024), or carinata in the southern US (Liu et al., 2024), but there remains a lack of available research on summer intermediate crops, a part from some initial attempts for camelina in northern France (Leclere et al., 2018). Additionally, in the Mediterranean basin, climate change effects are

often highly impactful on summer staple crops, such as corn (*Zea mays*). Consequently, farmers are more often adopting cropping systems based on winter crops, meaning they need summer intermediate crops that could potentially fill this otherwise fallow period in their rotations. Therefore, a two-year study was carried out to identify the main challenges and opportunities regarding the cultivation of carinata in summer with focus on sustainable agronomic practices.

2. Materials and methods

2.1. Genetic materials, experimental layout, and agronomic practices

The accessions of carinata tested during the two years were provided by Nuseed (Saskatoon, Canada, Table 1). Field trials consisted of six and seven varieties cultivated in the summers of 2021 and 2022, respectively. Carinata varieties included experimental breeding lines and an open-pollinated check from the NUSEED breeding program, as reported in Table 1. All carinata varieties were screened for the first time under Northern Italy growing conditions as a summer intermediate crop. Each season, newly released varieties were included in the trials, keeping two varieties (i.e., DH-129.B036 and HYB097) in common across both years to ensure a comprehensive evaluation of their performance. In 2022, an additional two commercial varieties, NUJET 400 and HYB093, were included in the experimental trial.

The field experiment was carried out at the Experimental Farm of Bologna University located at Cadriano (Bologna, 44°33' lat. N, 11° 21' E, 32 m a.s.l.), Northern Italy, in summer 2021 and summer 2022. According to historical climate records, the long-term average of summer precipitation (from June to September) at the study site is ~150 mm. The soil was classified as a clay loam soil (25 % sand, 50 % clay, 25 % silt) with high exchangeable potassium (239 mg kg⁻¹), and low assimilable phosphorus (22 mg kg⁻¹) and nitrogen content (1.31 mg kg⁻¹). The soil presented an alkaline pH of 8.05 and an average organic matter content of 1.9 %.

The trials were organized according to a randomized complete block design (RCBD) with three and four replications in 2021 and 2022, respectively. Bread wheat (*Triticum aestivum*) was the preceding crop in the previous growing seasons in both years. Before sowing, typical tillage adopted in the region was used, including ploughing 0.3 m deep, and superficial harrowing. Carinata was sown using a mechanical precision plot seeder (Vignoli group, Italy), with a seeding rate of 175 seeds m⁻², which corresponds to about 7.35 kg ha⁻¹. Row spacing was 0.13 m and seeding depth was adjusted to 10 mm. In 2021, plots were 1.75 m

Table 1

Accessions, main characteristics, and study year of tested carinata varieties provided by NUSEED.

Experimental hybrids*	Study year	
	2021	2022
DH-129.B036	OP check	OP check
HYB062	Test hybrid, EU Yr1	
HYB079	Test hybrid, EU Yr1	
HYB094	Test hybrid, EU Yr1	
HYB096	Test hybrid, EU Yr1	
HYB097	Test hybrid, EU Yr1	Test hybrid, EU Yr 2
NUJET 400		Commercial hybrid
HYB068		Test hybrid, EU Yr 2
HYB087		Early cycle, short stature, high oil advanced hybrid
HYB093 (NUJET 350)		Commercial hybrid
HYB095		Early cycle, short stature, high oil advanced hybrid

wide and 10 m long. In 2022, the plot size was adjusted to 1.75 m wide and 8 m long. Carinata was sown in early June for both 2021 and 2022, and was harvested in September 2021 and in October 2022, respectively. Nitrogen was applied at a rate of 60 kg ha⁻¹ in the form of urea before stem elongation, approximately 30 days after sowing (DAS). Weed control and removal was performed by hand, when necessary. In both years, chemical pest control was performed against *Altica oleracea*, while in 2022, pest control was also performed against *Nysius cymoides*. These pests were controlled by applying different pyrethroid-based pesticides as needed. In both years, irrigation was applied with a sprinkler system, providing approximately 70 mm of water between sowing and flowering initiation (end of July).

2.2. Measurements

Daily air temperature (min. and max.) and precipitation were recorded by the weather station of the Experimental Farm of the Bologna University in Cadriano (Bologna, Italy, 44°33' lat. N, 11° 21' E, 32 m a.s.l.). Growing Degree Days (GDD) were calculated considering the base temperature for carinata as 4°C (Zanetti et al., 2013). At 20 days after sowing (DAS), emergence count (plants m⁻²) was assessed in each plot by counting plants in two 1 m-long rows of each plot. The main phenological stages were surveyed, according to the BBCH scale for canola (Lancashire et al., 1991). Carinata soil coverage (%) was evaluated by taking three photos for each plot using the Canopeo mobile device application (Patrignani, Ochsner, 2015) at the stem elongation stage (55 DAS). Later, at BBCH 69 (flowering stage), occurring from 59 to 79 DAS in 2021, and from 60 to 71 DAS in 2022, plant height was assessed by measuring 10 plants in each plot. In the 2022 trial only, at BBCH 89 (92 DAS), corresponding to the ripening stage, the plants in two 1-m-long rows of each plot were sampled. The harvested biomass was then partitioned into leaves, stems, and siliques, and all plant parts were then weighed separately. Each part was oven-dried at 105°C until constant weight to determine the residual moisture content; then, the dry matter weight of leaves (Mg DM ha⁻¹), stems (Mg DM ha⁻¹) and siliques (Mg DM ha⁻¹) was determined.

2.3. Surveys at harvest

Carinata was hand-harvested at full seed maturity, corresponding to mid-September in 2021 and mid-October in 2022. A sampling area of 6 m in the central portion of each plot was manually harvested to determine the total biomass. At the same time, plant density was surveyed by counting plants in two 1-m rows in each plot. Seed yield (Mg DM ha⁻¹) was determined by using a plot combine (Wintersteiger, Austria). Sub-samples of seeds and straw were oven-dried at 105°C until constant weight to determine the residual moisture content. Then, 1000-seed weight was measured on representative seed samples of each variety by using the DATA COUNT S-25 seed counter machine at Seed Research and Analysis Laboratory (LaRAS) of the University of Bologna; then the precision balance METTLER TOLEDO PC180 was used to determine the 1000-seed weight.

2.4. Statistical analysis

Statistical analysis of data was carried out by using CoSTAT 6.451 (CoHort software). Before analysis of variance (ANOVA), the homoscedasticity of data was verified by performing Barlett's Test ($P \leq 0.05$). Two types of ANOVA were carried out: i) One-way ANOVA comparing the surveyed parameters among all the different varieties was performed for each year (2021 and 2022). ii) Two-way ANOVA only for the common varieties across different years, with "year" considered as a fixed factor. When the analysis of variance was significant ($P \leq 0.05$), the Least Significant Difference (LSD) test was used to separate means.

