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Agronomic and Environmental Benefits of Recovered Gypsum for Sulfur Fertilization in Camelina for Biofuel Production

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ABSTRACT

Camelina (*Camelina sativa* (L.) Crantz) is an underutilized oilseed crop proposed as low-input feedstock for biofuel production, such as sustainable aviation fuel, under Mediterranean climate. However, its productivity is lower than that of more commonly used biofuel crops. Among agronomic techniques, sulfur fertilization is an underrated practice that can positively affect crop seed yield. This study evaluated the agronomic and environmental performance of camelina under different sulfur fertilization strategies, using industrial gypsum as a recycled S source. Field trials were conducted in central Italy over two consecutive growing seasons (2023–2024), evaluating five N–S combinations on spring-sown camelina. Agronomic performance, seed quality, and Life Cycle Assessment (LCA) of camelina subjected to different fertilization strategies were evaluated. The combined application of 60 kg N ha^{-1} with 40 kg S ha^{-1} significantly increased seed (+39%) and straw (+33%) yields compared to N-only fertilization. Sulfur improved the agronomic efficiency of nitrogen fertilization by 78%, without negatively affecting seed quality (glucosinolates, oil and protein content). LCA revealed that the use of sulfur fertilizers reduced camelina's environmental impact compared to the typical fertilization strategy. This is mainly due to the reduction in land required to produce 1 Mg of seeds and to the process associated with land management (primarily tillage and N fertilizers). However, modeling choices such as the inclusion of indirect land use change can significantly affect the output assessment. Overall, moderate S fertilization optimized both productivity and environmental impact, supporting camelina's role as a promising alternative to be introduced in Mediterranean traditional cropping systems.

1 | Introduction

The Sixth Assessment Report of the International Panel of Climate Change (IPCC) identifies how to date, climate change caused by anthropogenic factors has already produced irreversible impacts on both natural and human systems (Lee and Romero 2023). If rapid mitigation actions are not implemented soon, agri-food systems will face severe disruption even if adaptation measures are adopted (Hultgren et al. 2025).

It is estimated that approximately 15% of net global greenhouse gas emissions come from the transport sector (Lee and

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Romero 2023). Aviation, as part of this sector, is considered hard-to-abate, as decarbonization has been slow due to technical, political, and economic factors (Groppi et al. 2025). Biofuels are identified as one of the ways to reduce the environmental impact of transportation and are among the options to mitigate climate change (Raji et al. 2025). However, criticism on biofuels has been frequent. Criticism mainly relates to the cost of replacing a large share of fossil fuels with biofuels (Nordin et al. 2024) due to the high cost of the agricultural phase of production (Pin et al. 2025), or the competition for land with food crops (Kant et al. 2025). Yet, the use of marginal areas for the cultivation of biofuel crops is claimed to be an acceptable solution, as food production is inefficient on low-fertility soils, which in Mediterranean climate are often prone to drought and with adverse rooting conditions (Russo et al. 2025; Scordia et al. 2022). In addition, the progressive phase-out of biofuel feedstock imported from non-European countries is expected to increase the demand for locally produced biofuel crops, benefiting local farmers' revenues (Heimann et al. 2024). In this context, diversifying oilseed crops would improve the matching of species to the diverse European pedoclimatic conditions, supporting the expanding biobased industry.

Camelina (*Camelina sativa* L. (Crantz)) is an emerging oilseed crop in the Brassicaceae family, with a short growing cycle that allows it as an intermediate crop—grown between two main crops—thereby enabling two harvests within the same year. Its climate-adapted traits also make it suitable for marginal areas, supporting the integration of bioeconomy development with agroecological approaches in European farming systems (Zanetti et al. 2021). Due to its high oil content and oil characteristics, such as kinematic viscosity, acid number, flash point, sulfur content, and glycerol content (Yang et al. 2016), camelina has been recognized along with other Brassicaceae species (*Thlaspi arvense* L. and *Brassica carinata* A. Braun) as a promising feedstock for sustainable aviation fuel (SAF) production (Stamenković et al. 2023; Taheripour et al. 2022). In addition to oil production, camelina cake has been proposed as a feed component for rainbow trout (Lu et al. 2020), laying hens (Lolli et al. 2020), pigs (Luise et al. 2024), quails (Cullere et al. 2023), and rabbits (Kokošková et al. 2025). However, its glucosinolate (GLS) content has been identified as a limiting factor for the use of camelina cake in the feed sector, due to GLSs' antinutritional properties (Tripathi and Mishra 2007). Though the study of how agronomic practices impact seeds' GLS concentration is needed to further improve crop utilization.

Despite its advantages, camelina faces strong competition from other oilseed crops used for biofuel production, mainly due to its relatively low yields and not yet fully optimized agronomic management (Zanetti et al. 2021). Therefore, research efforts should focus on identifying strategies that can enhance camelina's competitiveness relative to other crops. Optimizing sulfur nutrition could represent a promising strategy to increase camelina productivity, as sulfur plays a crucial role in protein synthesis, oil quality, and overall metabolic efficiency. Despite sulfur uptake by crops being similar to that of phosphorus (Weil and Brady 2017), S fertilization remains largely overlooked in agronomic practice. Sulfur is an important nutrient, since it is a constituent of proteins in the form of cysteine and methionine (Sharma et al. 2024), and S-containing compounds, such as glutathione and N-acetylcysteine, have an important role in plant stress tolerance (Rodrigues De Queiroz et al. 2023). The Brassicaceae family, together with Leguminosae, is the family with the highest S requirements, reaching up to $60\,kg\,S\,ha^{-1}$ in rapeseed (Grant et al. 2012; Sharma et al. 2024). However, the effect of sulfur fertilization has been inconsistent in this family, with reported responses varying from no effect (Solis et al. 2013) to moderate yield increase (Jankowski et al. 2019) to significant increases in productivity (Bhattarai et al. 2021; Jankowski et al. 2020). The response of camelina to sulfur fertilization has been investigated in a limited number of studies and pedoclimatic conditions. In several cases, no positive effect from sulfur application has been observed, probably due to the relatively high fertility of the soils in which the cultivation took place (Sintim et al. 2015; Solis et al. 2013).

