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# Is camelina a low-input feedstock for biofuel production? Responses to nitrogen and tillage: from literature review to field data

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ABSTRACT

Camelina (*Camelina sativa* L. Crantz) can produce substantial oil yield with limited N fertilization, providing a low-environmental-footprint feedstock for renewable fuel production. This study aimed to: (i) analyze and summarize existing literature on camelina N fertilization, (ii) identify optimal N rates, sowing dates, and tillage practices for camelina production in northern Italy, (iii) evaluate greenhouse gas (GHG) emissions from the agricultural phase of camelina production, (iv) and for the first time compile these three aspects of camelina production in a single manuscript. A three-year field study (2020–2023) conducted in northern Italy, using camelina cultivar 'Alba', evaluated two tillage practices (minimum tillage and no tillage), two sowing dates (early October and early November), and three top-dressed N rates (0, 60, and 120 kg N ha$^{-1}$). Sowing date significantly affected plant height, plant density, seed yield, and oil yield. Tillage practice significantly affected plant density, seed oil content, and straw, seed, and oil yields. Nitrogen rate significantly affected thousand seed weight (TSW) and straw, seed, and oil yields. Highest seed and oil yields resulted from later sowing, minimum tillage, and $\geq$ 60 kg N ha$^{-1}$. Nonetheless, the lowest carbon intensity (CI) was achieved without N fertilization, under both minimum and no-tillage, a scenario compliant with current European Union (EU) regulatory criteria for GHG emissions from the agricultural phase of biofuel production. Although less productive, this approach minimized GHG emissions, as $N_2O$ emissions from fertilizer and crop residues have the highest impact on overall CI. Further research, including breeding for improved N-use efficiency, will support scale-up of camelina as a sustainable biofuel feedstock.

## 1. Introduction

The environmental sustainability of biofuel feedstocks has gained increasing attention in recent years, particularly in response to evolving European Union (EU) energy policies. Within the EU, the Renewable Energy Directive (RED) allows the use of non-food/feed crops cultivated on severely degraded lands or those grown as intermediate crops for Sustainable Aviation Fuel (SAF) production, given that sustainability criteria are fulfilled (Delegated Regulation (EU) 2024/1405, https://eur-lex.europa.eu/eli/dir_del/2024/1405/oj/eng). Furthermore, the ReFuelEU Aviation Regulation establishes progressively increasing SAF blending mandates, requiring SAF to account for up to 70% of total EU aviation fuel consumption by 2050 (European Parliament and Council of the European Union, 2023. Regulation (EU) 2023/2405). In this context, oilseed crops have attracted considerable interest as alternative lipid feedstocks compatible with existing hydroprocessed esters and fatty acids (HEFA) technologies, which currently represents the most developed pathway for SAF production (van Dyk and Saddler, 2024). Consequently, camelina has been widely investigated as a potential low-carbon feedstock, and several life cycle assessment (LCA) studies have evaluated its environmental performance (Berti et al., 2025; Krzyżaniak et al., 2025; Karlsson Potter et al., 2023; Rossi et al., 2026). Under the current RED framework, biofuel pathways must achieve $\geq$ 65% greenhouse gas (GHG) emission reductions relative to the fossil fuel comparator (94 g$CO_2$e MJ$^{-1}$) (European Parliament and Council of the European Union, 2018. Directive (EU) 2018/2001, Annex V). However, beyond fuel conversion technology requirements, compliance with RED sustainability criteria includes requirements for the

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environmental performance of feedstock cultivation (Bacenetti et al., 2017; European Commission, 2022. Commission Implementing Regulation (EU) 2022/996). Cultivation-related emissions contribute substantially to the overall carbon intensity of biofuel pathways, emphasizing the importance of optimizing cultivation strategies and input use (Liu et al., 2024). Despite the growing body of LCA literature, relatively few studies have combined field experimentation with environmental assessment. To bridge this gap, this study integrates primary agronomic data collected under real field conditions to evaluate the effects of management practices on both productivity and environmental performance. Research like this which integrates field data and environmental assessment can help to identifying management strategies capable of maintaining seed and oil yields while reducing GHG emissions, which remains a key challenge for at-scale deployment of sustainable camelina-based biofuel supply chains.

Camelina [*Camelina sativa* (L.) Crantz] is an annual dicot oilseed crop from the *Brassicaceae* family, attracting ever-increasing worldwide interest despite producing lower seed yield than its well-known relative, canola (*Brassica napus* L.). For comparison, camelina seed yield potential ranges from 1300 to 3300 kg DM $ha^{-1}$ (Zanetti et al., 2021), while canola seed yield ranges from 1700 to 4400 kg DM $ha^{-1}$ (Page et al., 2020). Camelina oil comprises 30–41% of the seed weight (Berti et al., 2016). The suitability of camelina for European agricultural systems is further supported by the availability of both spring and winter biotypes, along with a short life cycle of 90 d to ~200 d for spring and autumn sowing, respectively (Zanetti et al., 2021). In the midwestern United States, suitability for relay cropping winter camelina with soybean [*Glycine max* (L.) Merr.] has been demonstrated. This system shows high nutrient-scavenging potential, which allows for lower rates of nitrate loss compared with traditional rotations and other cropping systems (Berti et al., 2017a; Liu et al., 2023; Peterson et al., 2019). When compared with other underutilized crops, camelina's nutrient-scavenging capacity and limited water requirement mean this crop may be highly suitable for low-input agriculture (Scott et al., 2021). Various studies conducted in arid and semi-arid environments, under low-input regimes, have reported mean seed yields of 1800 kg $ha^{-1}$ in southern Europe (Avola et al., 2021; Martín Sánchez et al., 2020) decreasing to 700–1100 kg $ha^{-1}$ in the USA (Hunsaker et al., 2011; Neupane et al., 2018; Sintim et al., 2015). The effects of mineral fertilization on camelina productivity have been broadly investigated, as optimizing profitability remains fundamental to improving the reputation and interest in producing this crop (Liu et al., 2023). Studies on this topic mainly focus on N, rather than K and P, as the latter two have demonstrated little to no influence on camelina seed yield (Mohammed et al., 2017; Solis et al., 2013). Existing literature suggests sulfur plays a synergistic role when combined with high N fertilization regimes (Jiang et al., 2013). Even so, no significant responses with less than 120 kg N $ha^{-1}$ or above 25 kg S $ha^{-1}$ have been reported (Jankowski et al., 2019; Mohammed et al., 2017; Sintim et al., 2015; Solis et al., 2013; Wysocki et al., 2013). In the reviewed literature, approximately 80% of fertilization studies tested N rates up to but no greater than 120 kg $ha^{-1}$, reflecting the low-input requirements of camelina (Supplementary Fig. S1). Nevertheless, the scientific community has yet to reach a comprehensive understanding and consensus on camelina fertilization. Fertilization management optimized to reduce the environmental impact of this crop is now a requirement of the biofuel industry, which relies on low-carbon-intensity feedstocks.

Existing literature reports improvements in seed yield and oil yield in response to increasing N rates, whereas seed oil content has remained unaffected or slightly negatively influenced by higher N rates (Jiang et al., 2014; Czarnik et al., 2017; Karčauskienė et al., 2014). In most cases, a threshold N rate for positive effect on camelina seed yield has been highlighted, while optimal N application rates differ depending on initial soil N availability (Wysocki et al., 2013).

To more clearly define an optimal N rate for camelina, a thorough analysis of the environmental impact of increasing N fertilization must first be conducted. Energy efficiency criticism arose from Jakowski and Sokólski (2021), who recorded an increase in energy inputs of 348% with 160 kg N $ha^{-1}$ fertilization, not counterbalanced by an increase in energy output of 58–86%, when compared with an unfertilized system. Therefore, low-input systems have been defined as the most energy-efficient per unit of output energy. Even if high-input systems have achieved the highest energetic gain per hectare, they are now only adoptable in scenarios where energy-efficiency is not a limiting factor or requirement.

Since N fertilization, in addition to transportation, are the most impactful phases within life cycle assessment (LCA) of camelina production (Martinez et al., 2021), N use efficiency (NUE) remains a key factor for improving both energy balance and ecological sustainability of camelina (Keshavarz-Afshar et al., 2015). This study by Keshavarz-Afshar et al. (2015) evaluated three N rates in combination with a no-tillage system, reporting similar results to conventional tillage. In Keshavarz-Afshar et al. (2015), camelina under a no-tillage system averaged across three N rates produced 26% less seed yield than under a conventional tillage system, whereas seed yield under minimum tillage systems as evaluated by Angelopoulou et al. (2023) and Avola et al. (2021) were comparable to a conventional tillage system. Similar results across varying tillage practices suggest that conservation agriculture may be a viable strategy to reduce the environmental and economic input costs of camelina production.

In the interest of the future of camelina as a feasible low-carbon intensity feedstock for sustainable biofuel production in Europe and worldwide, the present manuscript has three interlinked objectives: (i) to provide a review of the available literature on camelina response to N fertilization; (ii) to investigate how N fertilization, tillage practice, and sowing date impact seed and oil yield of autumn-sown camelina in northeastern Italy, to derive optimal agronomic guidance for farm-level management decisions; and (iii) to carry out an environmental impact analysis of data from the included field trials to identify the optimal management practices to reduce the environmental footprint of camelina production.

## 2. Materials and methods

### 2.1. Literature review and analysis

The literature review for this study focused on the response of camelina to nitrogen (N) fertilization in field trials. A systematic literature search was conducted using Scopus (www.scopus.com) with the following keywords: "camelina" AND "nitrogen" AND "fertilization". The search retrieved studies published between 1997 and 2025, representing over two decades of research into N fertilization response in camelina. Among the results, 30 studies were selected (Supplementary Table S2), meeting the following criteria:

1. Studies conducted under open field conditions (no controlled or semi-controlled environment).
2. Studies evaluated nitrogen treatments compared with an unfertilized control group.
3. Studies provided seed yield data, and sufficient data to calculate oil content and/or oil yield.

For each study, N application rates and seed yield data were extracted, while oil content and oil yield date were extracted if available. When more than one replicate in time or space was present, averaged data were utilized. Of the 30 total analyzed studies, only 23 reported both seed yield and oil content. For articles that provided both seed yield and oil content, oil yield was calculated as the product of seed yield and oil content where not explicitly provided. To allow for comparison between studies involving different N rates, variations between each study's tested N fertilization levels and the unfertilized control were calculated as follows:

$$\textit{Seed yield variation}\ (\%) = 100 * \frac{\textit{Seed yield fertilized}\left(\frac{Mg}{ha}\right) - \textit{Seed yield unfertilized}\left(\frac{Mg}{ha}\right)}{\textit{Seed yield unfertilized}\ \left(\frac{Mg}{ha}\right)}$$

$$\textit{Oil content variation}\ (\%) = 100 * \frac{\textit{Oil content fertilized}\left(\frac{Mg}{ha}\right) - \textit{Oil content unfertilized}\left(\frac{Mg}{ha}\right)}{\textit{Oil content unfertilized}\ \left(\frac{Mg}{ha}\right)}$$

$$\textit{Oil yield variation}\ (\%) = 100 * \frac{\textit{Oil yield fertilized}\left(\frac{Mg}{ha}\right) - \textit{Oil yield unfertilized}\left(\frac{Mg}{ha}\right)}{\textit{Oil yield unfertilized}\ \left(\frac{Mg}{ha}\right)}$$

.