3. Results and discussion

3.1. Meteorological conditions and crop phenology

The main meteorological data are reported in Table 2. During 2021, the total precipitation from sowing to harvest was only 26 mm, which was remarkably lower than the 10-year mean precipitation (150 mm). Temperatures followed a regular pattern, closely aligning with typical values for the study site (Table 2). In 2022, the cumulative precipitation, from sowing to harvest, was 162 mm, which was close to the 10-year mean precipitation (Table 2). Nonetheless, it is worth highlighting that only 40 mm of the total precipitation occurred from sowing until mid-August, when plants were at the end of the flowering phase and the beginning of the seed formation phase. The summer of 2022 was also characterized by exceptionally higher temperatures than historical means during June (+2 °C) and July (+1.3 °C). These conditions likely led to a massive attack by *Nysius cymoides*, an alien pest (Scaccini and Furlan, 2019), which caused relevant damages to carinata, particularly to earlier-maturing varieties, such as DH-129.B036, which were at flowering stage when the attack occurred.

According to a previous study conducted in Europe within a winter sowing cycle (Zanetti et al., 2013), carinata reached physiological maturity at 2000–2200 GDD. Meanwhile, data for summer sowing of carinata have not been reported in the literature. In the present study, the cumulative GDD from sowing to harvest were 2130 GDD in 2021, corresponding to a 101-d cycle, and 2885 GDD in 2022, corresponding to a 147-d cycle (Table 2). The main differences between the two growing seasons regarded the lack of precipitation in 2021 throughout the whole carinata life cycle, and the very uneven precipitation pattern coupled with heat waves in 2022. The prolonged drought of the 2021 growing season presumably caused the anticipated maturity of carinata, as confirmed by Licata et al. (2024). In contrast, the scattered precipitation pattern in 2022, starting in the second half of August, presumably led to a prolongation of the carinata life cycle. Nevertheless, results for carinata GDD accumulation were similar between years, while the cycle length in terms of days was more variable. This response to varying seasonal weather confirms that carinata is a rustic crop adaptable to harsh and challenging meteorological conditions, modulating the length of its cycle accordingly, a highly valuable trait for an emerging crop. The main phenological phases of carinata were surveyed in the two-year study and are reported in Table 3. The duration of each phase was influenced by different environmental factors (i.e., air temperature, soil

Table 2

Monthly average minimum (Tmin °C), maximum (Tmax °C), mean temperatures (T. avg °C), cumulative precipitation (mm), and Growing Degree Days (GDD) calculated during the carinata growing cycle in 2021 and 2022 compared with long-term period (2010–2020).

Month	Tmin (°C)	Tmax (°C)	Tavg (°C)	Precipitation (mm)	GDD *
2021					
Jun	17.0	31.5	24.6	4	602
Jul	18.7	32.7	25.9	13.2	657
Aug	17.3	31.9	24.8	8.8	644
Sept	12.6	29.5	21.5	0	228
2022					
Jun	16.3	29.7	25.1	11.8	634
Jul	18.6	32.1	26.9	23.0	711
Aug	18.0	31.9	24.9	80.6	648
Sept	14.2	26.3	19.9	46.2	476
Oct	10.2	19.8	17.4	1.0	416
Long-term data (2010–2020)					
June	16.4	29.3	23.0	47.7	
July	18.5	31.9	25.4	26.5	
August	18.2	32.0	25.1	35.5	
September	15.7	28.0	21.6	34.3	
October	10.2	19.9	14.7	64.3	

* Tbase for GDD calculation: 4°C.

Table 3

Bimonthly average minimum (Tmin °C), maximum (Tmax °C), mean temperatures (T. avg °C), cumulative precipitation (mm), phenological stage (BBCH code) calculated from carinata sowing to harvest, corresponding to June-August in 2021, and June-October in 2022.

Period	Tmin (°C)	Tavg (°C)	Tmax (°C)	Precipitation (mm)	Phenological stage	BBCH code
2021						
Jun 1–15	16	22.5	29.3	4	Germination	00–09
Jun 15–30	17.8	26.2	33.3	0	Leaf development/Stem elongation	10–39
Jul 1–15	17.6	25.4	32.3	0.6	Inflorescence Emergence	50–59
Jul 15–30	19.8	26.5	33.0	12.6	Flowering/Development of Fruit	60–79
Aug 1–15	18.8	26.7	34.1	2	Development of Fruit/Ripening	79–89
Aug 15–30	15.9	23	29.9	6.8	Ripening	81–89
2022						
Jun 1–15	16.4	23.2	29.7	11.8	Germination	00–09
Jun 15–30	18.5	26.5	33.1	0.2	Leaf development	10–29
Jul 1–15	17.5	26.1	33.4	22.8	Stem elongation	30–39
Jul 15–30	19.8	27.8	35.1	0.2	Inflorescence Emergence	50–59
Aug 1–15	18.6	26.4	33.7	6.4	Flowering	60–69
Aug 15–30	18.3	24.2	30.8	73.6	Flowering/Development of Fruit	60–79
Sept 1–15	17.0	23.3	29.9	12.6	Development of Fruit	71–79
Sept 15–30	10.9	17	23.4	34.2	Ripening	81–89
Oct 1–15	12.2	17.7	24.1	0.4	Ripening	81–89

temperature, precipitation) and possibly differing maturation speeds between varieties. As reported in the literature for oilseed rape, temperature influences crop physiology, but drought stress at early stages could severely affect establishment (Pullens et al., 2019). As is the case for canola, it is possible to hypothesize that temperature is one of the most important environmental factors regulating the phenological development of carinata (Morrison and Stewart, 2002).

3.2. Agronomic results

The results of the one-way ANOVA are reported in Table 4. Plant emergence was surveyed at ~20 DAS in 2021 and the mean value was 46 plants m⁻², with no statistically significant differences observed among varieties. In 2022, statistically significant differences emerged among varieties with plant emergence ranging from 19 plants m⁻² for DH-129.B036, up to 55 plants m⁻² for line HYB093 (Fig. 1). Interestingly, when analyzing the results for the two varieties common across the two years (i.e., DH-129.B036 and HYB097, Table 5), the effect of year, but not variety, was found significant and plant count was more than double (+113 %) in 2021 than in 2022 (Table 6). A study conducted by Gesch et al. (2019) indicated a baseline value for plant count at emergence carinata, ranging from 34 up to 117 plants m⁻², which aligns with the results obtained in the present study. The seeding rate adopted (175 seeds m⁻²) was significantly higher than the common values reported in the literature (129 seeds m⁻²) (Kumar et al., 2020). The increased seeding rate was considered appropriate for the experimental conditions, as summer intermediate crops grown in the Mediterranean basin would certainly face biotic and abiotic factors during their cycle. During the two-year trial, maximum air temperatures higher than 30°C and the scarcity of precipitation in the first part of the carinata life cycle led to a lower-than-expected emergence and consequent plant count. Carinata planted in the fall can benefit from higher precipitation at early stages and usually achieve a much better establishment (Hossain et al., 2019). On the other hand, as a result of delaying the sowing to late spring/summer, soil moisture is often inadequate to support quick and

even germination. According to Patanè and Tringali (2011), low or high temperatures combined with low soil water availability could negatively influence seed germination. However, according to Kebreab and Murdoch (1999), seedling survival is supported by faster germination at high temperatures in drying soil.