Multiple sources of variability affect sulfur uptake and remobilization in Brassicaceae, such as variety, availability of mineral S in the soil, and phenological phase (Borpatragohain et al. 2019; Grant et al. 2012). In rapeseed, for example, sulfur mobility from vegetative to reproductive organs is limited, so S deficiency before pod filling negatively affects yield and yield components (Dubousset et al. 2010). Beyond the above factors, in silico simulation in oilseed rape suggests that changes in phenology induced by climate change may affect S-uptake pattern, leading to a mismatch between crop S requirements and S supply, and potentially resulting in overfertilization (Poisson et al. 2018). To the best of our knowledge, there are no studies addressing sulfur remobilization in camelina; therefore, the precise timing of S requirements throughout its crop cycle remains uncertain. Assuming a behavior similar to other Brassicaceae, ensuring a consistent sulfur supply during the whole crop development through slow-release S fertilizers could be a reasonable strategy from the agronomic point of view.

Together with organic matter mineralization, main sources of available sulfur are atmospheric depositions, both natural and anthropogenic. Natural depositions are mainly related to emissions from volcanic eruptions or wildfires (Weil and Brady 2017). Anthropogenic depositions generally derive from fossil fuel combustion. In high-income countries S emissions—and hence depositions—were significantly reduced in recent decades, due to environmental regulations on fuel sulfur content (Zhong et al. 2020). Sulfur depletion in agroecosystems is further increased if crop management does not include the use of organic fertilizer, or the cultivation takes place in sandy soils, where sulfate leaching is promoted (Eriksen 2009). In the last decades, the reduction of S-input, with a parallel increase of S-uptake due to increased agricultural yields, has led to an increased risk of S-deficiencies in plants. The development of effective management strategies for sulfur fertilization is emerging as a pressing issue in agronomic research (Gerson and Hinckley 2023).

Gypsum ($CaSO_4 \times 2H_2O$) represents a valuable source of sulfur in agricultural systems. It can be extracted from quarries or can be obtained by chemical precipitation. The latter is usually a by-product of several industrial processes and, since it is produced in large volumes, its management is a challenge. Global production of gypsum from flue gas desulfurization is estimated to be 225 million Mg per year (Aakriti et al. 2023). In Tuscany (central Italy), the production of chemical gypsum

derived from regional titanium oxide manufacturing is estimated to be 500,000 Mg year^{-1}, which is currently disposed of in landfills (Marian et al. 2023). Additionally, sources of chemical gypsum from Na_2CO_3 production (Steinhauser 2008) are also locally available. Given the compliance of chemical gypsum with regulatory standards for its use in agriculture, its recovery for agronomic purposes could stimulate the local economy and enhance crop agronomic performance while reducing the amount of waste sent to landfills.

Life Cycle Assessment (LCA) is one of the most widely used methods for estimating the environmental footprint of goods or services. While the IPCC's Sixth Assessment Report focuses on the decarbonizing effect of biofuels in the transportation sector, LCA provides insights into other impact categories, including water or energy consumption, ecosystem toxicology, and human health. When applied to agricultural products, especially those evaluating different management practices, LCAs represent a key support tool for decision makers (Weidema et al. 2018). Previous LCA studies indicate that improving the environmental performance of camelina largely depends on increasing seed yield while simultaneously reducing inputs such as fertilizer and tillage (Bacenetti et al. 2017). If achieved through intensified tillage or increased NPK-water supply, however, higher seed yield could lead to an increase in the environmental impacts (Solinas et al. 2019).

For first-generation biofuels, land use change is indicated as one of the most impactful factors in the biofuel supply chain. Land use change can be classified into direct land use change, referring to changes occurring on the land where the land use takes place, and indirect land use change (iLUC) which refers to the upstream life cycle consequences of the land use (Schmidt et al. 2015). The prevalence of direct over iLUC largely depends on the geographical area where the cultivation took place (Brandão et al. 2021). If biofuel crops are cultivated in soils already used for agricultural purposes, iLUC is one of the most important factors affecting agricultural systems in consequential modeling analysis (Zhao et al. 2021). In literature, camelina is often represented as a crop with low iLUC mainly due to two management strategies: (i) cultivation in marginal areas with low agronomic values, and (ii) intercropping (Pagani et al. 2024). However, these assumptions are not usually confirmed by iLUC computation. To date, iLUC in camelina has been addressed only by Taheripour et al. (2022). However, this study merely compared camelina with other crops without examining the factors that may influence its value. Several environmental assessments have been published on camelina, focusing either on its cultivation systems (e.g., as traditional or reduced tillage, intercropping) or comparisons with other oilseed crops (Bacenetti et al. 2017; Berti et al. 2017; Krzyżaniak and Stolarski 2019). Differently, contributions on the effect of fertilization on camelina's environmental impact are scarce, and limited to nitrogen fertilization (Berti et al. 2025).

Despite the growing interest in camelina as a feedstock for SAF, several important knowledge gaps remain. Southern European environments have been identified as potentially favorable for camelina cultivation by modeling studies (Schillaci et al. 2023). However, the agronomic drivers affecting camelina productivity under Mediterranean conditions remain comparatively less investigated than in Central Europe or North America, where most field studies have been conducted. In particular, the role of sulfur nutrition in camelina cultivated under Mediterranean environments remains overlooked, despite the high sulfur requirements typically observed on Brassicaceae. In addition, important knowledge gaps also exist regarding the environmental assessment of camelina. Camelina is frequently described in literature as a crop with low iLUC risk; however, this assumption is not supported by iLUC calculations.

To address these gaps, this study evaluated the agronomic performance and seed quality traits (oil, protein, GLS concentration) of camelina under sulfur fertilization, in combination with conventional nitrogen management, under Mediterranean conditions. Gypsum derived from an industrial process was used as S source, representing a potential opportunity for the agronomic valorization of industrial wastes within a circular economy perspective. By combining field experimentation with environmental assessment, this study provides a novel and integrated assessment of the agronomic and environmental sustainability of fertilization strategies in camelina biofuels systems. In particular, the LCA performed in this study explicitly includes an estimation of iLUC-related emissions, a component that is often assumed but rarely quantified in previous assessments of camelina production systems. This integrated approach contributes to a more robust and transparent evaluation of the role of this crop in bioenergy supply chains.

2 | Material and Methods

2.1 | Industrially Recovered Gypsum as Sulfur Source

Raw gypsum, obtained as a by-product of sodium carbonate production via Solvay process, was collected from a chemical company located at Rosignano Solvay (Livorno province, Italy). During sodium carbonate production, crude brine is purified to prevent scaling. In this process, alkaline ions are precipitated, obtaining chemical gypsum which is considered a waste product (Steinhauser 2008). Gypsum was processed in the industrial plant of FerroDuo s.r.l, located in Piombino (Livorno province, Italy, 57 km from the chemical company), to obtain granules to be used as a sulfur fertilizer. The production process was carried out using a batch industrial granulator, that produced wet granules from raw gypsum, water and recycled milled granules. Wet granules were dried in fluid bed dryer fuelled by propane gas and subsequently sieved. Undersized and oversized granules were recycled into the granulation process as binders, after milling with a peg mill. The characteristics of granules comply with current EU and national regulation for agricultural use in terms of contaminants and minimum nutrient content requirements (European Parliament 2019). The final product is currently available on the market as sulfur fertilizer (35% SO_3, < 1% humidity).