Nitrogen rates were categorized into six classes with increments of 30 kg N ha$^{-1}$: *i)* 20–49 kg N ha$^{-1}$; *ii)* 50–79 kg N ha$^{-1}$; *iii)* 80–109 kg N ha$^{-1}$; *iv)* 110–139 kg N ha$^{-1}$; *v)* 140–169 kg N ha$^{-1}$; *vi)* > 170 kg N ha$^{-1}$. The number of observations in each class was utilized to analyze the distribution of data across nitrogen levels. Box plots were created for seed yield variation, oil content variation, and oil yield variation across nitrogen classes. Each box plot displays median value, average value, interquartile range (IQR), and outliers.

Regression analyses, including linear and quadratic polynomial models, were performed using the open-source curve-fitting software FindCurves (www.findcurves.com). Models providing the best fit based upon coefficient of determination ($r^2$) values were selected to describe relationships between nitrogen application rates and variation in seed yield, oil content, and oil yield.

### 2.2. Agronomic field trial

#### 2.2.1. Experimental design

A three-year study (2020–2023) was established in Cadriano (Bologna) at the University of Bologna Experimental Farm (44°33' N, 11° 24' E, 32 m above sea level). This soil has a loam texture (23% clay, 40% silt and 37% sand), and is characterized by a pH of 6.69, an organic matter content of 1.80%, a total N content of 0.98‰, and content of available P and K of 55 and 201 ppm, respectively. The longterm mean annual temperature at this experimental site is 13.2°C and the cumulative annual precipitation is 613 mm.

Agronomic management practices remained the same for the three growing seasons. Glyphosate was applied at a rate of 3.5 L ha$^{-1}$ (n-phosphono methyl glycine) (441 g L$^{-1}$ a.i.) before establishing the trials on both no-tillage and minimum tillage plots. The seedbed for plots under minimum tillage received 50-mm-depth harrowing without ploughing before sowing, while in plots under no-tillage received direct sowing. All plots were sown with a mechanical seed drill (Damax 17, DAMAX, Italy), using a row spacing of 0.15 m and a sowing rate of 6 kg

**Table 1**
Sowing and harvesting dates, growing degree days (GDD), and main meteorological data (mean minimum and maximum temperature, and cumulative precipitation) of the surveyed growing seasons for the two sowing times (SD1 = early sowing date, SD2 = optimal sowing date) evaluated for camelina cultivation in Italy.

| Sowing date (SD) | Sowing date | N application date | Harvest date | Cycle length (d) | Mean $T_{min}$ (°C) | Mean $T_{max}$ | Prec (mm) | GDD* (°C) |
|---|---|---|---|---|---|---|---|---|
| SD1 | Oct 8 2020 | Feb 8 2021 | May 21 2021 | 225 | 3.8 | 14.1 | 322 | 1166 |
| SD2 | Oct 28 2020 | Mar 5 2021 | Jun 14 2021 | 229 | 4.5 | 15.2 | 291 | 1399 |
| SD1 | Oct 12 2021 | Feb 9 2022 | Jun 1 2022 | 232 | 4.1 | 14.8 | 323 | 1303 |
| SD2 | Nov 12 2021 | Mar 8 2022 | Jun 14 2022 | 214 | 4.4 | 15.4 | 305 | 1334 |
| SD1 | Oct 11 2022 | Feb 6 2023 | Jun 8 2023 | 240 | 5.9 | 15.9 | 609 | 1664 |
| SD2 | Nov 8 2022 | Mar 8 2023 | Jun 12 2023 | 216 | 5.5 | 15.2 | 620 | 1391 |

*$T_{base}$ for GDD calculation = 4 °C.

seed $ha^{-1}$. The spring camelina variety tested was 'Alba' (provided by Camelina Company España, Madrid, Spain). The individual plot area was 18 $m^2$. Sowing dates were classified in two treatment groups, with sowing in the first 10-day period of October (SD1), and in the last 10-day period of October or early November (SD2). The exact sowing dates for each growing season are reported in Table 1. Nitrogen fertilization was applied when camelina reached the rosette stage (BBCH 107–08; Martinelli and Galasso, 2011), with application rates of 0, 60, and 120 kg N $ha^{-1}$ as urea (46% N) corresponding to each treatment.

The experimental design was a strip-split plot with four replicates (strip factor: tillage; main factor: sowing date; and sub-randomized factor: nitrogen rate). When camelina reached full maturity (BBCH 809; Martinelli and Galasso, 2011), the central area of each plot (4 $m^2$) was manually harvested by cutting all plants within the area at soil level, after which total biomass was weighed. Plants were then threshed with a plot combine (Nursery Master, Wintersteiger, Austria) and seeds and straw were separated before being weighed. Representative sub-samples (~100 g each) of fresh biomass, residual biomass (straw), and seeds were weighed fresh, then oven-dried at 105°C until a constant dry weight was achieved and recorded. Fresh and dried sample weights were then used to determine the residual moisture to adjust yield and productivity parameters to dry matter (DM = 0% residual moisture). To determine final plant density at harvest, camelina plants in two 1-m-long adjacent rows were counted. Final plant height was measured as mean height of the camelina stand in each plot, directly before harvest.

### 2.2.2. *Crop growth cycle and meteorological data*

Meteorological data including air temperature (minimum and maximum) and daily precipitation were collected throughout each growing season by the weather station located near the experimental location (Table 1). Growing degree days (GDD) were calculated for each sowing date and growing season (Table 1), from sowing date to harvest date using the following equation:

$$GDD = \sum[(T_{max} + T_{min})/2 - T_{base}]$$

.

Where $T_{max}$ and $T_{min}$ are the maximum and minimum air temperature, respectively, and $T_{base}$ for camelina was defined as 4°C (Gesch and Cermak, 2011).

### 2.2.3. *Quality analysis of seeds and straw*

Thousand seed weight (TSW) was determined using a seed counter (Seed Counter S−25, DATA Detection Technologies Ltd., IL) at the Seed Research and Testing Laboratory (LaRAS) of the University of Bologna. Total seed oil content was determined via a solvent extraction protocol performed on representative sub-samples of camelina seed from each plot (Zanetti et al., 2022). To determine total seed oil content, ~30 g of camelina seed was ground in a coffee grinder (Moulinex, AR1108) for 40 s. An aliquot consisting of 1.5 g of ground material was precisely weighed in a cellulose extraction thimble (22 × 80 mm), which was then inserted into a 30 mL glass extractor. Lipid extraction was performed in an in-line extraction unit for Soxhlet extraction (mod. R 306, Behr Labor-Technik, Düsseldorf, Germany), using 60 mL of n-hexane as the organic solvent. Soxhlet extraction was carried out for 2 h, from the start of solvent siphoning into the round bottom flask upon the heating element. Pieces of pumice stone were added to the distillation flask to avoid bubbling of liquid as the temperature increased. The extract containing the lipidic fraction was dried for 90 min over anhydrous sodium sulfate at 4°C, interspersed with occasional shaking. The organic solvent was then filtered through sodium sulfate in a 100 mL flat-bottom flask and removed under reduced pressure at 30°C in a rotary evaporator. The residual oil was further dried under nitrogen flow for 5 min, keeping the flask in a water bath (50–55°C), after which the oil was then precisely weighed. Subsequently, camelina oil yield was calculated by multiplying the dry seed yield by the seed oil content.

To determine $N_2O$ emissions from straw left in the field for LCA calculations, representative samples including stems, siliques, and leaf were ground with a ball mill (MM400, Retsch GmbH, Haan, Germany). The N content of the samples was determined using an elemental analyzer (Flash 2000, Thermo Fisher Scientific, Waltham, MA, USA).

### 2.2.4. *Statistical analysis of field data*

Prior to analysis of variance (ANOVA), the homoscedasticity of the data was verified by performing Barlett's Test ($P \leq 0.05$). Then, all data were subjected to a three-way ANOVA in which the three main fixed factors were sowing date, tillage technique, and nitrogen fertilization. Year was considered as a random factor in the analysis. When significant statistical differences emerged ($P \leq 0.05$), Tukey's Honestly Significant Difference (HSD) test was used to separate means. All statistical analyses were carried out using the Statgraphics Centurion 18 software (ver. 18.1.13, Statgraphics Technologies Inc., Virginia, USA).

**Table 3**
Life cycle inventory and conversion factors.

| Input | LHV MJ $kg^{-1}$ | GHG kg $CO_{2e}$ $kg^{-1}$ | References |
|---|---|---|---|
| *Agricultural emissions* | | | |
| Seeds | 25 | 0.729 | Matteo et al., (2020) |
| N- as urea | 49.45 | 1.57 | GREET, (2024) |
| Glyphosate | 267 | 23.3 | Miller and Kumar, (2013) |
| *Field emissions (%)* | | | |
| N from mineral fertilizer | | 1.33 | Berti et al., (2017b) |
| N from crop residues | | 1.264 | IPPC, 2019 |
| Fuel emissions | MJ $L^{-1}$ | kg $CO_{2e}$ $kg^{-1}$ | |
| Diesel | 45.3 | 0.09 | Miller and Kumar, (2013) |

**Table 2**
Description of the six cropping system scenarios and inputs used in the life cycle assessment.

| Scenario | Tillage | Sowing rate (kg $ha^{-1}$) | Herbicide management | Herbicide dose (L $ha^{-1}$) | N fertilization* | Diesel (L $ha^{-1}$) | Seed yield (kg $ha^{-1}$) |
|---|---|---|---|---|---|---|---|
| No tillage 0 N | Direct sowing into winter wheat stubble | 7 | Glyphosate application before sowing (Roundup, 441 g $L^{-1}$ of a.i.) | 3.5 | None | 46.8 | 998 |
| No tillage 60 N | | | | | 60 kg of N $ha^{-1}$ | 53.1 | 1100 |
| No tillage 120 N | | | | | 120 kg of N $ha^{-1}$ | | 1333 |
| Minimum tillage 0 N | 50-mm-deep harrowing without ploughing | | | | None | 52.1 | 1046 |
| Minimum tillage 60 N | | | | | 60 kg of N $ha^{-1}$ | 58.5 | 1373 |
| Minimum tillage 120 N | | | | | 120 kg of N $ha^{-1}$ | | 1567 |

*N was applied as urea (46% N).

### 2.3. Environmental impact – life cycle assessment (LCA)

#### 2.3.1. System boundary and functional unit

The system boundaries of the performed LCA were from cradle (crop planting) to farm-gate (harvesting) of each cropping system, as described in Section 2.2.1 (Experimental design). The different cropping systems (Table 2) were defined by the combination of tillage level and N fertilization rate, while sowing date was not considered as a factor of impact within the LCA analysis. Thus, LCA calculations were performed only on the most productive sowing date, as defined by the agronomic results.

The analysis included all inputs and processes required to produce seed at the farm-gate, including seed production, fertilizer and herbicide inputs, field operations, seed transportation to the farm-gate, and direct and indirect emissions associated with crop cultivation. Crop residues were assumed to remain in the field after harvest and were not considered co-products within the LCA framework; therefore, no allocation procedure was required.