In the present study, carinata growth until the flowering phase was characterized by a lack of precipitation and high temperatures. In 2021, the mean crop coverage at the stem elongation phase (BBCH 39) was 65 % and statistical analysis revealed no significant differences among varieties. In 2022, soil coverage was lower than expected, with a mean value of 34 %. (Table 4). The highest soil coverage values were observed in plants able to form a large rosette of leaves, while the varieties showing the lowest soil coverage were earlier in reaching the stem elongation stage. To confirm this, HYB095, which obtained the lowest soil coverage value (24 %) had tall plants (0.81 m). When analyzing the year effect on the common varieties (i.e., DH-129.B036 and HYB097), soil coverage was almost double in 2021 (66 %) than in 2022 (36 %) (Table 6). In 2022, the extremely high temperatures that occurred during June and July, coupled with high pest pressure, negatively affected the early-developing variety DH-129.B036 in particular, with a consequent impaired ability to cover the soil. Plant height was influenced by variety choice (Table 4, Fig. 2). The mean plant height was 0.70 m and the lowest value was observed in line DH-129.B036 in 2021 (0.63 m) and 2022 (0.43 m), respectively. The pest attack on DH-129.B036, at early growth stages, corresponding to leaf development (BBCH: 00–29), presumably reduced photosynthesis and the capacity of plants to allocate resources for stem elongation, both of which negatively affected final plant height. In 2021, the tallest plants were surveyed in line HYB097 at a height of 0.84 m; meanwhile, in 2022, the tallest varieties were HYB095 (0.81 m) and HYB068 (0.80 m), followed by HYB097 (0.76 m). Thus, concerning the two varieties grown in both years (Table 6), HYB097 produced tall plants with similar height in both years, while DH-129.B036 had taller plants in 2021 (0.63 m in 2021 vs. 0.43 m in 2022). The present results on plant height do not align with values reported in the available literature, for example, in carinata

Table 4

One-way ANOVA results (F-values) of the main parameters surveyed in 2021 and 2022 trials conducted at the Bologna experimental station. Surveyed parameters were: emergence count (plants m⁻²), soil coverage (%), plant height (m), total biomass (Mg DM ha⁻¹), seed yield (Mg DM ha⁻¹), and 1000-seed weight (g).

Year	Factor	Emergence count (plants m ⁻²)	Soil coverage (%)	Plant height (m)	Total biomass (Mg DM ha ⁻¹)	Seed yield (Mg DM ha ⁻¹)	1000-seed weight (g)
2021	Genotype	0.36 ^{ns}	0.79 ^{ns}	5.71 ^{**}	0.99 ^{ns}	0.65 ^{ns}	0.24 ^{ns}
2022		3.67 ^{**}	2.10 ^{ns}	46.5 ^{**}	2.54 ^{ns}	3.98 ^{**}	14.9 ^{**}

** significant for $P \leq 0.05$; ns = not significant

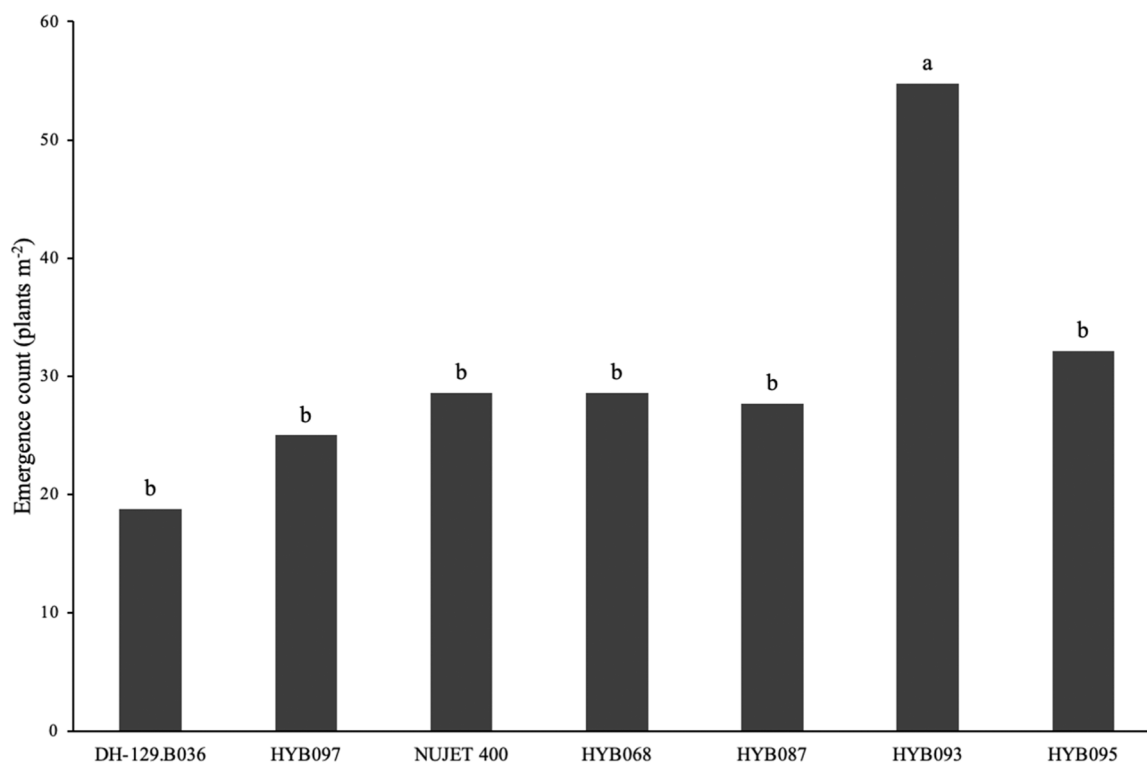


Fig. 1. Emergence count (plant m⁻²) of the seven different carinata varieties grown at Bologna in 2022. Different letters: significantly different values ($P \leq 0.05$, LSD test).

Table 5

Two-way ANOVA results (F-values) of the main parameters surveyed in two varieties (i.e., DH-129.B036 and HYB097) in common in the two-year screening trial conducted at Bologna experimental station. Surveyed parameters were: emergence count (plants m⁻²), soil coverage (%), plant height (m), total biomass (Mg DM ha⁻¹), seed yield (Mg DM ha⁻¹), and 1000-seed weight (g).

Factor	Emergence count (plants m ⁻¹)	Soil coverage (%)	Plant height (m)	Total biomass (Mg DM ha ⁻¹)	Seed yield (Mg DM ha ⁻¹)	1000-seed weight (g)
Genotype (A)	1.37 ^{ns}	0.02 ^{ns}	33.5**	N/A*	N/A*	N/A*
Year (B)	19.0**	19.6**	8.68**	0.45 ^{ns}	10.3**	0.10 ^{ns}
A x B	0.07 ^{ns}	0.41 ^{ns}	1.51 ^{ns}	N/A*	N/A*	N/A*

* The two-way ANOVA was not performed for total biomass, seed yield, and 1000-seed weight since variety DH-129.B036 did not reach harvest stage due to the strong attack of pests.