2.2 | Agronomic Trial Setup

Field-plot trials were conducted during 2023 and 2024 growing seasons at the experimental Centre of the Department of

Agriculture, Food and Environment (DAFE) of University of Pisa, Italy (43°40′29″, 20°18′47″, 1 m asl). In both years, commercial variety 'Calena' (Saatbau Linz eGen Leonding, Austria) was used. Prior to sowing, analyses of germination percentage (International Rules for Seed Testing 2015) and 1000-seed weight (TSW) were performed to assess the optimal seeding rates able to guarantee a target of 500 plants m^{-2}. The seeding rate, in both years, was 6.5 kg ha^{-1}. Camelina was sown in plots (6 × 3 m size), arranged in a randomized block design with three replicates. Spring sowing (17/03/2023 and 17/04/2024) was performed using a Wintersteiger plot drill, with rows spaced 0.15 m, at a depth of 0.01 m. Agronomic trials took place in two adjacent fields inside the illuvial plain of the Arno river. In both years of cultivation, durum wheat (*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.) preceded spring camelina, assuming a rainfed cereal-based cropping system. For these experiments, five fertilization strategies were compared. The tested treatments were: (i) control (no application of N or S); (ii) 60_0 (60 kg N ha^{-1}); (iii) 60_20 (60 kg N ha^{-1} + 20 kg S ha^{-1}); (iv) 60_40 (60 kg N ha^{-1} + 40 kg S ha^{-1}); (v) 60_60 (60 kg N ha^{-1} + 60 kg S ha^{-1}). Nitrogen was applied as ammonium nitrate (27% N), while sulfur was applied as gypsum. The chosen nitrogen dose is consistent with values reported in the literature, where use of 60 kg N ha^{-1} provides the maximum grain yield and energy gain in camelina biofuel production system (Stolarski et al. 2019). Fertilization took place before sowing. No P and K fertilizers were applied. Weeding was performed manually, and no pest control was required.

TABLE 1 | Soil physical and chemical characteristics (0–30 cm) during the 2 years of experimentation.

Characteristics		2023	2024
pH (McLean method)		7.8	8.1
Total Nitrogen (Kjeldahl method)	g kg^{-1}	1.0	0.6
Organic Matter (Walkley-Black method)	%	1.7	1.1
Available phosphorus (Olsen method)	mg kg^{-1}	5.8	16.5
Sulfate (Ion chromatography)	mg kg^{-1}	8.1	n.d.
EC	µS cm^{-1}	50.9	67.5
CEC (Method $BaCl_2$)	meq 100 g^{-1}	4.6	2.4
Total $CaCO_3$	%	62.8	61.8
Active $CaCO_3$	‰	3.5	6.0
Clay	%	10.6	18.4
Silt	%	44.0	33.5
Sand	%	45.4	48.4

Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity.

Soils were Typic Xerofluvents and, in both years, soil samples were collected at 0–30 cm depth at the beginning of the trials for physical and chemical analyses (Table 1). The soils used were calcareous, characterized by a loam texture, sub-alkaline reaction, and medium to low content of organic matter, nitrogen, and phosphorus. Given the calcareous soil conditions of the experimental site and the relatively low gypsum application rates compared with those used for soil reclamation, no significant modifications of soil chemical properties were expected. Therefore, changes in soil characteristics after gypsum application were not specifically evaluated.

The climate in the area is hot summer Mediterranean (Csa—Köppen classification). Meteorological data (temperature, rainfall, radiation, humidity, atmospheric pressure, wind speed) was registered with 1 h resolution, using an automatic weather station located near (≈150 m) the experimental site. Reference evapotranspiration (ET0) was computed using Penman-Monteith model in the form reported by Allen et al. (1998). Air temperatures, cumulative rainfall and ET0 of the two growing seasons were then aggregated on a 10-day basis and plotted in Figure 1.

2.3 | Plant Sampling and Measurements

For each growing season, crop development was monitored using the phenological scale proposed by Martinelli and Galasso (2011). Furthermore, accumulated growing degree days (GDD) for both years of experimentation were calculated using daily maximum air temperature (T_{max}), daily minimum air temperature (T_{min}), and crop base temperature (T_{base}) of 4°C (Gesch 2014), as follows: $\mathrm{GDD} = \sum\left(\frac{T_{max} - T_{min}}{2} - T_{base}\right)$.

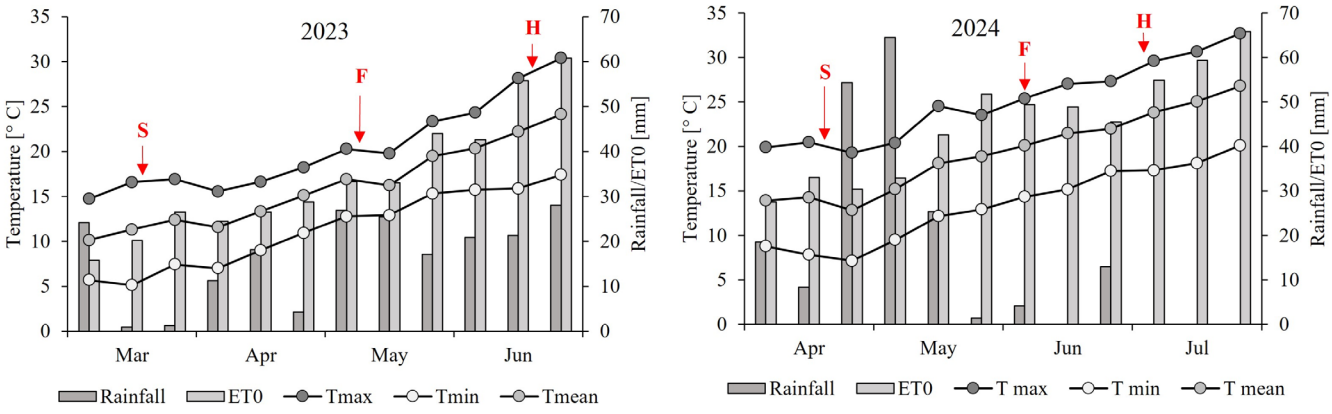


FIGURE 1 | Rainfall (mm)/ET0 (mm) (bars) and mean, minimum and maximum air temperatures (°C) (dotted lines), during 2023 and 2024 growing seasons, at the experimental site (San Piero a Grado, Pisa). Red arrows indicate sowing (S), beginning of flowering (F) and seed harvest (H).