Life cycle assessment methodology includes the selection and definition of a functional unit that characterizes the production purpose of the analyzed system. This study referred to impacts using two functional units: *i)* kg $CO_{2e}$ $ha^{-1}$ and *ii)* g $CO_{2e}$ $MJ^{-1}$. The area-based functional unit was used to quantify the environmental burden associated with crop cultivation and management practices, whereas the energy-based

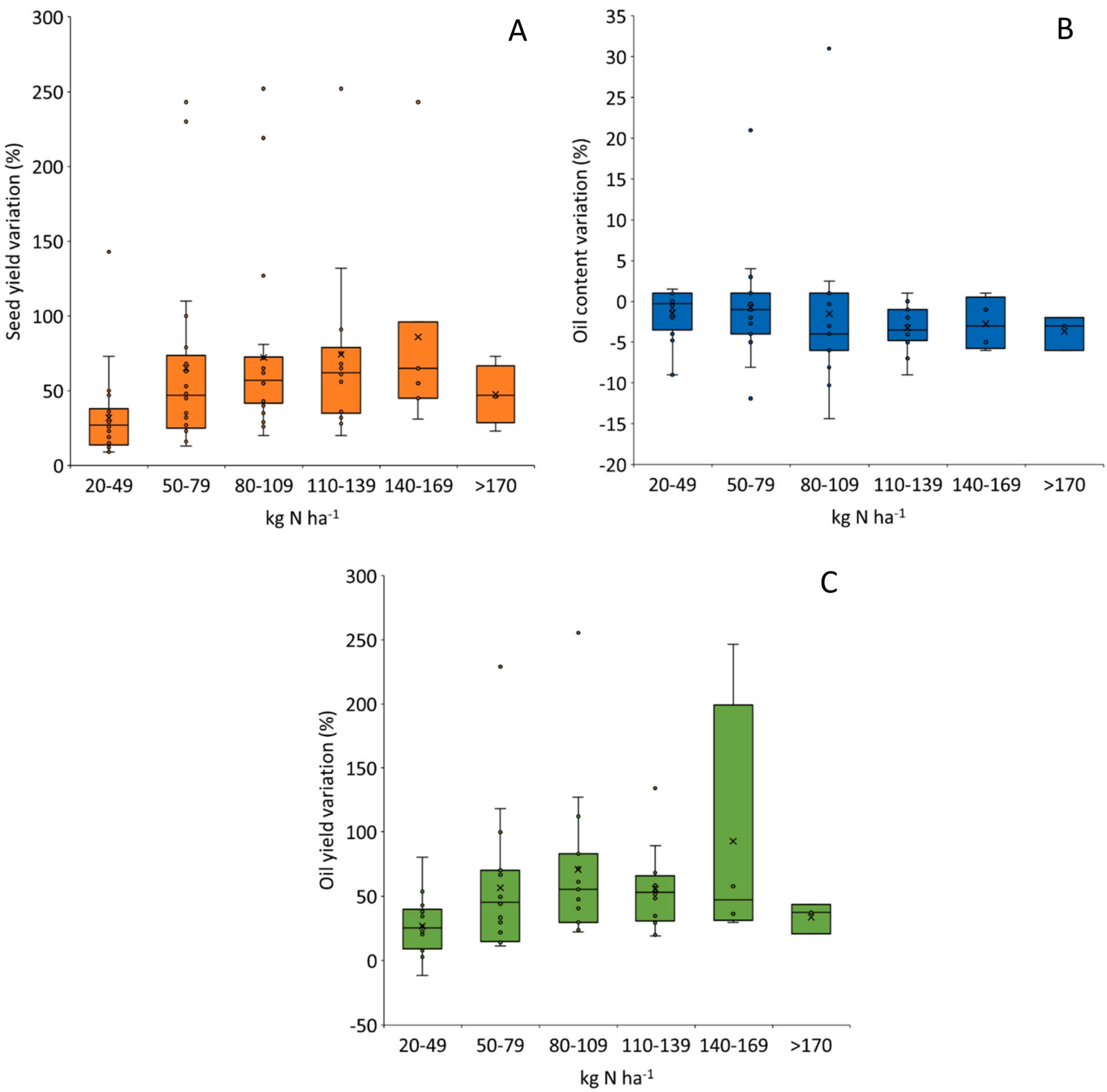


**Fig. 1.** Boxplot of seed yield variation (A), oil content variation (B), and oil yield variation (C) of N fertilized camelina compared with unfertilized condition, according to the analyzed available literature on camelina response to N field fertilization (30 studies conducted from 1997 and 2025). The median and the average variation for each nitrogen class are respectively represented by the central line and the X point in the boxes. The boxes span from the 25th percentile to the 75th percentile. Whiskers show the range of non-outlier data points within 1.5 times the interquartile range, outliers are indicated by individual points beyond the whiskers.

functional unit was adopted to account for differences in seed yield and energy production among treatments. The latter is particularly relevant for evaluating the suitability of camelina as a bioenergy feedstock, as it expresses the greenhouse gas intensity per unit of energy produced. As recommended by IPCC 2013 for environmental impact assessment with a 100-year time horizon, amount of $CO_2$ equivalents ($CO_{2e}$) was reported (Myhre et al., 2013; Cecchin et al., 2021).

### 2.3.2. Life cycle inventory

Camelina is suitable for cultivation in northern Italy (Alberghini et al., 2022; Berzuini et al., 2024; Zanetti et al., 2017) as an autumn cash cover crop or intermediate crop that replaces the winter fallow period and precedes typical summer crops [e.g., soybean, sunflower (*Helianthus annuus* L.), etc.]. Seed yield, agronomic inputs, and field operations are reported in Table 2 and were compiled from the agronomic field trial described within Section 2.2. Three different fertilization rates were applied under minimum tillage and no-tillage practices to evaluate differences in seed yield and carbon intensity (CI).

Global warming potential for the agricultural phase was calculated through an arithmetic calculation developed by Berti et al. (2025) of the estimated $CO_{2e}$ emissions derived from inputs, labor, and services required by each cropping system. Conversion factors and references used for the calculation are reported in Table 3. The lower heating value (LHV) for seeds was obtained from Matteo et al. (2020), the LHV for fertilization was obtained from GREET (2024), and the LHV for herbicide was obtained from Miller and Kumar (2013). Concerning the diesel consumption for field activities, these values were calculated from estimated data (Buratti et al., 2012).

The nitrous oxide ($N_2O$) emissions were determined using an empirical emission factors (EF) approach, as reported by Liu et al. (2024), using two sources of N inputs to soil, via N from fertilizer application and N remaining in crop residues left in the soil. The $N_2O$ field emission factor was assumed to be 1.33% per kg of N applied as fertilizer, in line with the IPCC default value of 1.374% (Berti et al., 2017b; IPCC, 2019). The total amount of N returned to the soil through crop residues was multiplied by the IPCC emission factor of 1.264% (IPCC, 2019).

### 2.3.3. Economic benefits analysis

An economic benefit analysis was performed to evaluate the profitability of camelina cultivation under different tillage systems and nitrogen fertilization rates tested during the three-year field experiment. Production costs are reported in Table (S4, supplementary materials) and included seed purchase, herbicide and fertilizer. Input prices were based on the actual purchase prices paid by the Experimental Farm of the University of Bologna. In addition, costs associated with mechanical operations, including sowing, harvesting, and tillage practices under both no-tillage and minimum-tillage systems, were considered. Under the no-tillage system, direct drilling was adopted, whereas minimum tillage consisted of shallow harrowing prior to sowing. The costs of mechanical operations were estimated according to the standard rates published by Confederazione Agromeccanici e Agricoltori Italiani (APIMAI, 2024). Gross revenue was calculated based on seed yield and camelina seed price, commonly traded at an average price of 600 € 1000 $Kg^{-1}$ of seeds.

Economic performance was assessed by calculating net profit value (NPV) and the benefit-cost ratio (BCR) according to the following equations (Tan et al., 2025):

$$NPV = GR - TC$$

$$BCR = \frac{GR}{TC}$$

where GR is the gross revenue (€ $ha^{-1}$) obtained from seed production and TC represents the total production costs (€ $ha^{-1}$). Net profit value indicates the economic return after deducting production costs from gross revenue, whereas the benefit-cost ratio provides an estimate of the economic efficiency of each management strategy.

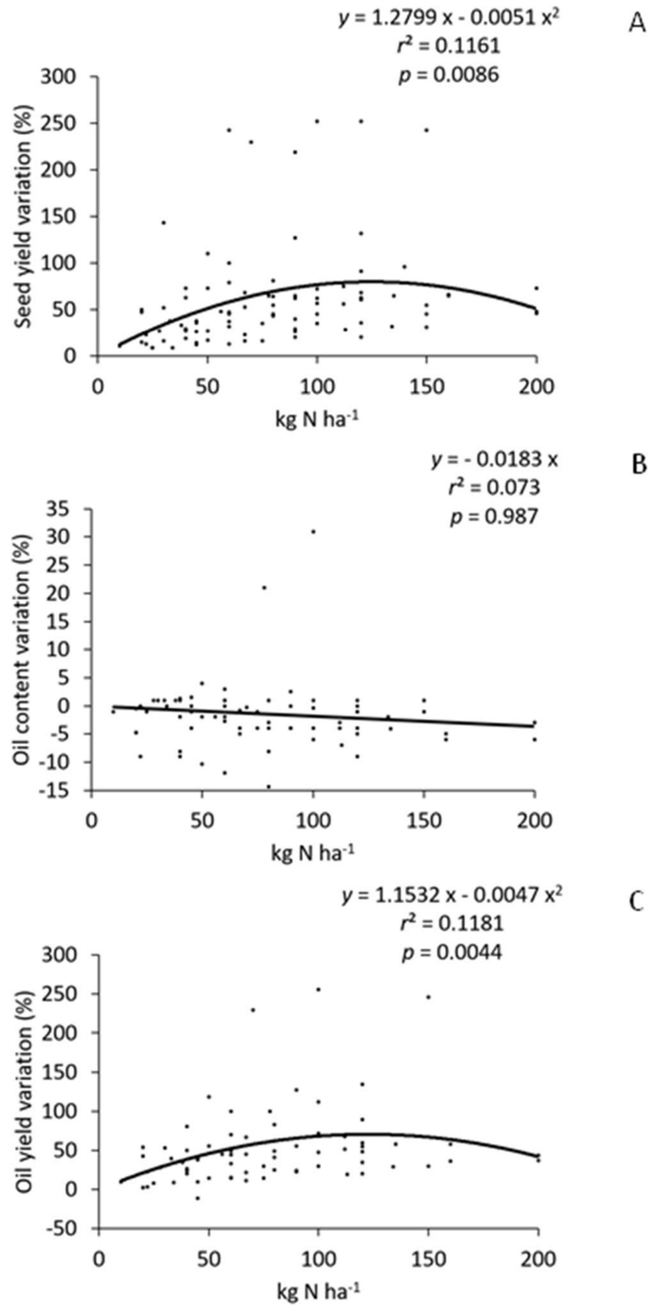


**Fig. 2.** Quadratic response to N fertilization of seed yield variation (A), oil content variation (B), and oil yield variation (C) compared with unfertilized condition, according to the analyzed available literature on camelina response to N field fertilization (30 studies conducted from 1997 and 2025). Quadratic equations, $r^2$, and *p*-value are reported for each curve.