** significant for $P \leq 0.05$; ns = not significant

Seepaul et al. (2021) indicated a plant height of 1.16 m at the flowering stage and 1.34 m at harvest. In a study conducted in Northern Italy, carinata plants reached a final height of 1.61 m which was lower than the results reported for Southern Italy (1.87 m) (Del Gatto et al., 2015). The main difference between the aforementioned results and the present ones relate to the sowing season. As a consequence of drought and high temperatures, the limited water availability presumably resulted in extensive root growth as a strategy to fulfill carinata water requirements (Hossain et al., 2018). This condition might have led to a greater development of below-ground biomass at the expense of the above-ground biomass. The decrease in carinata aboveground biomass and consequent plant height, in response to drought, could be linked to biochemical limitations, as demonstrated in studies conducted on *Brassica napus* (Sangtarash et al., 2009). Despite the application of

Table 6

Results for emergence count (plants m⁻²), soil coverage (%), plant height (m), total biomass (Mg DM ha⁻¹), seed yield (Mg DM ha⁻¹) and 1000-seed weight (g) of the 2 common carinata varieties (i.e., DH-129.B036 and HYB097) grown at Bologna in the two consecutive growing seasons (2021–2022). Different letters: significant different values ($P \leq 0.05$, LSD test).

Parameter	Year	
	2021	2022
Emergence count (plants m ⁻¹)	49.3 ^a	23.2 ^b
Crop coverage (%)	66.2 ^a	36.2 ^b
Plant height (m)	0.74 ^a	0.60 ^b
Total biomass. (Mg DM ha ⁻¹)	5.29 ^a	5.95 ^a
Seed yield (Mg DM ha ⁻¹)*	0.38 ^b	1.13 ^a
1000-seed weight (g)*	4.49 ^a	4.57 ^a

* Total biomass, seed yield and 1000-seed weight results refer only to variety HYB097, since DH-129.B036 did not reached harvest stage due to the strong attack of pests.

external irrigation to support the development of carinata in summer, the crop seems to require a prolonged rehydration period to achieve complete growth (Galmés et al., 2007).

From the biomass partitioning (leaves, stems, siliques) (Fig. 3), performed only in 2022, stem biomass was on average 5.2 Mg DM ha⁻¹, while leaves and siliques produced both a biomass of 1.1 Mg DM ha⁻¹, each. According to the literature, the dry biomass of different plant parts is affected by water deficit (Husen et al., 2014). Furthermore, high temperature can also affect biomass production, particularly for siliques (Angadi et al., 2000), while leaf biomass is influenced by the self-defoliation that occurs during the reproductive stages as a strategy to redirect plant resources toward seed production (Seepaul et al., 2018).

At harvest, carinata total aboveground biomass was on average 4.29 Mg DM ha⁻¹ and 8.99 Mg DM ha⁻¹ in 2021 and 2022, respectively, without reporting statistical differences among varieties (Table 4). In

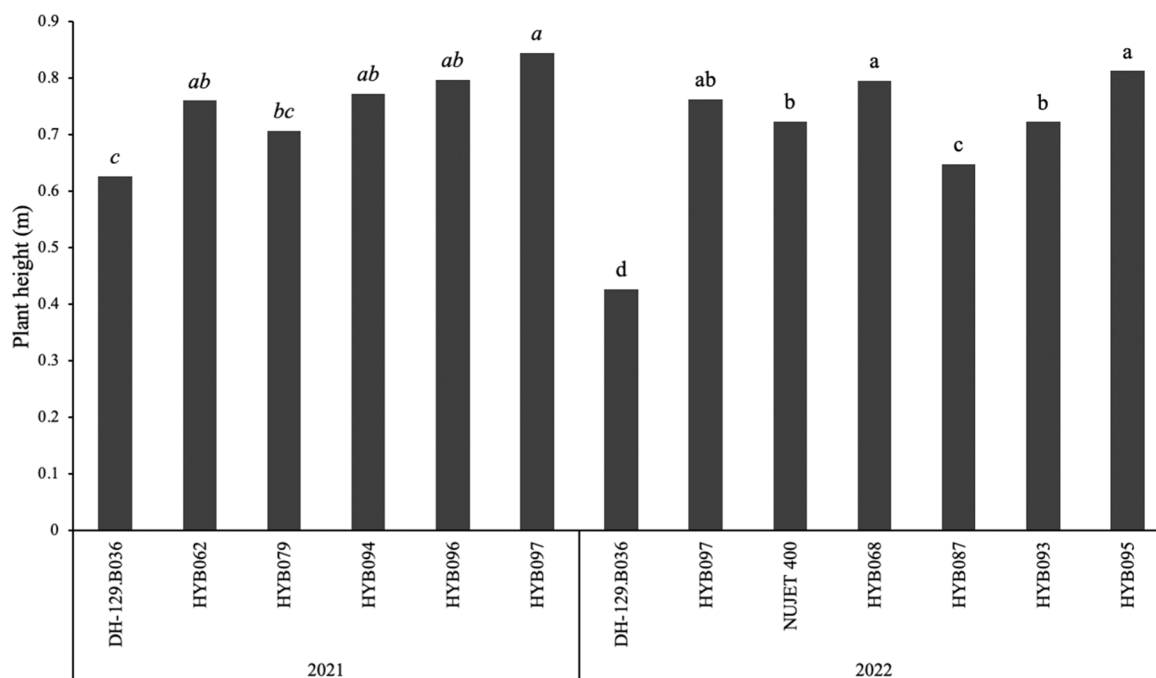


Fig. 2. Plant height (m) of the six and seven different carinata varieties grown at Bologna in 2021 and 2022, respectively. Different letters: significantly different values ($P \leq 0.05$, LSD test). Italic letters refer to the year 2021, while regular letters refer to the year 2022.