Destructive samplings were performed at seed maturity (BBCH 89, June 19, 2023 and July 04, 2024). A sampling area of 1.6 m^2 (seven rows, each 1.5 m long) from the central portion of each plot was manually collected, removing the whole aboveground biomass. Plant density was evaluated, and within the harvested biomass, sub-samplings of 10 plants were randomly selected to measure plants' height and yield components (number of siliques per plant, number of seeds per silique). Aboveground biomass was separated into seeds and threshing residues (straw and opened pods) using a fixed-point threshing machine. Subsequently, a subsample of each was dried in a ventilated oven (60°C) to constant weight for moisture determination. Seeds were subjected to thousand seed weight (TSW) analyses using ISTA methodology (International Rules for Seed Testing 2015). The dry matter harvest index (HI) was also evaluated as a ratio between seeds' dry weight and dry weight of total aboveground biomass. Agronomic Efficiency (AE) of Nitrogen fertilization was calculated as reported in Fageria and Baligar (2005) and expressed as kg seed per kg N applied.

2.4 | Chemical Analyses

Nitrogen concentration in plant organs (straw and seeds) was measured using the Kjeldahl standard method. Seed crude protein content was calculated by multiplying nitrogen concentration by 6.25. For seed oil concentration, 1.5 g of ground camelina seeds were placed in a 0.22 × 0.8 cm Axiva Sichem Biotech extraction thimble. The thimble was inserted in a Soxhlet apparatus (mod. R 306) Beht Labor-Technik (Düsseldorf, Germany), and extraction was carried on for two hours using 60 mL of n-hexane as solvent. The extract was filtered with anhydrous sodium sulfate in a 100 mL flask and the solvent was removed under reduced pressure at 30°C in a rotary evaporator. Oil was dried under nitrogen flow for 5 min at 55°C and then weighed.

Glucosinolates (GLSs) were determined as reported by Pozzo et al. (2023). Briefly, GLSs were extracted from the defatted meal overnight at room temperature with 70% ethanol. The extract was centrifuged for 15 min at 15,000 rpm and added on the top of a DEAE Sephadex A-25 column (Sigma_Aldrich, Milan, Italy). The substance not retained by the resin was washed twice with 1 mL of 20 mM Na-acetate at pH 4.0. Bound GLSs were desulfated by the addition of 30 μL (10 U) of sulfatase Type H1 at 37°C overnight. Desulfoglucosinolates were eluted from the DEAE column with 1 mL of 100% ethanol and the samples dried at 55°C. The pellets were resuspended in 20% ethanol and filtered with 0.22 μm Costar Spin-X Centrifuge Tube Filter (Corning Incorporated, NY, USA) before conducting HPLC analysis. Desulfoglucosinolates were separated by HPLC according to Russo et al. (2014). A calibration curve with desulfo-sinigrin was generated. Total content of GLSs was expressed as μmol g^{-1} dry defatted meal.

Sulfur concentration in seeds was determined oven-drying a sample at 104°C for 24 h. Subsequently, a 0.2 g subsample was placed in a microwave digestion system (Start D, Milestone) with 8 mL of nitric acid (65%). The digested samples were diluted (1:10 v/v) with ultrapure water, filtered with PTFE filters (0.45 μm), and analysed by inductively coupled plasma mass spectrometry (ICP-MS; Shimadzu 2030 LF). The operating conditions were: (1) gas flow rate: 1 L min^{-1}; (ii) plasma temperature: 7000 K; (iii) plasma power: 1400 W; (iv) radiofrequency: 27 MHz. A calibration curve was obtained using sulfur standard solution at a known concentration (1000 mg L^{-1}).

2.5 | Life Cycle Assessment

Consequential LCA analyses were conducted with open-source software Activity Browser (2.11.1); missing data from background processes were obtained using Ecoinvent 3.11 consequential database. Consequential LCA analyses a system of interlinked activities that are expected to change as a consequence of a change in demand for a product (Weidema et al. 2018). The LCA was conducted from cradle to farm-gate, focusing on the agricultural phase. This approach was chosen because high-quality primary data were available for the farm-level processes—including information on sulfur fertilizer production—allowing for a robust assessment. Geographical boundaries of the analyses included the Tuscan area. The use of fertilizers obtained with the methodology described in the *Industrially recovered gypsum as sulfur source* section was carried out within a 100 km radius from the production site. For fertilizer production, only material and energy inputs required for processing were considered, while no upstream environmental burdens were attributed to recovered chemical gypsum. Oil extraction, biodiesel production, and utilization phases were excluded from the foreground system. No primary data from industrial facilities were available for these stages, and selecting a processing technology arbitrarily would have introduced substantial uncertainty due to variability of environmental impacts across different processing technologies (Resurreccion et al. 2021). Including oil extraction would also require accounting for coproduct management, for which no high-quality data were available both on destination and characterization. Not all tested fertilization strategies were evaluated in the LCA, but only those that were statistically different from the conventional fertilization strategy for camelina (60 kg N ha^{-1}), in terms of seed yield. Among them, the 60_40 treatment was selected for further analysis, as it represented the most efficient fertilization strategy, providing the highest yield response, whereas higher or lower sulfur rates did not provide any additional productivity benefits and would represent an unnecessary use of input. In addition, the unfertilized control was also included in the LCA. The uncertainty associated with the foreground processes was quantified using a pedigree matrix (Ciroth et al. 2016).

The functional unit used in the LCA was 1.0 Mg of camelina seeds (on dry matter basis). The fertilization strategy did not affect seed oil content, therefore downstream effects of cake production were not considered since it did not lead to a change in the system (for given functional unit, the same amount of oil and cake is produced). Similarly, neither emissions from residues nor biogenic carbon stored in residues were modeled, as no statistical effect of fertilization on HI was observed. Mineral nitrogen supplied in excess compared to the calculated crop N uptakes was assumed to be lost through nitrate leaching. Direct N_2O emissions from ammonium nitrate application, were estimated using the emission factor (0.0035) estimated by Ottaiano et al. (2025) for loam soils in Mediterranean climate. Indirect N_2O emissions from nitrogen leachate, were estimated by applying the emission

factor (0.005) reported in IPCC (2019). For biomass production, field operation and fuel consumption, data were collected during the agronomic experimental trials. Primary data on sulfur fertilizer production, including energy and material consumption, were collected on-site from FerroDuo s.r.l. industrial facility and reflect the actual production processes of a commercial product. Regional data on electricity generation and geothermal emissions in Tuscany were sourced from official reports issued by the electricity provider and the public environmental monitoring agency. The inventory used for the LCA is reported in the supporting information (Tables S1–S5).