## 3. Results

### 3.1. Camelina response to N fertilization: analysis of literature data

The literature review analyzed the effects of nitrogen fertilization on camelina seed yield, oil content, and oil yield across various field trials by comparing fertilized treatments to unfertilized controls. Of the 95 N rates tested, 73% were equal to or less than 109 kg N $ha^{-1}$ , confirming camelina's low-input requirements, while only 12% of N rates tested exceeded 140 kg N ha$^{-1}$ (Supplementary Fig. S1). The boxplots reported in Fig. 1 summarize both the central tendency and the variability of camelina response across N fertilization classes. Median values represent the typical response within each N range, whereas the height of the boxes indicates the interquartile range and therefore the degree of variability among studies. Whiskers and outliers further highlight the presence of extreme responses.

As shown in Fig. 1A, seed yield response exhibited high variability across all tested N rates, with several positive outliers recorded across N fertilization classes. The class median values suggest a higher seed yield

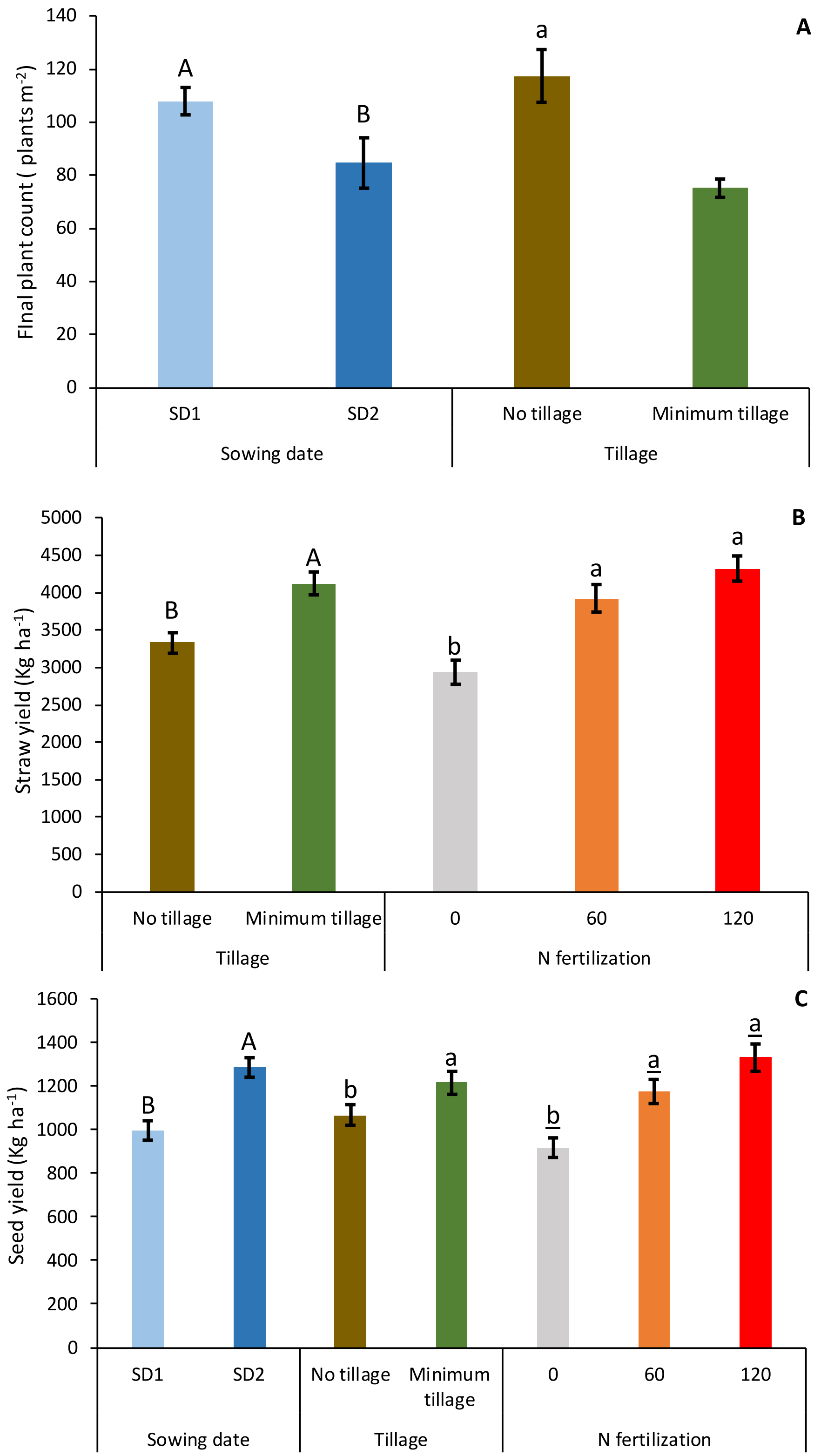


**Fig. 3.** (A) Final plant count in response to the significant main factors sowing date and tillage, (B) straw yield in response to the significant main factors: sowing date and tillage, and (C) seed yield in response to significant main factors: sowing date, tillage and nitrogen fertilization. Different letters: significant different means ($P \leq 0.05$, HSD Tukey test), within the same factor and parameter. Vertical bars: standard error.

increase in the 50–79 kg N $ha^{-1}$ class compared with the 20–49 kg N $ha^{-1}$ class, reaching the highest values in the 80–109 kg N $ha^{-1}$ class. However, the distribution of values indicates that yield increase started to plateau beyond 80 kg N $ha^{-1}$ , while the slight decline observed in the > 170 kg N $ha^{-1}$ class suggests that very high N rates did not consistently provide additional yield benefits.

Seed oil content variation (Fig. 1B) showed more moderate variability compared with seed yield. Lower N ranges (20–49 and 50–79 kg N $ha^{-1}$) exhibited moderate variability, with medians generally near 0–1%, indicating negligible response of oil content to N fertilization. Higher N ranges (80–109 kg N $ha^{-1}$ and above) displayed increased variability and more extreme outliers, including both positive and negative responses. However, the negative medians observed at higher N rates, particularly around −3% and reaching approximately −4% in the > 170 kg N $ha^{-1}$ class, indicate that increasing N fertilization did not improve oil content and may have reduced it instead.

Oil yield variation across nitrogen ranges (Fig. 1C) exhibited an upward trend in median values, peaking in the 80–109 kg N $ha^{-1}$ range before decreasing slightly in the 140–169 kg N $ha^{-1}$ range. The 140–169 kg N $ha^{-1}$ range demonstrated substantial variability in oil yield variation, suggesting inconsistent responses among studies at high N rates. The > 170 kg N $ha^{-1}$ range, though data-limited, showed reduced median values, suggesting a plateau in oil yield response at high N rates.

The quadratic model for seed yield variation in response to N fertilization rate (Fig. 2A) resulted as significant ($P \leq 0.05$), with an $r^2$ value of 0.12. The positive coefficient for the linear term indicates that seed yield tends to increase with increasing N application rates; however, the low $r^2$ value suggests that most of the observed variation is likely due to field variability and other uncontrolled environmental and management factors. Meanwhile, the negative quadratic coefficient indicates that the rate of increase for seed yield slows as nitrogen rates rise. Despite the N fertilization rate for maximized seed yield occurring at approximately 129 kg N $ha^{-1}$, responsiveness of seed yield begins to reduce around 80 kg N $ha^{-1}$. Beyond 80 kg N $ha^{-1}$, further increases in N continue to improve seed yield, but at a significantly slower rate of yield increase per unit of additional N fertilization.

The quadratic model for oil content variation in response to N fertilization rate (Fig. 2B), reported a low $r^2$ value of 0.01 and a not significant *P*-value. As such, the data does not provide strong evidence that nitrogen application rate has a meaningful impact on oil content. The quadratic model for oil yield variation in response to N fertilization rate (Fig. 2C) resulted as significant ($P \leq 0.05$), with an $r^2$ value of 0.12. The peak oil yield is predicted to occur at approximately 128 kg N $ha^{-1}$, where the combined effects of the linear term increase and the quadratic term decrease are balanced. However, the responsiveness of oil yield starts to reduce around 80 kg N $ha^{-1}$, indicating diminishing returns beyond this point. These results suggest that a N application rate up to 80 kg N $ha^{-1}$ is effective for improving oil yield, with diminishing benefits at higher rates.

### 3.2. Camelina response to N fertilization rate, tillage system and sowing date: field results

#### 3.2.1. Meteorological data

Camelina growth cycle length was generally longer when planted on SD1 than on SD2, ranging from 214 d for SD2 in 2021–2022, up to 240 d for SD1 in 2022–2023 (Table 1). Temperatures across seasons and sowing dates were similar, withstanding the 2022–2023 season, which was characterized by higher means for minimum and maximum temperatures. Conversely, precipitation greatly varied across growing seasons and sowing dates. This was exemplified by an extreme rain event in May 2023, during which almost 300 mm of precipitation occurred in the first 20 d of May, corresponding to half of the cumulative precipitation of the entire 2023 for the study location. This exceptional precipitation event could be considered a meteorological outlier as similar time-concentered precipitation in May were never report in the last 30 years in the study site.

A total precipitation amount of ∼300 mm during the camelina growth cycle is typical for the test location, as reported in previous studies (Righini et al., 2019; Zanetti et al., 2020). Thus, a cumulative precipitation rate exceeding 600 mm, as occurred in 2022–2023, must be considered an exceptional condition for camelina in northern Italy. Interestingly, GDD accumulation from sowing to harvest was similar across study years for SD2, while for SD1, there was large variation from 1166 GDD in 2020–2021 up to 1664 GDD in 2022–2023, the latter being the warmest and the wettest year (Table 1). Despite this significant variation in cumulative precipitation for both sowing dates, and in GDD for SD1, 'Alba' camelina was able to successfully adapt to local meteorological conditions, producing high yields in each year and demonstrating suitability as a reliable oilseed crop under varying conditions.

#### 3.2.2. Agronomic results

The ANOVA for the results of the agronomic field trial in Section 2.2 are reported in Supplementary Table S3 (supplementary materials). It is worth noticing that across the surveyed parameters, only main effects resulted significantly in the ANOVA, while interactions among factors were never significant. Concerning final plant height, surveyed immediately before harvest, significant differences resulted only in response to the main factor of sowing date, with 'Alba' planted on the later date (SD2) producing taller plants (0.84 m for SD2 vs. 0.78 m for SD1, $P \leq 0.05$). Concerning the final plant density, also measured at harvest, significant differences emerged in response to both main factors: sowing date and tillage (Fig, 3 A). In the earlier sowing date (SD1), plant density was about 30% higher than in the later sowing date (SD2). In terms of tillage, plots under no tillage had about 50% higher plant density compared with the minimum-tillage plots (Fig. 3 A).