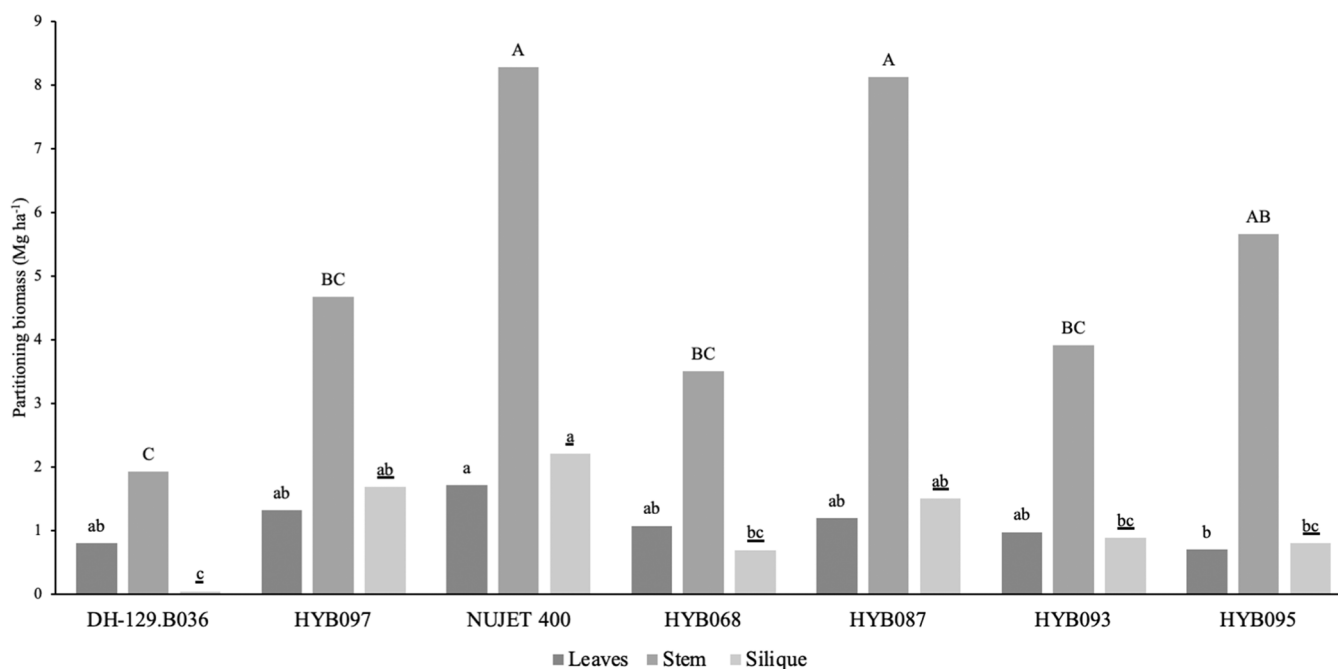


Fig. 3. Biomass partitioning of leaves (Mg DM ha^{-1}), stems (Mg DM ha^{-1}), and siliques (Mg DM ha^{-1}) of the seven different varieties grown at Bologna in summer 2022. Different letters: significantly different values ($P \leq 0.05$, LSD test).

other studies conducted in Italy in fall/winter sowing (Del Gatto et al., 2015), the biomass production yielded about three times higher in comparison with the present results, presumably due to the concurrent effect of both heat and drought stress (Licata et al., 2024), together with the shortened life cycle as a response to summer sowing. In 2021, carinata seed yield was on average $0.34 \text{ Mg DM ha}^{-1}$, without statistical differences among varieties (Table 4). In 2022, the average seed yield was remarkably higher (grand mean: $1.32 \text{ Mg DM ha}^{-1}$) and variety choice played a significant role. Seed yield varied greatly among

varieties, ranging between $0.70 \text{ Mg DM ha}^{-1}$ (NUJET 400) up to $1.92 \text{ Mg DM ha}^{-1}$ (HYB087), confirming the presence of genetically superior varieties in this second screening trial (Table 4, Fig. 4). It is noteworthy that variety DH-129.B036 recorded a seed yield of 0.4 Mg ha^{-1} in 2021, while in 2022 it was not harvested due to major pest injury. In particular, the alien pest, *Nyctelia cymoides*, caused relevant damages to the siliques, leading to abortion and seed malformation. Productivity losses might be also related to the early damage caused by other pests at the seedling stage, such as flea beetles (*Altica oleracea*). Flea beetles attack

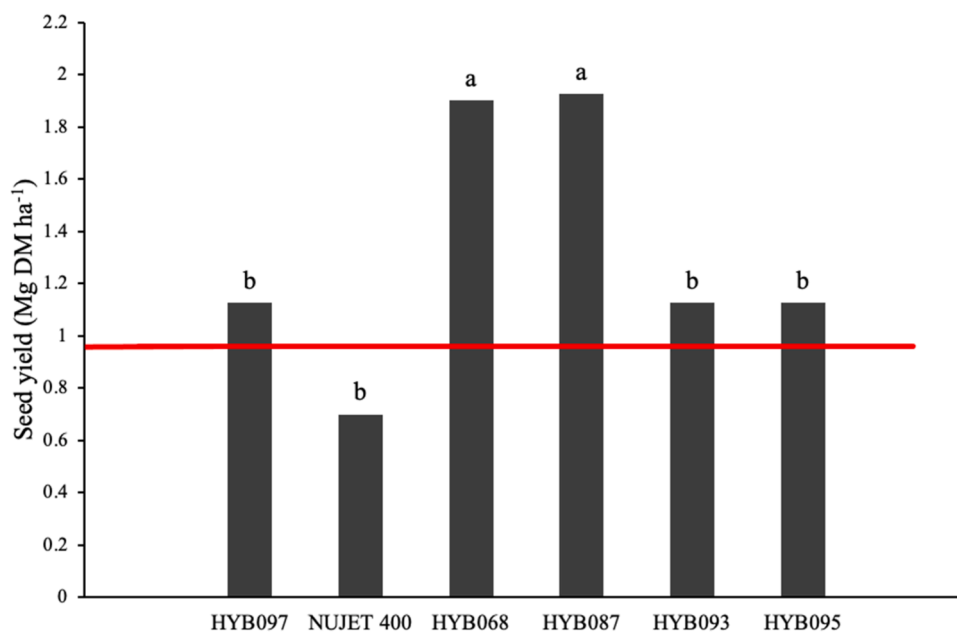


Fig. 4. Seed yield D.M (Mg DM ha⁻¹) of the seven different carinata varieties grown at Bologna in 2022. Different letters: significantly different values ($P \leq 0.05$, LSD test). The red line represents the break-even yield for carinata of 0.96 Mg DM ha⁻¹, calculated to compensate the cultivation costs in the present study.

plants at the cotyledon stage and, after their dissemination, also cause injury to young carinata stems. However, several pesticide applications were performed during the carinata life cycle, but pests persisted in causing significant damages. Furthermore, pesticides were sprayed directly after the visual detection of flea beetles, which was presumably too late to prevent the spread of the pest.

In a study conducted on some carinata varieties sown in the fall in Northern Italy under different input levels (Zanetti et al., 2009), resulting seed yields were remarkably higher (2.73 Mg ha⁻¹) than the ones obtained in the present study. According to Del Gatto et al. (2015), the seed yield of three different carinata varieties was on average 1.92 Mg ha⁻¹ in Northern Italy, a value in line with the results obtained in the present study but only for the most productive varieties in 2022.

Meanwhile in Central and Southern Italy, carinata achieved seed yields of 0.91 Mg ha⁻¹ and 3.10 Mg ha⁻¹, respectively. Considering the variety HYB097, which was grown across the two years, seed yield was significantly higher in 2022 (1.13 Mg ha⁻¹) than in 2021 (0.38 Mg ha⁻¹), mainly due to the higher precipitation availability during the final part of its cycle, and the consequent prolonged life cycle duration (Table 6). Nevertheless, it is important to note that in 2022 carinata emergence and soil coverage were lower than in 2021, thus confirming the outstanding capacity of the crop to cope with environmental stressors and compensate for low plant population by increasing branching and flowering potential. Carinata seed yields of approximately 2 Mg DM ha⁻¹ in summer sowing represent an outstanding result for a summer intermediate crop, particularly in the harsh environmental conditions