ILUC computation for the Climate Change impact category was performed using the method described by Schmidt et al. (2015). The theoretical assumption underlying iLUC is that the production of goods requiring land occupation induces a local loss of biomass production capacity, measured as net primary production (NPP_0). This loss can be recovered by marginal land suppliers by converting 'land not in use' to 'land in use'. The indirect CO_2 eq emissions associated with land conversion are then attributed to the produced good. The iLUC calculation required four factors: (i) kg of NPP_0 m^{-2} lost due to land occupation; (ii) kg CO_2 eq associated with the recovery of 1 kg of NPP_0; (iii) share of emissions attributed to 1-year anticipation of land conversion; (iv) land used (m^2) to produce 1 Mg of camelina seeds. The first factor, NPP_0 m^{-2} loss in Tuscany due to camelina cultivation, was obtained from Copernicus repository as a 20-year average (European Environment Agency 2023). The second factor was modeled as transformation of forest to arable land. According to Global Forest Review (2025), 92% of permanent deforestation is likely to occur in five countries (Brasil, Indonesia, Congo, Malaysia, and Bolivia), which were considered in this study as marginal suppliers for land. For each country, CO_2 eq per kg of recovered NPP_0 were obtained from Ecoinvent, and final value (53.9 kg CO_2 eq kg $NPP_0{}^{-1}$) was calculated as weighted mean of the contribution of each country to permanent deforestation. The third factor, following the procedure described in Section 2.6 of Schmidt et al. (2015), was set at 0.00783.

LCA results were calculated with Environmental Footprint (3.1) methodology for five impact categories: Climate Change ("CC," as CO_2 eq), Land Use ("LU," as soil quality index score), Freshwater Ecotoxicity ("FWE," as Comparative Toxic Units), Energy Resource—fossil fuel ("ERff," as Mj), Water Use ("WU," as m^3 eq deprived).

2.6 | Statistical Analyses

To account for uncertainties in background processes, the LCA results were subjected to a Monte Carlo analysis with 1000 runs, implemented in Activity Browser and using the uncertainty distributions as defined in the Ecoinvent 3.11 database. Statistical analysis of agronomic data and LCA results was performed using "R Studio" software (version 4.3.1.). Agronomic data were subjected to one-way ANOVA, fitting a mixed effect linear model ('lme()' function - 'nlme()' package) with "Fertilization Strategy" as fixed factor and "Year" as random factor, while for Monte Carlo results a generalized least square model was fitted ('gls()' function – 'nlme' package). For parameters statistically affected by fertilization strategy, estimated marginal means ('emmeans()' package), were separated via Tukey's HSD test at $p \leq 0.05$ level.

3 | Results

3.1 | Meteorological Data, Crop Phenology, and Agronomic Evaluation

During the trials, no differences among fertilization strategies were observed in the timing of the main phenological stages or in the overall duration of the crop cycle. In both years, spring-sown camelina completed its growth cycle by accumulating approximately the same amount of GDDs (1116 and 1108 GDD in 2023 and 2024, respectively), although differences were observed in the total cycle length (94 and 79 days, in 2023 and 2024, respectively). Rainfall was more evenly distributed in the first year (Figure 1), although total precipitation was comparable (147 mm in 2023 vs 170 mm in 2024). During the two growing seasons, ET0 was similar too, with cumulative values almost double those registered for rainfall (316 mm in 2023 and 335 in 2024).

A significant effect of fertilization strategies was observed in seed and straw yield (Table 2). The application of sulfur at the rate of 40 kg ha^{-1} significantly increased both seed (+39%) and straw (+33%) yields compared to plots receiving only ammonium nitrate. No significant differences were observed among the sulfur application rates of 20 and 60 kg S ha^{-1} (Table 2). As expected, the unfertilized control showed lower seed and straw yields compared to all fertilized plots. No statistical effect of fertilization on HI was observed, that was on average 0.27.

Plants that received fertilization, either with nitrogen alone or with the combined $N+S$ treatment, showed a significantly greater (+34%) height compared to unfertilized plants, while no differences were observed among the fertilization strategies (Table 3). Regarding yield components, no significant differences among fertilization strategies were observed in the number of seeds per siliqua or in the TSW. Conversely, the application of 40 kg S ha^{-1}

TABLE 2 | Effect of fertilization strategies on seed and straw yield of spring-sown camelina at seed maturity (BBCH 89).

	Seed yield (Mg ha^{-1})	Straw yield (Mg ha^{-1})	Harvest index
Control	0.6 ± 0.1 c	1.9 ± 0.3 c	0.25 ± 0.02
60_0	1.3 ± 0.1 b	3.6 ± 0.3 b	0.26 ± 0.02
60_20	1.5 ± 0.1 ab	4.2 ± 0.3 ab	0.27 ± 0.02
60_40	1.8 ± 0.1 a	4.7 ± 0.3 a	0.27 ± 0.02
60_60	1.6 ± 0.1 ab	4.3 ± 0.3 ab	0.27 ± 0.02
p	< 0.001	< 0.001	0.443

Note: Estimated marginal means ± SE followed by identical letter are not significantly different according to Tukey's HSD test. Control = no application of N or S; 60_0 = 60 kg N ha^{-1}; 60_20 = 60 kg N ha^{-1} + 20 kg S ha^{-1}; 60_40 = 60 kg N ha^{-1} + 40 kg S ha^{-1}; 60_60 = 60 kg N ha^{-1} + 60 kg S ha^{-1}.

resulted in the highest number of siliques per plant, with statistically significant increases of 55% and 193% compared to nitrogen-only treatment and the unfertilized control, respectively.

Moreover, the AE, expressed as the amount of seed produced per kilogram of applied nitrogen, increased by 8.3 kg with the application of 40 kg S ha^{-1}, compared to nitrogen fertilization alone (Table 4). On the contrary, among the three sulfur application rates, no significant differences were detected.

No significant differences among fertilization strategies were observed in seed oil, protein and sulfur concentration, while total GLS concentration was significantly affected by fertilization strategy (Table 4). The higher GLS concentration was observed in the unfertilized control, showing a 10.3% increase compared to 60_0 treatment. All sulfur fertilization strategies slightly increased GLS concentration compared to 60_0, although these differences were not statistically significant.