Plant residue yield of 'Alba' was significantly affected by two of the main factors: tillage and N fertilization rate (Fig. 3B). Under minimum tillage, straw yield increased significantly compared with no tillage (4124 vs. 3328 kg DM $ha^{-1}$, minimum vs. no-till, $P \leq 0.05$). Concerning N fertilization, significant differences in straw yield emerged only between unfertilized plots (0 N) and the fertilized ones (60 and 120 kg N $ha^{-1}$), as reported in Fig. 3B. The application of N fertilization increased straw yield by 34% under 60 N kg N $ha^{-1}$ and by 47% under 120 kg N $ha^{-1}$ compared with the unfertilized plots, but without any significant differences between these two N rates.

Seed yield was significantly affected by all the considered main factors: sowing date, tillage, and N fertilization rate. In details, 'Alba' seed yield increased significantly in response to delayed sowing (SD2), minimum tillage, and N fertilization rate (Fig. 3 C). Camelina seed yield in the later sowing date (SD2) was about 30% higher than in the earlier sowing date (SD1) (1287 vs. 995 kg DM $ha^{-1}$, $P \leq 0.05$). The differences in response to tillage were more restrained, but still significant, with only 14% higher yield in the minimum-tillage plots compared with the no-till plots. The response of seed yield to N fertilization followed a similar trend to the trend for straw yield, with unfertilized plots demonstrating the significantly lowest seed yield (918 kg DM $ha^{-1}$). The increase in seed yield due to N fertilization was + 28% when applying 60 kg N $ha^{-1}$, and + 45% when applying 120 kg N $ha^{-1}$, without significant differences in seed yield between these two rates (Fig. 3 C).

Fertilization rate significantly, but negligibly, affected the TSW (Fig. 4A). The heaviest seeds were produced under 0 N and the lightest seeds under 120 kg N $ha^{-1}$, while plots with 60 kg N $ha^{-1}$ reported an intermediate value between these two which was not significantly different from either. Seed oil content was significantly affected by tillage (Fig. 4B). Plots under no-till management had significantly higher seed oil content than those under minimum tillage (325 for no tillage vs. 311 g $kg^{-1}$ for minimum tillage, $P \leq 0.05$). These values are generally lower than the typical seed oil content of camelina grown in similar conditions (Zanetti et al., 2021; Alberghini et al., 2022), however, the adverse meteorological conditions and extended flooding during May

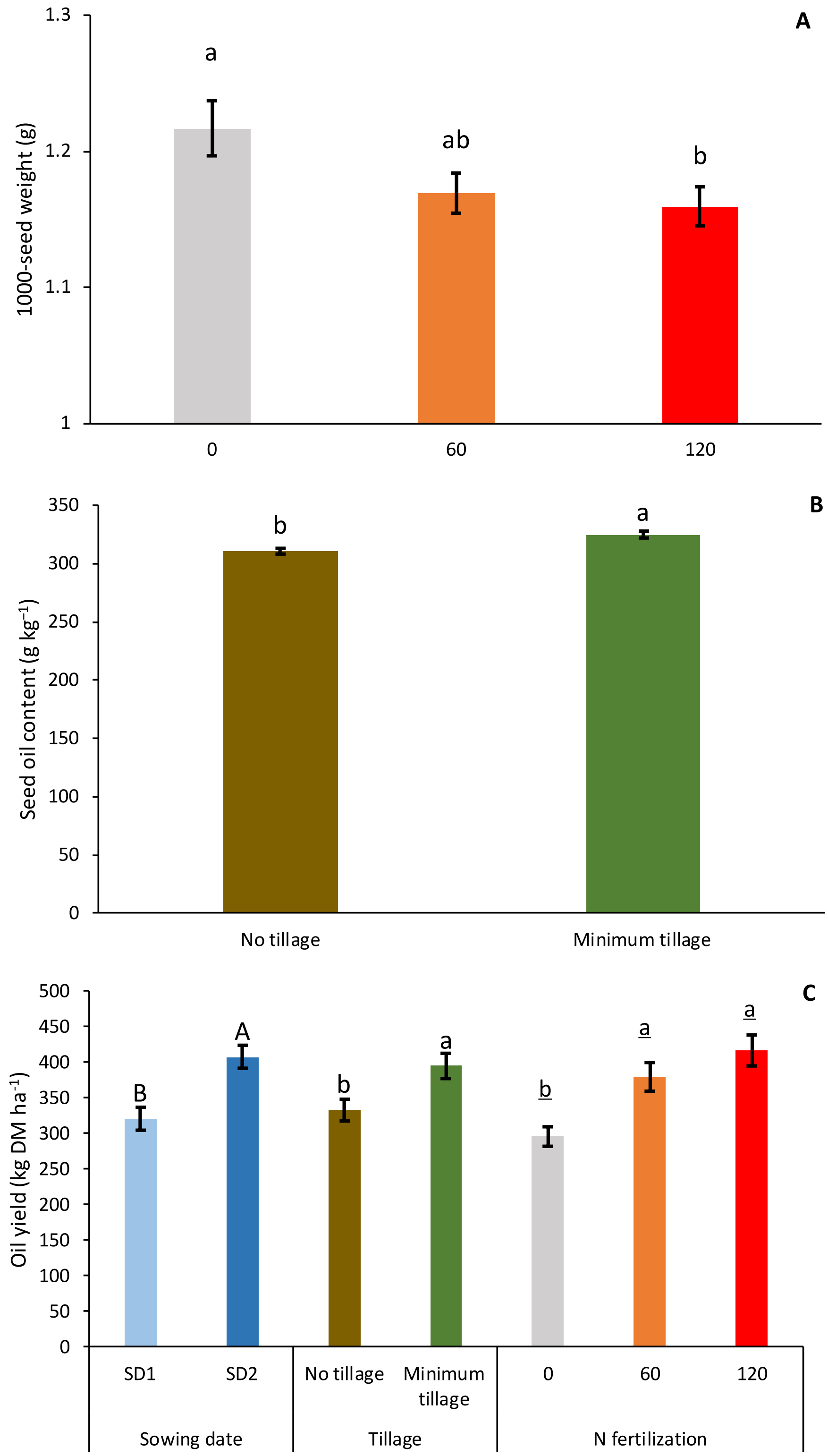


**Fig. 4.** Camelina thousand seed weight (A), seed oil content (B), and oil yield (C) in response to the main factors: sowing date, tillage and nitrogen fertilization. Different letters within each factor and parameter: significant different means ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

2023 likely led to a decrease in seed oil content of camelina. The mean seed oil content values of 300–330 g $kg^{-1}$ are about 5–8 %age points lower than typical oil content of camelina under similar conditions.

Finally, oil yield was determined through multiplying corresponding seed yield and oil content values. Oil yield was significantly influenced by all three main factors: tillage, sowing date, and N fertilization rate (Fig. 4C). Camelina oil yield increased significantly by ~20% under minimum tillage, while oil yield increased significantly by ~30% when camelina was sown later (SD2) rather than early (SD1) (Fig. 4C). The tested fertilization rates of 60 or 120 kg N $ha^{-1}$ both led to significantly lower oil yield when compared with the unfertilized control (0 N). Nonetheless, differences in oil yield between N rates of 60 and 120 kg N $ha^{-1}$ were not significant (Fig. 4C). This confirms a similar trend as was demonstrated by seed yield in response to N rate, however, with even

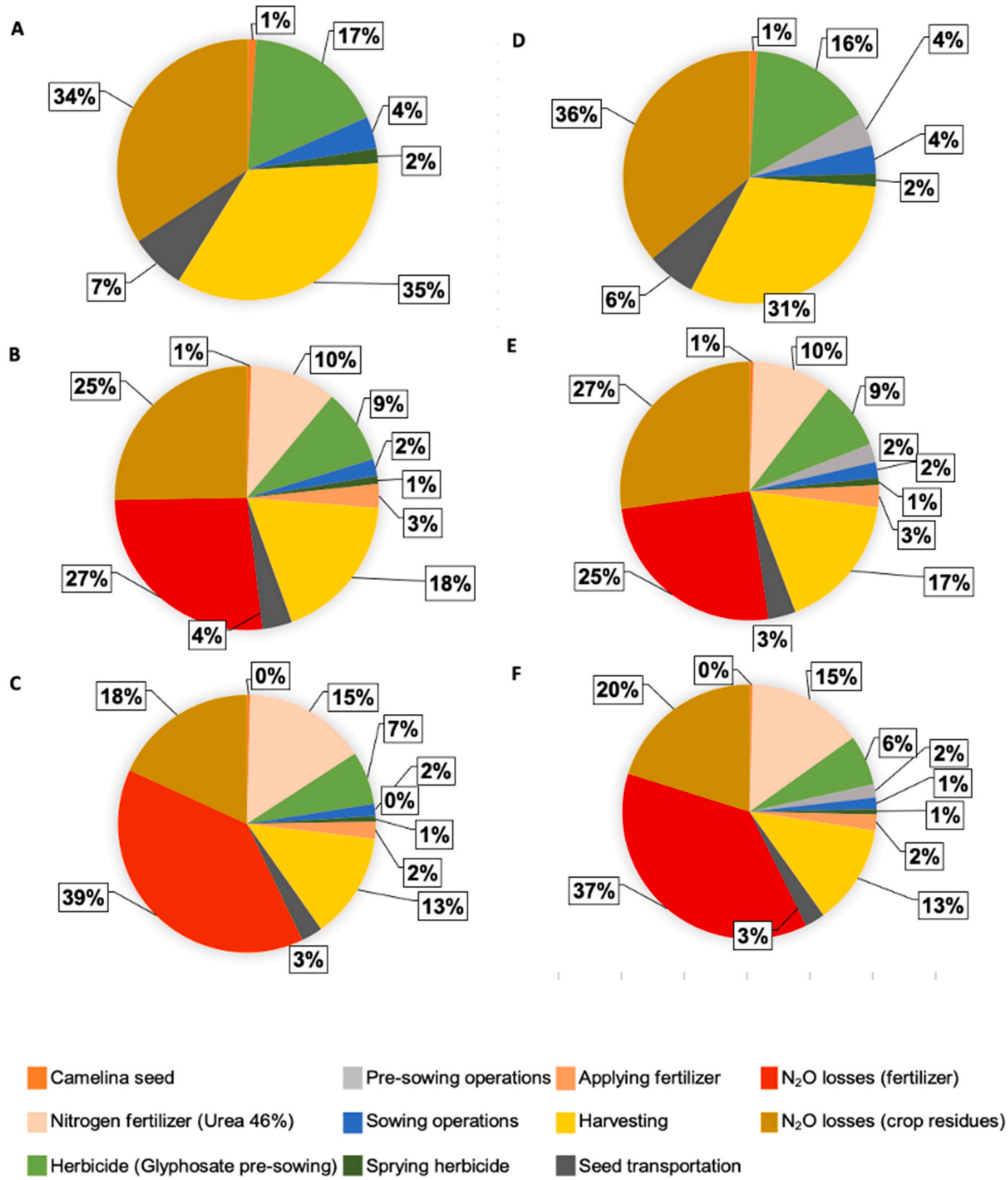


**Fig. 5.** Detailed breakdown of the farming carbon intensity (Kg $CO_{2e}$ $ha^{-1}$) for camelina under no-tillage with 0 (A), 60 (B), and 120 (C) kg N $ha^{-1}$, and minimum tillage with 0 (D), 60 (E), and 120 (F) kg N $ha^{-1}$. Different colors in the pies show the relative contribution of process inputs to the total farming carbon intensity.