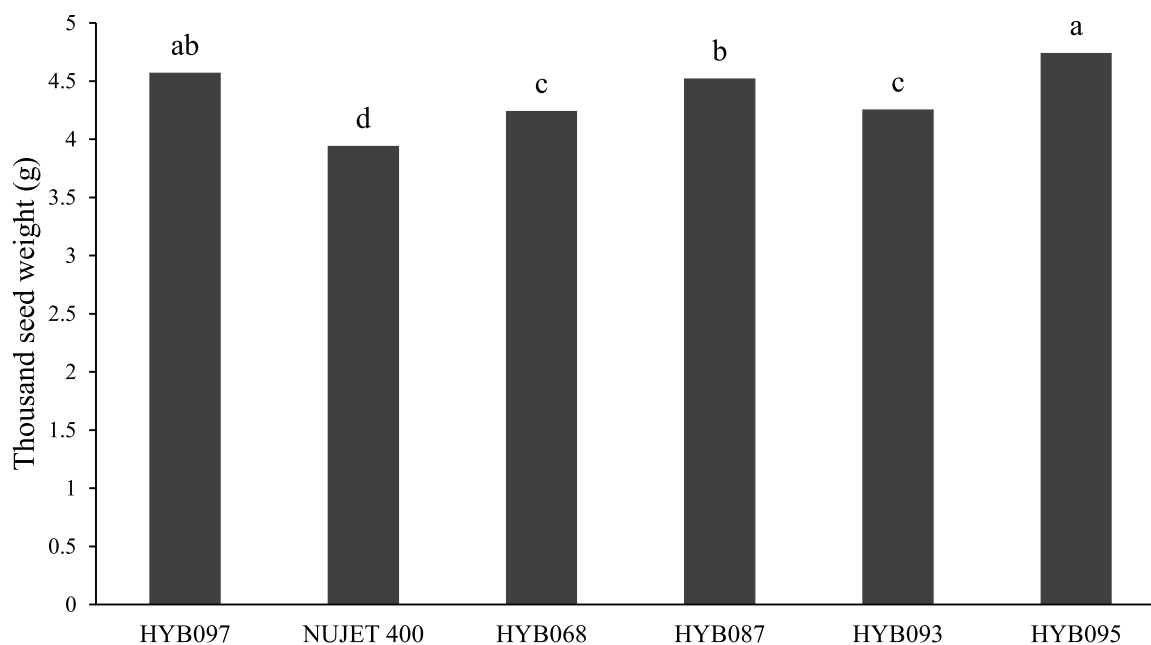


Fig. 5. Thousand seed weight (g) of the seven different carinata varieties grown at Bologna in 2022. Different letters: significantly different values ($P \leq 0.05$, LSD test).

found in Northern Italy. This result confirms the great potential of some carinata varieties (i.e., HYB068 and HYB087) for this type of sustainable cropping system.

Finally, 1000-seed weight was on average 4.4 g in both 2021 and 2022, a value higher than those reported in the literature by Seepaul et al. (2021), who indicated a mean 1000-seed weight of 4.12 g, and by Del Gatto et al. (2015), who investigated three different varieties of carinata in three locations (Northern, Central and Southern Italy) and reported a mean 1000-seed weight of 4.0 g. In 2022, among the different varieties, the 1000-seed weight ranged from 3.94 g (NUJET 400) up to 4.74 g (HYB095) suggesting that this trait is mainly under genetic control rather than influenced by biotic or abiotic factors (Fig. 5). This hypothesis is supported by variety HYB097 which obtained a 1000-seed weight of about 4.5 g in both years (Table 6).

Based on the findings of the present study, to determine whether carinata as summer intermediate crop can represent a sustainable source of income for farmers, it would be essential to compare the cultivation costs and the potential revenues derived from carinata seed sales. According to Basili and Rossi (2018), the production cost of carinata-derived biodiesel in Italy is estimated at 801.31 € Mg⁻¹, with the farming stage accounting for 501.70 € Mg⁻¹. In the present study, the data for the calculation of the cultivation are summarized in Table 7. The total production cost was 685.30 € ha⁻¹. However, farmers may receive additional revenues for cultivating intermediate crops between primary food crop cycles depending on local agricultural policies. For instance, in Italy, according to the CAP 2023–2027 [Regulation (EU) 2021/2115], the GEAC 7 established crop rotation obligation and, through the Eco-scheme 4, provides an extra payment of 110 € ha⁻¹ for farmers who introduce specific crops, such as oilseeds and legumes, into their rotation to preserve soil fertility and biodiversity. When including this payment, the total production cost of carinata could decrease up to 575.30 € ha⁻¹. Currently in Europe, there is no established market for carinata seeds to produce SAF, therefore no directly observable selling price is available. However, an alternative benchmark price could be based upon camelina seeds, certified according to RED III (Annex IX) [Directive (EU) 2023/2413] and eligible for SAF production, which are commonly traded at an average price of 600 € Mg⁻¹ of seeds. From this rough calculation, the farmer profit from carinata seed sales could be as high as 564.70 € ha⁻¹ for the most productive variety, i.e., HYB087 which achieved a seed yield of 1.92 Mg ha⁻¹ in 2022. In contrast, in 2021, the mean seed yield of the entire screening trial was 0.34 Mg ha⁻¹ which would lead to a loss of 371.3 € ha⁻¹ for farmers. The break-even yield of carinata, defined as the minimum seed yield required to cover production costs as a summer intermediate crop, was calculated to be 0.96 Mg ha⁻¹. This value was achieved in 2022 by almost all the tested carinata varieties (Fig. 4).

4. Conclusions

In the Mediterranean basin, drought and heat waves are becoming more frequent, and finding resilient crops adaptable to harsh climatic conditions is essential to fortify sustainable agriculture. In particular, as staple winter crops are likely to expand in the near future, the identification of summer intermediate crops is still very limited or completely absent. A summer intermediate crop, such as carinata, could provide raw material for the expanding bio-based industry sector while offering an additional income to farmers. The present study, to the best of the authors' knowledge, is the first on carinata as a summer intermediate crop in the Mediterranean region, highlighting several interesting opportunities as well as a few drawbacks. For example, variety selection is still in its infancy and would need to be further developed to produce elite-performing varieties that are available for other crops. The variety DH-129.B063 proved unsuitable to summer sowing in Northern Italy, mainly due to an extremely short life cycle and high susceptibility to pests. On the other hand, HYB068 reached the highest seed yield while soil coverage was quite low, thus possibly exposing the crop to high

Table 7

Total costs of carinata production as summer intermediate crop as calculated in the experimental trials.

Item	Cost (€ ha ⁻¹)
Sowing	70.0
Carinata seeds	54.0
Fertilization	55.0
Fertilizer	36.0
Spraying	55.0
Pesticide	4.0
Irrigation*	144.0
Water*	27.3
Harvesting	240.0
Total cost (€ ha ⁻¹)	685.30

* Irrigation treatment was assumed to be applied twice per hectare per growing season, giving 35 mm of water per application, as the typical amount used in the study area.

weed competition. Overall, HYB087 was the best variety when grown as a summer intermediate crop in the present experimental conditions, reporting high seed yield and soil coverage. In general, any variety able to provide seed yields higher than 1 Mg ha⁻¹ might represent a variety with potential, as any variety meeting this could cover all cultivation costs. In conclusion, while the inclusion of carinata into traditional cropping systems ensures crop diversification and a source for new bio-based feedstocks, it is necessary to carefully consider methods of agronomic management to couple cost reduction with sustainable production. In addition, new eco-friendly solutions to control flea beetles are required to overcome the problem of chemical products which are largely banned in Europe. Moreover, the perfect timing for pesticide applications is essential to eradicate the pest and ensure desired yields in the summer season.