3.2 | LCA

The LCA was carried out by comparing only the fertilization strategies that showed statistically different values for seed yield (control, 60_0 and 60_40). For each impact category (CC = climate change without iLUC; CC(+)iLUC = climate change with iLUC; LU = land use; FWE = freshwater ecotoxicity; ERff = energy resources—fossil fuel; WC = water consumption), the obtained scores are reported in Table 5. With the exception of FWE, all impact categories were affected by fertilization strategy.

For CC without iLUC the highest impact was observed in 60_0 followed by 60_40, that produced on average 34.4 and 192.8 more kg CO_2 eq compared to the control respectively (Table 5). For both strategies, the major contributor was N fertilizer, which accounted for 46.9% and 41.2% of the overall impact respectively (Figure 2). For the control, tillage had the highest contribution (47.8% of CO_2 eq emissions). If iLUC is included in the assessment, it was the main contributor to CO_2 eq emissions, ranging from 87.3% the control, to 70.4% in 60_40 (Figure 2). With iLUC, the unfertilized control became the strategy with the highest CC impact, followed by 60_0 and 60_40 (Table 5).

Direct occupation of land by the crop was the first-tier contributor that accounted for almost the totality (on average 98.2%) of the Land Use impact (Figure 3). For LU, impact among fertilization strategies followed the opposite trend to seed yield, with control having an impact 2.8 and 2.0 times higher than 60_40 and 60_0, respectively (Table 5). The increase of productivity per hectare requires a lower amount of land to produce one functional unit, reducing land demand and thus land consumption.

Similarly, lower yield in the control required tilling a larger area. Consequently, the energy resources impact category (Table 5) was higher in the strategy without the application of fertilizers (+1245.8 and + 227.9 MJ) compared to 60_40 and 60_0

TABLE 3 | Effect of fertilization strategies on plant height, yield components, and thousand seed weight (TSW) of spring-sown camelina at seed maturity (BBCH 89).

	Plant height (cm)	Siliques (*n*. plant^{-1})	Seeds (*n*. silique^{-1})	TSW (g)
Control	51.5 ± 8.5 b	53.7 ± 14.1 c	8.8 ± 0.7	1.13 ± 0.02
60_0	66.5 ± 8.5 a	102.1 ± 14.1 bc	8.1 ± 0.7	1.16 ± 0.02
60_20	68.9 ± 8.5 a	122.9 ± 14.1 ab	7.6 ± 0.7	1.16 ± 0.02
60_40	71.4 ± 8.5 a	157.8 ± 14.1 a	8.7 ± 0.7	1.15 ± 0.02
60_60	70.9 ± 8.5 a	116.4 ± 14.1 ab	7.5 ± 0.7	1.15 ± 0.02
p	< 0.001	< 0.001	0.461	0.699

Note: Estimated marginal means ± SE followed by identical letter are not significantly different according to Tukey's HSD test. Control = no application of N or S; 60_0 = 60 kg N ha^{-1}; 60_20 = 60 kg N ha^{-1} + 20 kg S ha^{-1}; 60_40 = 60 kg N ha^{-1} + 40 kg S ha^{-1}; 60_60 = 60 kg N ha^{-1} + 60 kg S ha^{-1}.

TABLE 4 | Effect of fertilization strategies on Agronomic Efficiency (AE), seed oil, protein, total glucosinolates (GLS), and sulfur content of spring-sown camelina at seed maturity (BBCH 89).

	AE	Oil (%)	Protein (%)	Total GLS (μmol g^{-1} dry meal)	Seed sulfur concentration (g kg^{-1})
Control	—	39.8 ± 2.4	21.9 ± 1.7	38.1 ± 0.7 a	1.1 ± 0.1
60_0	10.6 ± 5.0 b	38.9 ± 2.4	24.3 ± 1.7	34.6 ± 0.7 b	1.0 ± 0.1
60_20	15.1 ± 5.0 ab	39.4 ± 2.4	25.2 ± 1.7	35.5 ± 0.7 ab	0.8 ± 0.1
60_40	18.9 ± 5.0 a	39.1 ± 2.4	24.4 ± 1.7	37.0 ± 0.7 ab	0.9 ± 0.1
60_60	16.4 ± 5.0 ab	39.8 ± 2.4	22.9 ± 1.7	36.6 ± 0.7 ab	0.8 ± 0.1
p	0.025	0.819	0.118	0.027	0.444

Note: Estimated marginal means ± se followed by identical letter are not significantly different according to Tukey's HSD test. Control = no application of N or S; 60_0 = 60 kg N ha^{-1}; 60_20 = 60 kg N ha^{-1} + 20 kg S ha^{-1}; 60_40 = 60 kg N ha^{-1} + 40 kg S ha^{-1}; 60_60 = 60 kg N ha^{-1} + 60 kg S ha^{-1}.

TABLE 5 | Effect of fertilization strategies on environmental impact of producing 1 Mg of camelina seeds.

	CC (kg CO_2 eq)	CC(+)iLUC (kg CO_2 eq)	LU (Soil quality index)	FWE (CTUe)	ERff (MJ)	WC (m^3 of water eq)
Control	694.9 c	5360.7 a	$7.9\times(10^5)$ a	1707.8 a	7757.3 a	99.4 c
60_40	729.3 b	2372.0 c	$2.8\times(10^5)$ c	1596.1 a	6511.5 c	171.7 b
60_0	887.7 a	3235.5 b	$4.0\times(10^5)$ b	1963.8 a	7529.4 b	226.8 a
p	<0.001	<0.001	<0.001	0.597	<0.001	<0.001

Note: Estimated marginal means followed by the same letter, are not significantly different according to Tukey's HSD test. CC = climate change without iLUC; CC(+)iLUC = climate change with iLUC; LU = land use; FEW = freshwater ecotoxicity; ERff = energy resources – fossil fuel; WC = water consumption. Control = no application of N or S; 60_0 = 60 kg N ha^{-1}; 60_40 = 60 kg N ha^{-1} + 40 kg S ha^{-1}.