**Table 4**
Environmental and economic performance of camelina production under different management scenarios in terms of tillage and N fertilization, including carbon intensity (expressed as g of $CO_{2e}$ $MJ^{-1}$ and kg of $CO_{2e}$ $ha^{-1}$), GHG emissions savings (%) of camelina-based biofuel, net profit value (NPV, € $ha^{-1}$), and benefit-cost ratio (BCR).

| Tillage method | N fertilization (kg N $ha^{-1}$) | Carbon intensity (kg $CO_{2e}$ $ha^{-1}$) | Carbon intensity (g $CO_{2e}$ $MJ^{-1}$) | GHG emission savings of camelina-based biofuel vs. fossil fuel (%) | NPV (€ $ha^{-1}$) | BCR |
|---|---|---|---|---|---|---|
| No tillage | N0 | 471 | 18.9 | 73 | 182.3 | 1.44 |
| | N60 | 893 | 32.5 | 53 | 175.5 | 1.36 |
| | N120 | 1222 | 36.7 | 47 | 282.3 | 1.55 |
| Minimum tillage | N0 | 519 | 19.8 | 72 | 186.1 | 1.42 |
| | N60 | 948 | 27.6 | 60 | 314.3 | 1.62 |
| | N120 | 1277 | 32.7 | 53 | 397.7 | 1.73 |

more restrained differences between 60 and 120 kg N $ha^{-1}$. Consequently, plots under the highest N fertilization rate had higher yield but lower seed oil content than those under 60 kg N $ha^{-1}$.

### 3.2.3. Results for carbon intensity calculation

Among the life cycle stages, the agricultural phase contributes the largest share of overall GHG emissions (Liu et al., 2024). Within the agricultural phase, $N_2O$ emissions (from fertilizer and from plant residues) have high global warming potential, and thus the highest impact on carbon intensity. This makes $N_2O$ emissions difficult to counterbalance with increases in seed yield scenarios that rely on the input of additional fertilizer. In the present study, the percentage of $CO_{2e}$ per hectare produced by field $N_2O$ emissions and fertilizer applications had the highest impact among the other inputs and processes of the agricultural phase, ranging from 25 to 39% (Fig. 5).

The global warming potential estimated for camelina cultivation under minimum- and no-tillage practices and among three N fertilization rates varied from 471 to 1277 kg $CO_{2e}$ $ha^{-1}$ and from 18.9 to 36.7 g of $CO_{2e}$ $MJ^{-1}$ (Table 4). When g $CO_{2e}$ $MJ^{-1}$ was used as the functional unit, the greatest differences in $CO_{2e}$ emissions were observed when N fertilization was avoided (0 N) and no tillage was performed. When N fertilization was applied (60 and 120 kg N $ha^{-1}$), differences between the two tillage strategies decreased, and minimum tillage reported even lower emission rates when compared with no tillage. Applying 60 kg N $ha^{-1}$, 32.5 and 27.6 g of $CO_{2e}$ $MJ^{-1}$ were emitted under no-tillage and minimum-tillage practices, respectively. At the highest N rate application (120 kg N $ha^{-1}$), emissions increased to 36.7 and 32.7 g of $CO_{2e}$ $MJ^{-1}$ under no-tillage and minimum-tillage practices, respectively. These results indicate that the highest seed yields were achieved when fertilization was increased under the minimum-tillage strategy. When considering g $CO_{2e}$ $ha^{-1}$ as the functional unit, the smallest difference in $CO_{2e}$ emissions between minimum tillage and no tillage was observed under 120 kg N $ha^{-1}$ (1222 vs. 1277 kg $CO_{2e}$ $ha^{-1}$). When N fertilization rate was reduced, a corresponding reduction in $CO_{2e}$ emissions was observed in both no-tillage and minimum-tillage scenarios ((Table 4).

When analyzing the detailed calculation of agricultural GHG emissions in the six different scenarios (three N fertilization rates x two tillage strategies) notable differences emerged in GHG emissions when comparing N rates and when comparing the two tillage strategies within each N level (Fig. 5). With increasing N fertilization rates, emissions via $N_2O$ losses from the fertilizer represent the largest share (e.g., 39% and 37% of total GHG emissions in scenarios with 120 kg N $ha^{-1}$, under no tillage and minimum tillage, respectively). Meanwhile, in the unfertilized scenarios, the main share of emissions came from $N_2O$ losses from crop residues and harvest operations (34% of total GHG emissions under no tillage vs. 36% under minimum tillage). Nitrogen losses from crop residues accounted for similar shares of total GHG emissions across different N fertilization levels (Fig. 5).

With respect to mechanized operations, including sowing and herbicide application, GHG emissions showed limited differences between tillage systems. Herbicide use exhibited a higher relative contribution in the 0 kg N $ha^{-1}$ scenario under no-tillage, accounting for 34% of total GHG emissions. GHG emissions associated with pre-sowing operations decreased from 4% in the unfertilized scenario, to 2% at 120 kg N $ha^{-1}$ under minimum tillage. Overall, increasing N application rates increased the proportion of fertilizer-related emissions under both tillage practices, while reducing the share of GHG emissions derived from mechanized field operations.

### 3.2.4. Results for economic benefit analysis

Economic performance was positive under all management strategies, as indicated by NPV ranging from 175.5 to 397.7 € $ha^{-1}$ , and BCR values exceeding 1 (Table 4). The effect of nitrogen fertilization differed according to the tillage system. Under no-tillage, the increase in seed yield from 998 to 1100 kg $ha^{-1}$ between the lowest and intermediate nitrogen rates was not sufficient to offset the additional fertilizer costs, resulting in a slight reduction in both NPV (from 182.3 to 175.5 € $ha^{-1}$) and BCR (from 1.44 to 1.36). Conversely, the highest nitrogen rate increased seed yield to 1333 kg $ha^{-1}$, leading to improved economic returns, with a NPV of 282.3 € $ha^{-1}$ and a BCR of 1.55. Under minimum tillage, profitability increased with nitrogen fertilization. NPV increased from 186.1 to 314.3–397.7 € $ha^{-1}$ at each of the three N rates, while BCR increased from 1.42 to 1.62–1.73 as nitrogen rates increased. These results indicated that the additional expenditure associated with nitrogen fertilization was compensated by the corresponding increase in seed yield, which ranged from 1046 to 1567 kg $ha^{-1}$ across different scenarios.

Overall, the results suggest that differences in profitability were mainly associated with differences in crop productivity rather than differences in production costs. Although minimum tillage involved higher field operational costs than no-tillage, the greater seed yields obtained under this system generated higher gross revenues and consequently higher NPV and BCR values. The most profitable treatment was minimum tillage combined with the highest nitrogen rate, whereas the intermediate rate under no-tillage resulted in the lowest economic return. In general, the best trade-off between economic return and CI was achieved via the unfertilized scenarios, slightly further improved by the no-till system.

## 4. Discussion

Analysis of literature on the effects of N fertilization on camelina seed yield, oil content, and oil yield revealed several critical insights. First, the literature analysis seems to confirm the low-input N suitability of camelina, as 73% of the N rates used across studies were $<$ 109 kg N $ha^{-1}$. These N rates for camelina are significantly lower than rates usually applied to rapeseed, which can often exceed 200 kg N $ha^{-1}$ (Rathke et al., 2006). Available literature suggests an increasing trend for seed yield increase when compared with the unfertilized control, though only up to a certain threshold of N fertilization. The plateau observed beyond 80 kg N $ha^{-1}$ along with the slight decline in seed yield increase at N rates above 170 kg N $ha^{-1}$ demonstrates diminishing returns for camelina produced at higher N levels. This trend was further validated by the significant quadratic model, with maximum seed yield at approximately 129 kg N $ha^{-1}$, whereas seed yield responsiveness started to diminish at ~80 kg N $ha^{-1}$.

The present findings summarize the results of 93 observations. Mohammed et al. (2017) observed that camelina seed yield was maximized at 60 kg N $ha^{-1}$, even though N levels up to 134 kg $ha^{-1}$ were tested. Consistently, Berti et al. (2025) reported the maximum seed yield of camelina at 60 kg N $ha^{-1}$, with no positive effects at higher rates. Urbaniak et al. (2008) reported similar results, with seed yield increasing with N rates up to 80 kg N $ha^{-1}$, despite testing rates up to 120 kg N $ha^{-1}$. Additionally, Jankowski et al. (2019) achieved a maximum seed yield increase of 61% when increasing fertilization from 0 to 120 kg N $ha^{-1}$, despite testing levels up to 160 kg N $ha^{-1}$.

It is noteworthy that higher N levels may have environmental and economic disadvantages, as emphasized by Solis et al. (2013), Jiang and Caldwell (2016), Bronson et al. (2019), and Johnson et al. (2018). For example, Bronson et al. (2019) highlighted a relevant decrease in nutrient use efficiency between 120 kg N $ha^{-1}$ and 150 kg N $ha^{-1}$, despite obtaining the highest seed yield of 1600 kg $ha^{-1}$ with the latter rate. Similarly, Johnson et al. (2018) reported that 130 kg N $ha^{-1}$ produced the highest seed yield of 1500 kg $ha^{-1}$, whereas a fertilization rate of only 34 kg N $ha^{-1}$ was still able to achieve a yield of 1200 kg $ha^{-1}$ and was identified as the optimal amount when considering efficiency parameters.

The variability in seed oil content across N ranges presents a clearer picture. Lower N fertilization rates exhibited relatively stable oil content, showing minimal changes. Conversely, higher N rates (80–109 kg N $ha^{-1}$ and above) demonstrated increased variability and more extreme outliers, with overall lower median values. The negative median of around −4% in the > 170 kg N ha$^{-1}$ class clearly indicates that high N application rates do not increase oil content and may in fact adversely affect oil content.

Variation for oil yield exhibited an increasing trend, peaking in the 80–109 kg N ha$^{-1}$ range, before decreasing in the 140–169 kg N ha$^{-1}$ range and reaching a plateau for the > 170 kg N ha$^{-1}$ range. The quadratic model for oil yield suggested that the optimal N rate is around 128 kg N ha$^{-1}$. Similarly, to seed yield, oil yield responsiveness to N fertilization reduces at about 80 kg N ha$^{-1}$, indicating that higher N rates yield diminishing benefits. The increasing variability observed in the higher N fertilization classes, especially from 80 to 109 kg N ha$^{-1}$ and above, together with the relatively low explanatory power of the regression models for seed yield and oil yield ($r^2 = 0.12$), should also be acknowledged. These results suggest that N fertilization rate alone explained only a small portion of the observed variation and that camelina response became less consistent as N inputs increased.

One possible explanation is that, at higher fertilizer rates, differences in starting soil N can strongly alter the actual amount of N available to the crop, leading to contrasting responses among studies. Wysocki et al. (2013) reported that seed yield response depended on total available N (calculated as soil-test N plus fertilizer N) and that response to high fertilization rates decreased when initial soil N was already high. Therefore, the same fertilizer class could include studies with very different total N availability, helping to explain the wider distributions and outliers observed at higher N rates.