CRedit authorship contribution statement

Maria Giovanna Sessa: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Monti:** Writing – review & editing, Supervision, Funding acquisition. **Agustina Sans:** Writing – review & editing. **Rick Bennett:** Writing – review & editing. **Micah Gartenberg:** Writing – review & editing. **ZANETTI FEDERICA:** Writing – review & editing, Writing – original draft, Conceptualization.

Funding

The present research received funding in a private collaboration agreement between the University of Bologna and Nuseed.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andrea Monti reports financial support was provided by University of Bologna Department of Agri-Food Sciences and Technologies. Andrea Monti reports a relationship with Nuseed that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

References

- Achten, W.M.J., Trabucco, A., Maes, W.H., Verchot, L.V., Aerts, R., Mathijs, E., Vantaomme, P., Singh, V.P., Muys, B., 2012. Global greenhouse gas implications of

- land conversion to biofuel crop cultivation in arid and semi-arid lands e lessons learned from *Jatropha*. *J. Arid Environ.* 1–11. <https://doi.org/10.1016/j.jaridenv.2012.06.015>.
- Alam, A., Hossain Masum, M.F., Dwivedi, P., 2021. Break-even price and carbon emissions of carinata-based sustainable aviation fuel production in the Southeastern United States. *GCB Bioenergy* 13, 1800–1813. <https://doi.org/10.1111/gcbb.12888>.
- Angadi, S., Cutforth, H., Miller, P., McConkey, B., Entz, M., Brandt, S., Volkmar, K., 2000. Response of three Brassica species to high temperature stress during reproductive growth. *Can. J. Plant Sci.* 80 (4), 693–701. <https://doi.org/10.4141/P99-152>.
- Basili, M., Rossi, M.A., 2018. *Brassica carinata*-derived biodiesel production: economics, sustainability and policies. The Italian case. *J. Clean. Prod.* 191, 40–47. <https://doi.org/10.1016/j.jclepro.2018.03.036>.
- Berzuini, S., Zanetti, F., Alberghini, B., Leon, P., Prieto, J., Herreras Yambanis, Y., Trabelsi, I., Hannachi, A., Udupa, S., Monti, A., 2024. Assessing the productivity potential of camelina (*Camelina sativa* L. Crantz) in the Mediterranean basin: Results from multi-year and multi-location trials in Europe and Africa. *Ind. Crops Prod.* 291, 119080. <https://doi.org/10.1016/j.indcrop.2024.119080>.
- Brady, N.C., Weil, R.R., 1999. *The Nature and Properties of Soils, 12th Edition*. Prentice Hall Publishers, London.
- Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B., 2008. The global potential of bioenergy on abandoned agricultural lands. *Environ. Sci. Technol.* 42, 5791–5794. <https://doi.org/10.1021/es800052w>.
- Cardone, M., Mazzoncini, M., Menini, S., Rocco, V., Senatore, A., Seggiani, M., Vitolo, S., 2003. *Brassica carinata* as an alternative oil crop for the production of biodiesel in Italy: agronomic evaluation, fuel production by transesterification and characterization. *Biomass. Bioenergy* 25 (6), 623–636. [https://doi.org/10.1016/S0961-9534\(03\)00058-8](https://doi.org/10.1016/S0961-9534(03)00058-8).
- Del Gatto, A., Mellilli, M., Raccuia, S., Pieri, S., Mangoni, L., Pacifico, D., Signor, M., Duca, D., Foppa Pedretti, E., Mengarelli, C., 2015. A comparative study of oilseed crops (*Brassica napus* L. subsp. *oleifera* and *Brassica carinata* A. Braun) in the biodiesel production chain and their adaptability to different Italian areas. *Ind. Crops Prod.* 75, 98–107. <https://doi.org/10.1016/j.indcrop.2015.04.029>.
- Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). (<https://eur-lex.europa.eu/eli/dir/2018/2001/oj/eng>).
- Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. <http://data.europa.eu/eli/dir/2023/2413/oj>.
- Fendrich, A.N., Matthews, F., Eynde, E.V., Carrozzi, M., Li, Z., d'Andrimont, R., Lugato, R., Martin, P., Ciais, P., Panagos, P., 2023. From regional to parcel scale: a high-resolution map of cover crops across Europe combining satellite data with statistical surveys. *Sci. Total Environ.* 873, 162300. <https://doi.org/10.1016/j.scitotenv.2023.162300>.
- Galmés, J., Medrano, H., Flexas, J., 2007. Photosynthesis and photoinhibition in response to drought in a pubescent (var. *minor*) and a glabrous (var. *palau*) variety of *Digitalis minor*. *Environ. Exp. Bot.* 60, 105–111. <https://doi.org/10.1016/j.envexpbot.2006.08.001>.
- George, S., Seepaul, R., Geller, D., Dwivedi, P., DiLorenzo, N., Altman, R., Coppola, E., Miller, S., Bennett, R., Johnston, G., Streit, L., Csonka, S., Field, J., Marois, J., Wright, D., Small, I., Philippidis, G., 2021. A regional inter-disciplinary partnership focusing on the development of a carinata-centered bioeconomy. *GCD Bioenergy* 13 (7), 1018–1029. <https://doi.org/10.1111/gcbb.12828>.
- Gesch, R., Long, D., Palmquist, D., Allen, B., Archer, D., Brown, J., Davis, J., Hatfield, J., Jabro, J., Kiniry, J., Vigil, M., Oblath, E., Isbell, T., 2019. Agronomic performance of Brassicaceae oilseeds in multiple environments across the Western USA. *Bioenergy Res.* 12 (2). <https://doi.org/10.1007/s12155-019-09998-1>.
- Hossain, Z., Johnson, E., Blackshaw, R., Liu, K., Kapiniak, A., Gampe, C., Molnar, L., Luan, L., Poppy, L., Gan, Y., 2018. Agronomic responses of *Brassica carinata* to herbicide, seeding rate, and nitrogen on the Northern Great Plains. *Crop Sci.* 58 (6), 2633–2643. <https://doi.org/10.2135/cropsci2018.05.0312>.
- Hossain, Z., Johnson, E., Wang, L., Blackshaw, R., Cutforth, H., Gan, Y., 2019. Plant establishment, yield and yield components of Brassicaceae oilseeds as potential biofuel feedstock. *Ind. Crops Prod.* 141, 111800. <https://doi.org/10.1016/j.indcrop.2019.111800>.
- Husen, A., Iqbal, M., Aref, I., 2014. Growth, water status, and leaf characteristics of *Brassica carinata* under drought and rehydration conditions. *Rev. Bras. De Bot.* 37 (3), 217–227. <https://doi.org/10.1007/s40415-014-0066-1>.