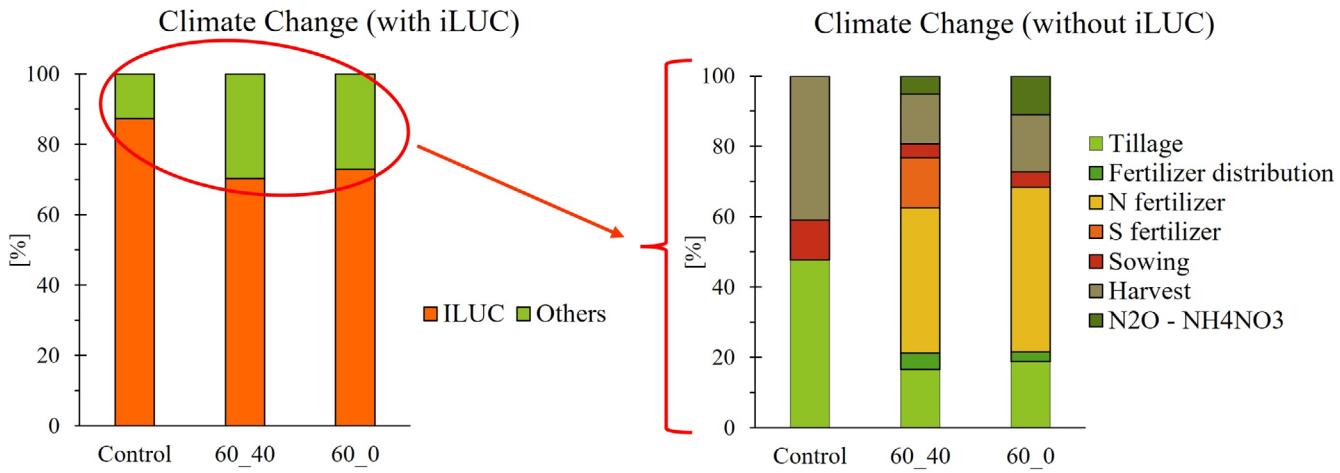


FIGURE 2 | Results of contribution analyses for the Climate change impact category, with (Left) and without (Right) iLUC, as affected by fertilization strategy (Control = no application of N or S; 60_0 = 60 kg N ha^{-1}; 60_40 = 60 kg N ha^{-1} + 40 kg S ha^{-1}).

respectively, with tillage accounting on average for 55.3% of energy depletion (Figure 3). In the strategies with the application of ammonium nitrate, N fertilizer was the larger first-tier contributor (43.1% in 60_40 and 44.8% in 60_0). In 60_0 higher use of NH_4NO_3 per functional unit compared to 60_40, increased energy consumption on average by 418.6 MJ.

The water use impact category (Table 5) was mainly driven by water consumption for ammonium nitrate production (on average 74.4% of the overall impact in fertilized plots), therefore unfertilized control scored a significant lower impact compared both to 60_40 (−76.5 m^3 water eq) and 60_0 (−127.0 m^3 water eq).

4 | Discussion

The results of this study demonstrated that sulfur fertilization can substantially improve camelina productivity under the tested experimental conditions (Mediterranean climate, spring sowing, and low soil organic matter), while also influencing its environmental footprint when integrated within nitrogen-based fertilization regimes. The combined application of 60 kg N ha^{-1} and 40 kg S ha^{-1} produced the highest seed and straw yields, with a 39% and 33% increase compared to the nitrogen-only treatment, respectively. Seed yield obtained under the 60_40 strategy is consistent with the average spring-sown camelina yield in Italy (Weiss et al. 2024). The seed yield enhancement in camelina was mainly driven by a higher number of siliques per plant, rather than changes in seed size (TSW) or number of seeds per silique, which remained stable across treatments. Similar findings were reported by Solis et al. (2013), who indicated that S fertilization promoted reproductive development and siliques formation rather than altering seed filling processes. Furthermore, Gregg et al. (2024) observed a strong correlation between the number of siliques per plant and camelina seed yield. However, D'Hooghe et al. (2025) recently highlighted how changes in S supply induced different adaptative S metabolism in two varieties of *B. napus*, resulting in changes in yield components tuning and seeds chemical characteristics. Therefore, different camelina genotypes might have different response to S application. Responses of seed and straw yield to fertilization strategy are similar, without a significant effect of fertilization on dry matter allocation. Differently, in other Brassicaceae species, S fertilization has been observed to affect HI (Seepaul et al. 2019). Nevertheless, our results confirm that sulfur nutrition represents a limiting factor for camelina yield in low-S soils. In this study, baseline soil sulfate content was determined only during the first growing season. However, soil organic matter content in the second year was slightly lower than the first year (Table 1). Considering the documented relationship between soil organic matter and available sulfur pool in soil (McKenna et al. 2025), sulfate content during the