Environmental conditions may have further contributed to this variability. In the same Wysocki et al. (2013) study, precipitation differed strongly among environments, ranging from about 1090 mm yr$^{-1}$ in the wetter environment to around 690 and 430 mm yr$^{-1}$ in the drier environments. The wetter environment generally showed a stronger response to N fertilization, whereas lower-precipitation environments showed weaker or less consistent responses, indicating that water availability can influence the capacity of camelina to use applied N. Similarly, Nleya et al. (2021) showed that camelina response differed between environments with contrasting soil organic matter, nitrate-N availability, temperature, and precipitation, finding that lower oil concentration was observed under drier and warmer conditions.

Differences in N fertilizer source and application strategy may have also contributed to variability among studies. For example, Nleya et al. (2021) applied N mainly as urea, whereas Bronson et al. (2019) used urea ammonium nitrate in split applications. Fertilizer forms can differ in N availability and potential leaching and emissions losses depending on soil moisture, rainfall after application, soil pH, and incorporation method. These differences confirm that the wider distributions observed in the boxplots and the low $r^2$ values likely reflect the broad range of soil fertility, residual N, precipitation, temperature, fertilizer management, and site productivity conditions represented in the dataset, rather than a lack of biological response of camelina to N fertilization. Therefore, the significant quadratic models should be interpreted cautiously and mainly as indicators of general response trends rather than precise predictive models.

Considering this information, the results of the literature review underscored the importance of optimizing N inputs for camelina cultivation, with moderate N applications (up to 80 kg N ha$^{-1}$) demonstrating improved seed yield and oil yield. Exceeding this threshold did not proportionally increase seed yield and may even negatively impact oil content. This is a critical insight from an ecological and soil health perspective, as when yield response reaches a plateau, additional N is less efficiently converted into harvested product, meaning a larger proportion of the applied fertilizer may remain unused or be leached into the soil system. Bronson et al. (2019) reported lower recovery of applied N at higher fertilization rates, indicating reduced fertilizer-use efficiency when N inputs exceeded crop demand. Similarly, Gregg et al. (2022) found that N-fertilized camelina increased biomass and grain yield, but also increased residual soil N. Therefore, excessive N fertilization may reduce the environmental advantages of camelina by increasing the risk of residual mineral N accumulation, nitrate-N losses, and $N_2O$ emissions. This effect can be further exacerbated under conditions where water availability, initial soil N, or crop uptake limit the use of applied N. This is consistent with Berti et al. (2025), who showed that camelina carbon intensity is strongly affected by seed yield and N fertilization rate. Moderate N fertilization is important not only to improve seed and oil yield, but also to maintain soil N balance, reduce unused fertilizer N, and preserve the low-input profile of camelina. This is of particular importance when considering camelina as a sustainable feedstock for biofuel production, as reducing agricultural GHG emissions is necessary to fulfill the requirements of existing legislation (European Parliament and Council of the European Union, 2023. Directive (EU) 2023/2413).

Although the field trial focused on spring camelina sown in autumn under northern Italian conditions, the literature synthesis was not restricted to autumn-sown camelina. This broader approach was necessary because only a limited number of autumn-sown or overwintering camelina cases were available in the literature, preventing a separate analysis for this specific planting system. Therefore, the literature-derived trends are used as a general framework for interpreting camelina response to N fertilization under field conditions and for contextualizing the N fertilization levels tested in the field experiment.

The field experiment then provides specific data to identify suitable agronomic management practices for autumn-sown camelina in northern Italy. This study focused on the cultivar Alba, which at the time of the study, was the reference commercial variety for Southern Mediterranean environments, assuring stable productions across very variable conditions (Berzuini et al., 2024). The availability of commercial camelina varieties in Europe is still minimal, meaning that while Alba is a valid reference material, it's intended breeding for dry pedo-climates of central Spain may mean northern Italy provides a suboptimal condition for this cultivar. The aim was to identify the optimal combination of sowing date, tillage strategy, and N fertilization rate. Sowing camelina in northern Italy in early October, when temperatures are still warm (i.e., mean daily temperature in the range of 10–15°C), led to greater shoot development. As a result of maturing after overwintering, early-sown plants suffered from more winter injury and ultimately resulted in shorter plants after exhibiting slower spring re-growth. The final plant density had a similar pattern as observed in previous studies (Gesch and Cermak, 2011), demonstrating higher density under early sowing (SD1). Even under later sowing (SD2), plant densities were similar to values reported in the literature (Hossain et al., 2019), or slightly lower than previous findings for winter camelina under similar conditions (Zanetti et al., 2020). Straw yield was influenced by N fertilization rate. According to Avola et al. (2021), a reduction in N fertilization rate drastically diminishes biomass and straw production. In this study, significant differences in straw production were found only between the unfertilized plots and the lowest N fertilization rate (0 vs. 60 kg N ha$^{-1}$), as has been previously reported by Jankowski et al. (2019). Meanwhile, no significant differences for straw production were observed between the 60 and 120 kg N ha$^{-1}$ rates, confirming findings observed by Gregg et al. (2024).

When producing upon marginal lands, 1000 kg ha$^{-1}$ can be considered a profitable camelina seed yield (Zanetti et al., 2024). In the present study, seed yield resulted below this value only in the unfertilized control (918 kg ha$^{-1}$ at 0 kg N ha$^{-1}$), however, it is worth noting that the soil utilized in this study cannot be considered marginal. Concerning the tested N fertilization rates, seed yield had a similar response as seen for straw, corroborating results from Afshar et al. (2016) who did not observe differences in seed yield when N rates increased from 45 to 90 kg N ha$^{-1}$. Similar results were recently reported also by Berti et al. (2025) in winter camelina. Notably, the present study evaluated spring camelina genotypes grown with an overwintering cycle, further demonstrating autumn-sown spring camelina in mild environments like northern Italy behaves similarly to winter camelina planted in more extreme northern pedo-climates (i.e., northern USA).

In the present study, seed yield was higher, but not significantly, when the highest N rate was applied. Nonetheless, the rate at which seed yield increased in response to N fertilization tended to decrease above the application of 60 kg N ha$^{-1}$, corroborating the results of Berti et al. (2025). The same trend has also been reported throughout the present literature analysis, as camelina seed yield reached a plateau in response at N fertilization rates around 80 kg N ha$^{-1}$. While N rates exceeding 120 kg ha$^{-1}$ may enhance seed yield, the environmental and economic disadvantages of this high-input strategy have been emphasized in most instances (Solis et al., 2013; Jiang and Caldwell, 2016; Bronson et al., 2019; Johnson et al., 2018; Berti et al., 2025).

Moreover, when identifying the optimal N rate, additional important aspects of plant health and development should be evaluated. Solis et al. (2013) evaluated N rates up to 300 kg N ha$^{-1}$, finding 75 kg N ha$^{-1}$ as the optimal rate to avoid lodging of stems and shatter of seed pods in camelina. Even so, in Solis et al. (2013), the relative seed yield with 75 kg N ha$^{-1}$ resulted lower than when applying 185 kg N ha$^{-1}$. Jiang and Caldwell (2016) registered 200 kg N ha$^{-1}$ as an optimal N rate for seed yield, however, they found significant increases in downy mildew (*Peronospora camelinae*) infection at N fertilization rates higher than 100 kg ha$^{-1}$. Similar results for downy mildew infection on spring-sown camelina were recently reported by Berti et al. (2025). In the present study, autumn-sowing the spring variety 'Alba' may have led to an almost null infection rate when surveyed.

Among measured parameters, seed weight decreased with higher N rates, as reported by Jankowski et al. (2019). This study found different results compared with Končius and Karčauskiene (2010), which found higher TSW at higher N rates. Seed oil content was not affected by N fertilization rate in the present study, confirming findings of the literature review, which reported negligible and often contrasting results for this parameter in response to N fertilization rate.

The results on our study for oil yield were in line with the results for seed yield, with significantly lower values under 0 kg N ha$^{-1}$ compared with 60 and 120 kg N ha$^{-1}$. This pattern of results aligns with the literature analysis, which described a decrease in responsiveness to N around 80 kg N ha$^{-1}$. Nevertheless, it is worth highlighting that the exceptional precipitation event of May 2023 had a greater effect on seed oil content than on seed yield, as flooding occurred toward the end of camelina growing cycle. This likely meant the negative impact was more meaningful for oil accumulation rather than yield determination. The aforementioned rain event was exceptional and when compared to other crops commonly grown in the area, like winter wheat (*Triticum eastivum*), the effect on camelina was tangible but did not catastrophic, confirming the high resilience of this crop.

Regarding tillage, seed yield was higher under minimum tillage compared with under no tillage. This is worth noting as minimum tillage can often be more easily adopted by local farmers than direct sowing, as specific equipment is required to optimize sowing under no-tillage management. Even so, in the present field study, the only available mechanical cereal seeder was used for both tillage systems, which could partially explain better performance under minimum tillage (Cannel 1985; Morris et al., 2010; Soane et al., 2012; Tebrügge and Düring, 1999). Thus, minimum tillage could be recommended as a transitional technique for new crops before moving to no tillage, still providing various benefits as reported in Table (S5, supplementary materials). Full adoption of no-tillage techniques usually requires a transition period (3–7 years) to return to previously achieved yield levels (Dick et al., 1991), requiring acquisition of specific equipment (i.e., no-till seed drill). The present results are in contrast with Gesch and Cermak (2011) who found higher seed yields when direct sowing was performed, reporting + 30% compared with conventional tillage. Meanwhile, Angelopoulou et al. (2023) did not find any significant differences in seed yield across varying tillage techniques. Again, the same mechanical seeder was utilized in both tillage strategies, even though the University of Bologna Experimental Farm is not usually managed under no-tillage. Presumably, this may mean that the minimum tillage technique allowed for an earlier and more even establishment of camelina, which may have improved competition against early emerging weeds. Nonetheless, final stand count increased under no tillage, despite the reduced straw and seed yield benefits (Fig. 3 A). One possible explanation could be the mild autumn/winter temperatures found in the local environment. This may have promoted shoot development under lower stand density, while at higher stand density (i.e., no-tillage system) competition among camelina plants may have been increased.

In terms of productivity, the seed yields obtained under no tillage (>1000 kg DM ha$^{-1}$, mean of all tested fertilization rates) can be considered slightly above the threshold for economic profitability of this crop (Zanetti et al., 2024; Guerrieri et al., 2026), especially if certified as a low iLUC (indirect land use change) feedstock for biofuel production. As a reminder, the studied systems meet requirements for iLUC certification, as fall-planted spring camelina in northern Italy can easily allow double cropping with soybean and sunflower.