- Karami, O., Huang, Y., Dwivedi, P., 2024. Does carinata, an oilseed crop for sustainable aviation fuel, improve the eco-efficiency of crop rotations in South Georgia, United States? *J. Clean. Prod.* 453, 141986. <https://doi.org/10.1016/j.jclepro.2024.141986>.
- Kebreab, E., Murdoch, A., 1999. Modelling the effects of water stress and temperature on germination rate of *Orobanchae aegyptiaca* seeds. *J. Exp. Bot.* 50 (334), 655–664. <https://doi.org/10.1093/jxb/50.334.655>.
- Kumar, S., Seepaul, R., Mulvaney, M., Colvin, B., George, S., Marois, J., Bennett, R., Leon, R., Wright, D., Small, I., 2020. *Brassica carinata* genotypes demonstrate potential as a winter biofuel crop in South East United States. *Ind. Crops Prod.* 150, 112353. <https://doi.org/10.1016/j.indcrop.2020.112353>.
- Lancashire, P.D., Bleiholder, H., Boom, T., Van Den, Langeliudeke, P., Stauss, R., Webern, Elfriede, Witztenberger, A., 1991. A uniform decimal code for growth stages of crops and weeds. *Ann. Appl. Biol.* 119 (3), 561–601. <https://doi.org/10.1111/j.1744-7348.1991.tb04895.x>.
- Leclere, M., Loyce, C., Jeuffroy, M.H., 2018. Growing camelina as a second crop in France: a participatory design approach to produce actionable knowledge. *Eur. J. Agron.* 101, 78–89. <https://doi.org/10.1016/j.eja.2018.08.006>.
- Licata, M., Farruggia, D., Di Miceli, G., Salamone, F., Iacuzzi, N., Tuttolomondo, T., (2024). Productivity of two *Brassica* oilseed crops in a Mediterranean Environment and Assessment of the Qualitative Characteristics of Raw Materials for Bioenergy Purposes. <https://doi.org/10.1016/j.heliyon.2024.e26818>.
- Liu, X., Cai, H., Wang, M., 2024. Life cycle greenhouse gas emissions of growing winter oilseed feedstocks for sustainable aviation fuel production. *ACS Sustain. Chem. Eng.* 12, 16064–16072. <https://doi.org/10.1021/acssuschemeng.4c06429>.
- Montemurro, F., Diacono, M., Scarcella, M., D'Andrea, L., Boari, F., Santino, A., Mastrotrilli, M., 2016. Agronomic performance for biodiesel production potential of *Brassica carinata* A. Braun in Mediterranean marginal areas. *Ital. J. Agron.* 11 (1), 57–64. <https://doi.org/10.4081/ija.2016.684>.
- Morrison, M.J., Stewart, D.W., 2002. Heat stress during flowering in Summer Brassica. *Crop Sci.* 42 (3), 797–803. <https://doi.org/10.2135/cropsci2002.7970>.
- Pan, X., Caldwell, C.D., Falk, K.C., Lada, R., 2012. The effect of cultivar, seeding rate and applied nitrogen on *Brassica carinata* seed yield and quality contrasting environments. *Can. J. Plant Sci.* 92, 961–971. <https://doi.org/10.4141/cjps2011-169>.
- Patané, C., Tringali, S., 2011. Hydrotime Analysis of Ethiopian Mustard (*Brassica carinata* A. Braun) seed germination under different temperatures. *J. Agron. Crop Sci.* 197 (2), 94–102. <https://doi.org/10.1111/j.1439-037X.2010.00448.x>.
- Patrignani, A., Ochsner, T.E., 2015. Canopeo: a powerful new tool for measuring fractional green canopy cover. *Agron. J.* 107 (6), 2312–2320. <https://doi.org/10.2134/agonj15.0150>.
- Pieters, A.J., McKee, R., 1938. *The Use of Cover and Green-manure Crops. Soils and Men. USDA Yearbook of Agriculture*, Washington DC, pp. 431–444.
- Pullens, J.W.M., Sharif, B., Trnka, M., Balek, J., Semenov, M.A., Olesen, J., 2019. Risk factors for European winter oilseed rape under climate change. *Agric. For. Meteorol.* 272–273, 30–39. <https://doi.org/10.1016/j.agrformet.2019.03.023>.
- Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 Establishing Rules on Support for Strategic Plans to Be Drawn up by Member States under the Common Agricultural Policy (CAP Strategic Plans) and Financed by European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulations (EU) No 1305/2013 and (EU) No 1307/2013. <https://eur-lex.europa.eu/eli/reg/2021/2115/oj/eng>.
- Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). <https://eur-lex.europa.eu/eli/reg/2021/1119/oj/eng>.
- Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation). (<https://eur-lex.europa.eu/eli/reg/2023/2405/oj/eng>).
- Sangtarash, M.H., Qaderi, M.M., Chinnappa, C.C., Reid, D.M., 2009. Differential sensitivity of canola (*Brassica napus*) seedlings to ultraviolet-B radiation, water stress and abscisic acid. *Environ. Exp. Bot.* 66, 212–219. <https://doi.org/10.1016/j.envexpbot.2009.03.004>.
- Sarrantonio, M., Gallandt, E., 2003. The role of cover crops in North American cropping systems. *J. Crop Prod.* 8 (1–2), 53–74. https://doi.org/10.1300/J144v08n01_04.
- Scaccini, D., Furlan, L., 2019. *Nyctus cymoides* (Hemiptera: Lygaeidae), a potential emerging pest: overview of the information available to implement integrated pest management. *Int. J. Pest Manag.* <https://doi.org/10.1080/09670874.2019.1666174>.
- Schulmeister, T., Ruiz-Moreno, M., Silva, G., Garcia-Ascolani, M., Ciriaco, F., Henry, D., Lamb, G., Dubeux, J., DiLorenzo, N., 2019. Evaluation of *Brassica carinata* meal of ruminant metabolism and apparent total tract digestibility of nutrients in beef steers. *J. Anim. Sci.* 97 (3), 1325–1334. <https://doi.org/10.1093/jas/skz009>.
- Seepaul, R., Kumar, S., Boote, K.J., Small, I.M., George, S., Wright, D.L., 2021. Physiological analysis of growth and development of winter carinata (*Brassica carinata* A. Braun). *GCB Bioenergy* 13, 1112–1133. <https://doi.org/10.1111/gcbb.12831>.
- Seepaul, R., Marois, J., Small, I., George, S., Wright, D., 2018. Optimizing swathing and chemical desiccant timing to accelerate winter carinata maturation. *Agron. J.* 110 (4), 1379–1389. <https://doi.org/10.2134/agonj2017.08.0496>.
- Zanetti, F., Monti, A., Berti, M.T., 2013. Challenges and opportunities for new industrial oilseed crops in EU-27: a review. *Ind. Crops Prod.* 50, 580. <https://doi.org/10.1016/j.indcrop.2013.08.030>.
- Zanetti, F., Vamerli, T., Mosca, G., 2009. Yield and oil variability in modern varieties of high-erucic winter oilseed rape (*Brassica napus* L. var. *oleifera*) and Ethiopian mustard (*Brassica carinata* A. Braun) under reduced agricultural inputs. *Ind. Crops Prod.* 30, 265–270. <https://doi.org/10.1016/j.indcrop.2009.05.002>.