In Europe, the agricultural sector accounts for 11% of total GHG emissions (EEA 2022). Of this agricultural share, 48% of emissions are derived from field $N_2O$ emissions from fertilization and soil management (EEA 2022). While several studies have evaluated the impact of N fertilization rate on camelina cultivation, a gap in knowledge still remains for the impact of this agricultural input on the life cycle assessment for camelina cultivation in Europe (Krzyżaniak and Stolarski 2019; Masella and Galasso, 2020; Matteo et al., 2020). When considering camelina as sustainable feedstock for biofuel production, efforts to optimize fertilization management must aim to balance the impact of inputs and outputs on GHG emissions, beyond just seed yield and productivity parameters alone. In Europe, the Directive (EU) 2018/2001 (European Parliament and Council of the European Union, 2018), also known as RED II, provides a detailed methodology for evaluating GHG emissions and establishes that GHG emission reductions should be at least 65% (after 1 January 2021), when comparing oilseed feedstocks-based biofuels with fossil counterparts. To fulfill this requirement, the agronomic management of agricultural feedstocks, such as camelina, should aim to minimize GHG emissions rather than simply to increase seed yield.

The present results for the environmental impacts of camelina cultivation, evaluated across six management scenarios (three N fertilization levels x two tillage strategies) for the most productive sowing date (SD2; Fig. 5), corroborate previous findings indicating that N fertilization represents largest contributing share of greenhouse gas (GHG) emissions from camelina production (Berti et al., 2017b, 2025; Guerrieri et al., 2026). In particular, Berti et al. (2017b) showed that monocropped camelina fertilized with 70 kg N ha$^{-1}$ under no tillage exhibited a carbon intensity (CI) ranging between 579 and 922 kg $CO_{2e}$ ha$^{-1}$ , which aligns well with the present study, in which the mean CI amounted to 888 kg $CO_{2e}$ ha$^{-1}$ .

Matteo et al. (2020) reported a value of 34.2 g $CO_{2e}$ MJ$^{-1}$ for camelina produced under low agronomic inputs (including conventional tillage, with ploughing and harrowing, and an N fertilization rate of 26 kg N ha$^{-1}$). This value is slightly higher than values obtained in the present study under minimum tillage and no-tillage, when nitrogen fertilization was avoided (19.8 and 18.9 g $CO_{2e}$ MJ$^{-1}$, respectively). This indicates that avoiding the use of conventional soil tillage techniques can help to reduce diesel and energy input requirements, which can help to reduce the impact of camelina cultivation without drastically reducing seed yield. Furthermore, Liu et al. (2024) estimated a CI of 32 g $CO_{2e}$ MJ$^{-1}$ for the agricultural phase of camelina feedstock production, assuming a seed yield of 1147 kg ha$^{-1}$ and an N fertilization rate of 59 kg N ha$^{-1}$ . This result aligns with the value obtained in the present study under minimum tillage and 60 kg N ha$^{-1}$ fertilization, which resulted in comparable values for seed yield (1170 kg ha$^{-1}$; Table 2) and CI (32.5 g $CO_{2e}$ MJ$^{-1}$; Table 3).

Overall, CI increased with increasing N fertilization rates despite the higher seed yields obtained, indicating that yield increases were insufficient to compensate for the additional corresponding $N_2O$ emissions. This pattern is consistent with response of camelina to N fertilization reported by the literature. Gregg et al. (2024) observed that seed yield increases with N application up to ~ 67 kg N $ha^{-1}$ , beyond which further N fertilization results in marginal or non-significant yield gains, indicating a plateau effect and both site- and year-specific variability.

Under both no-tillage and minimum-tillage systems, the highest GHG emissions were associated with $N_2O$ losses from N fertilizer and crop residues, as well as with emissions derived from N fertilizer production (Fig. 5). In particular, $N_2O$ emissions from fertilizer accounted for 27% and 39% of total emissions under no-tillage at 60 and 120 kg N $ha^{-1}$, respectively, and for 25% and 37% under minimum tillage. At 60 and 120 kg N $ha^{-1}$, respectively, emissions from crop residues contributed 25% and 18% under no-tillage, and 27% and 20% under minimum tillage. These values are consistent with those reported by Liu et al. (2024), who found that direct and indirect $N_2O$ emissions from fertilizers and residues accounted for 42–56% of agricultural GHG emissions, while emissions from nitrogen fertilizer production accounted for 17–21%. This was an expected result since the present study used Liu et al. (2024) coefficients for N content in the straw for all rates. Similarly, Guerrieri et al. (2026) reported a 22% increase in GHG emissions when camelina was cultivated as a double crop, compared with a conventional tillage-fallow baseline scenario, mainly driven by higher $N_2O$ emissions at increased nitrogen application rates. These results highlight the central role of nitrogen use efficiency and of the agricultural stage in determining the overall CI of camelina-based biofuels.

Nevertheless, the environmental benefits associated with reduced nitrogen inputs should be considered alongside their economic performance. Although all management scenarios evaluated in the present study were economically sustainable (BCR >1), profitability was affected by crop productivity. Indeed, the positive relationship observed between carbon intensity and net profit value (Supplementary, Figure S6) indicates that management practices associated with greater economic returns also tended to generate higher GHG emissions. In particular, the highest profitability (397.7 € $ha^{-1}$) was achieved under minimum tillage combined with the highest nitrogen application rate, whereas lower-input systems, despite demonstrating lower carbon intensities, generally resulted in lower economic returns. These findings suggest that the optimization of camelina cultivation for biofuel production should not rely exclusively on either environmental or economic criteria, but rather on an integrated assessment balancing GHG mitigation goals with farm profitability.

Beyond agronomic management, the economic viability of camelina-based value chains could be further enhanced through the valorization of co-products and bio-based products derived from camelina processing, thereby increasing the overall value generated per unit of seed produced (Nouira et al., 2026; Guerrieri et al., 2026). Additionally, the economic viability of camelina-derived biofuels is strongly influenced by policy incentives and regulatory frameworks promoting low-carbon fuels, including blending mandates and GHG reduction targets (Buffi et al., 2026; Nouira et al., 2026; Panoutsou et al., 2022).

From an environmental perspective, further opportunities for improving the sustainability of camelina production may arise from residue management strategies that influence soil $N_2O$ dynamics. According to Belleville et al. (2026), $N_2O$ emissions from crop residues are controlled by multiple factors. In this study, crop residues were assumed to remain on the soil surface under both tillage systems. While the effect of surface residues under no-tillage may vary with environmental and management conditions, minimum tillage generally involves crop residue incorporation into the soil, which has been associated with reduced $N_2O$ emissions (Abalos et al., 2022; Fiorini et al., 2020; Kesenheimer et al., 2019; Karlsson Potter et al., 2023). In addition, crop residue incorporation can promote soil carbon sequestration, leading to GHG emission savings through soil carbon accumulation (ESCA) as defined under the RED framework and IR (EU) 2022/996. However, this potential benefit must be weighed against the additional mechanical operation (e.g., harrowing) required, which may increase diesel consumption and partially offset the overall GHG savings.

Masella and Galasso (2020) reported that camelina cultivation accounted for 74% of total life cycle emissions of camelina-based biodiesel. This value was adopted to provide a preliminary estimate of the overall biofuel carbon intensity since downstream processes, including oil extraction, fuel conversion, transport, and distribution, were not assessed in the present study. Under this approach, camelina-derived biofuels obtained under the evaluated agronomic scenarios achieved GHG emission reductions ranging from 47% to 73% relative to the fossil fuel reference value (94 g $CO_{2e}$ $MJ^{-1}$, RED II). Among the tested management practices, the no-fertilizer treatments (0 N) under both no-tillage and minimum tillage systems showed the greatest mitigation potential, reaching estimated savings of 73% and 72%; respectively. Both of these management scenarios comply with the 65% requirement for GHG emissions reductions enforced by the current RED directives. These findings are in line with the results reported in other studies. Dangol et al. (2017) estimated GHG emissions reductions for camelina biofuel of ~ 69%, while Krohn and Fripp (2012) assessed a GHG emissions reduction ranging from 39% to 73% when compared with conventional diesel.

A further reduction in GHG emissions could be achieved by accounting for indirect land use change (iLUC), which was not considered in the present study, even if the studied cropping system qualifies as iLUC with cultivation of camelina as a winter intermediate crop. According to Taheripour et al. (2022), oilseed crops grown as intermediate crops are associated with a reduced iLUC value, resulting in an emission credit of 15.3 g $CO_{2e}$ $MJ^{-1}$ for camelina-based hydrotreated renewable jet fuel (HRJ). Including this credit would further reduce the overall CI of camelina-derived biofuels, which could enable additional management scenarios to comply with EU sustainability requirements.

The variability observed within these results is primarily driven by the agronomic inputs used in the farming stage; however, variability could also come from the methodology (e.g., allocation approach) adopted for the environmental impact calculation (Karlsson Potter et al., 2023). Although the CI values obtained may appear relatively high, it is noteworthy that the field study was conducted despite challenging environmental conditions; nonetheless with camelina confirming its high degree of resilience. Seed yields of the 'Alba' spring camelina were lower than those reported in previous studies under similar environmental conditions (Berzuini et al., 2024). Nonetheless, the adoption of conventional tillage could potentially increase seed yield, demonstrating that there is room for improvement for both productivity and CI of camelina production.

## 5. Conclusions

For the future scale-up of camelina as a sustainable biofuel feedstock, compliance with RED sustainability criteria and established environmental and regulatory is absolutely necessary. As highlighted by the literature review, the majority of existing literature on camelina focuses on the optimization of agronomic management as reflected by seed yield results and productivity parameters alone. However, when considering camelina as a sustainable biofuel feedstock, achieving a low carbon intensity (CI) may be as important as maximizing seed yield. Therefore, future research and agronomic recommendations should prioritize management strategies that enhance nitrogen use efficiency (NUE), while maintaining productivity and limiting cultivation-related GHG emissions. The results of this study suggest that improving NUE represents a key leverage point for improving both the agronomic and the environmental performance of camelina production systems, thereby supporting compliance with sustainability requirements and greenhouse gas emission reduction targets.

Even so, camelina production must provide a reasonable economic profit for farmers, which may require a full reconfiguration of the research approach. Synthesizing optimization of low CI with high seed yield must become the main objective of future studies on camelina management, as well as in future breeding programs. Finding equilibrium between low CI and high seed yield will allow producers to confer synergistic financial benefits from credits and incentives on top of profitable seed yields. Cultivar selection for improved NUE would be of high importance and value for camelina, as identifying cultivars able to produce higher yields without requiring increased N fertilization will directly reduce the CI of the system, promoting further sustainability. Additionally, multi-site experiments will be needed to validate the obtained results at larger scale and to develop a model to predict CI in different scenarios, pedoclimates and regions. To actualize camelina as a leading feedstock for biofuel production, collaboration between industry and science must aim to make this crop more productive and sustainable while fully complying with certification requirements.

## CRediT authorship contribution statement

**Sara Berzuini:** Writing – original draft, Formal analysis, Data curation. **Federica Zanetti:** Writing – review & editing, Writing – original draft, Conceptualization. **Rossella Mastroberardino:** Writing – original draft, Visualization, Data curation. **Maria Giovanna Sessa:** Writing – original draft, Data curation, Visualization. **Marisol T. Berti:** Writing – review & editing, Writing – original draft. **Micah Gartenberg:** Writing – review & editing. **Andrea Monti:** Writing – review & editing, Supervision, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2026.123875.

## Data availability

Data will be made available on request.

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