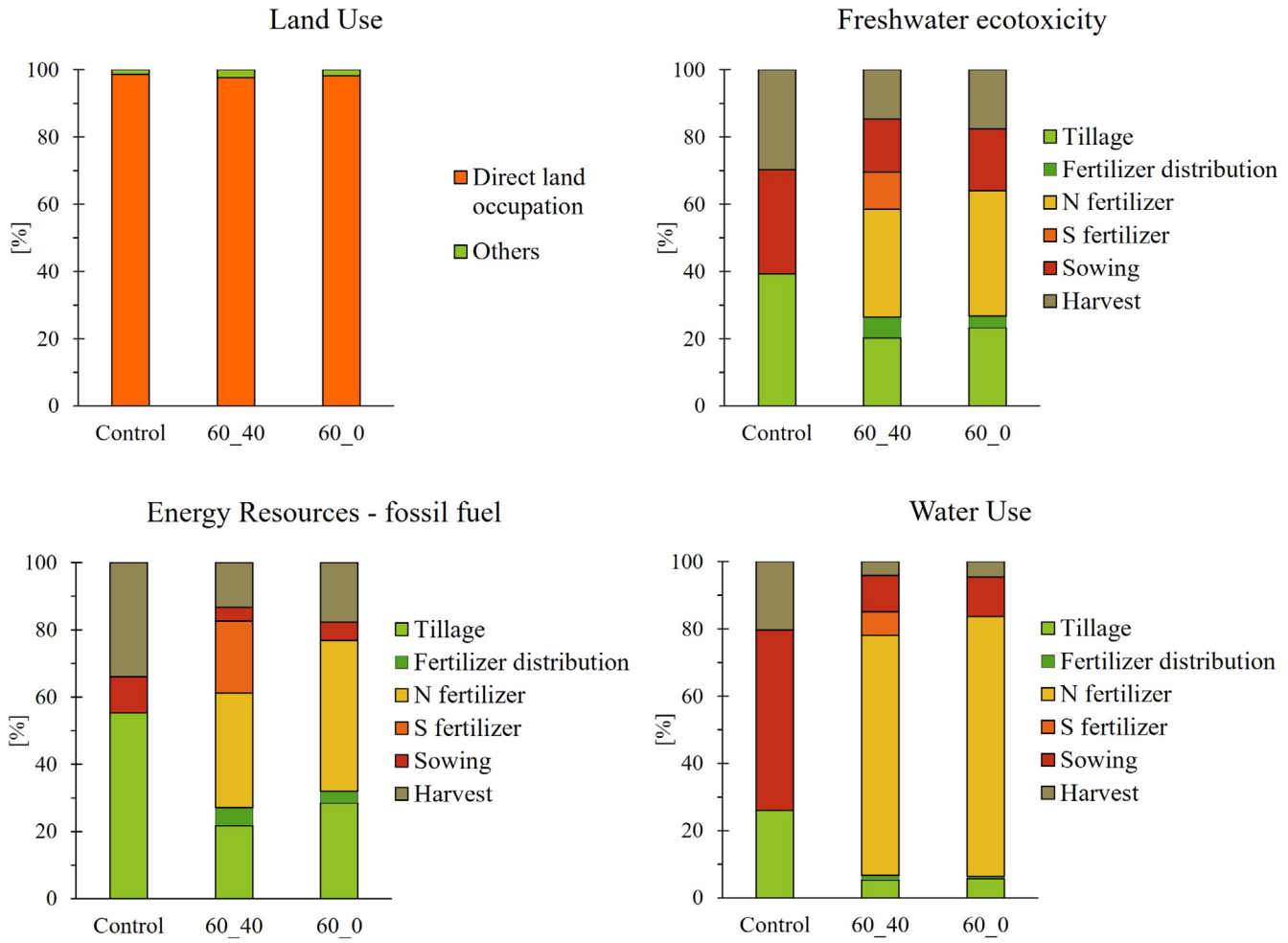


FIGURE 3 | Results of contribution analyses for Land Use (top left), Freshwater ecotoxicity (top right), Energy resources – fossil fuel (bottom left) and Water consumption (bottom right), as affected by fertilization strategy (Control = no application of N or S; 60_0 = 60 kg N ha^{-1}; 60_40 = 60 kg N ha^{-1} + 40 kg S ha^{-1}).

second year was likely lower compared to the first one. Under these conditions, and without external inputs, the amount of nutrients released through organic matter mineralization was insufficient to meet crop requirements when nitrogen fertilization was applied alone. This is further supported by the low yield observed in the unfertilized control, where plant nutrition relied exclusively on nitrogen and sulfur released through mineralization processes, which proved largely inadequate to sustain optimal crop growth. Accordingly, conducting the same experiment on soil with higher organic matter and sulfur content likely result in less pronounced responses to sulfur fertilization, due to greater nutrients availability, in agreement with the observations of Solis et al. (2013). In literature, the response of Brassicaceae species to sulfur fertilization shows considerable variability, mainly due to the heterogeneity of experimental conditions across experiments. For example, Sintim et al. (2015) conducted a study on camelina cultivated in soil with a high organic matter content, where external sulfur was supplied in elemental form. Under these conditions, no significant effects were observed on plant height, seed yield, HI, protein concentration, or estimated biodiesel production. However, elementary sulfur requires oxidation to sulfate (SO_4^{2-}) to be available for plant uptake (Mahal et al. 2022). So, the combined effects of low S-availability of the external sulfur and the higher amount of S released from SOM mineralization, could have hidden the effect of S fertilization. Differently, in white mustard, Jankowski et al. (2020) observed that sulfur application at 20 kg S ha^{-1} increased seed yield and, in S-deficient soils, Malhi et al. (2007) found a strong increase in seed yield in 4 genotypes of *B. juncea* and *B. napus*, already at low S rate (10 kg S ha^{-1}).

Furthermore, the significant improvement in AEunder S fertilization highlighted the synergistic role of sulfur in enhancing nitrogen utilization efficiency. As S is an essential component of amino acids such as cysteine and methionine, its availability directly affects protein synthesis and N assimilation (Sharma et al. 2024). The 78% increase in AE observed with the 60_40 treatments in comparison with the N-only fertilization, suggests that, in camelina, balanced S nutrition can optimize metabolic processes linked to N use. These observations are consistent with previous studies reporting that sulfur fertilization in Brassicaceae enhances nitrogen fertilization efficiency (Ma et al. 2020), highlighting the importance of nutrient interactions in maximizing crop productivity and resource use efficiency. Based on this synergism, sulfur fertilization may also contribute to reducing the environmental footprint of nitrogen fertilization by improving

nutrient uptake efficiency. As a result, a larger share of applied N is retained within cropping system, reducing potential environmental losses through nitrate leaching and nitrous oxide emissions, and ultimately decreasing associated environmental burdens (Duncan et al. 2018).

Contrary to other authors (Avola et al. 2021), in the present study seed oil and protein contents were not significantly affected by the fertilization strategy, suggesting that camelina seed quality is relatively stable across a range of nutrient inputs. However, sulfur fertilization slightly increased total GLS concentrations compared to the N-only treatment, though differences were not statistically significant. Abiotic stress and nutritional status are known to influence GLS seeds concentration in Brassicaceae (Amiri-Darban et al. 2020; Jiang et al. 2016). Therefore, higher GLS concentration in the defatted meal of the unfertilized control may reflect nutritional stress, suggesting GLS accumulation as a defence-related metabolic adjustment. Crop GLS concentration in response to S fertilization is still a debated topic. For example, Jiang et al. (2016) reported an increase in GLS content with S fertilization in camelina, without sulfur x genotype interaction, while Malhi et al. (2007) found that GLS concentration in *B. juncea* and *B. napus* is a genotype-related trait, and the amplitude of the responses to S fertilization can change substantially among genotypes. A lack of positive effect of sulfuric fertilization on GLS concentration found in the present study has to be considered positively, as it retains the possibility to use camelina by-products from oil extraction in feed industry, where GLS are an undesirable factor (Ban et al. 2017).

The LCA results showed that the fertilization strategy with sulfur application was found to have a lower impact than standard fertilization management. This indicates that under the adopted experimental conditions, seed yield increase due to sulfur addition was able to offset the impact associated with the production and application of fertilizers. These findings are consistent with those of Krohn and Fripp (2012), who observed a reduction of environmental impact of camelina with increasing yield.

In the tested experimental conditions, iLUC outperformed other factors in terms of CC, in agreement with the observations of previous studies (Brandão et al. 2021). Since iLUC computation inherently implies a high level of uncertainty (Brandão et al. 2022), and can vary due to different modeling choices, the absolute values of emission associated to CC(+)iLUC reported here have to be prudently considered. Nevertheless, the reduction in indirect CO_2 eq emissions due to land use change is highly influenced by camelina seed yield. Therefore, alongside strategies hypothesized in literature, such as intercropping or using marginal lands (Pagani et al. 2024; Panoutsou et al. 2022; Schlecht et al. 2025), there should be further efforts to improve crop's production performances in order to reduce iLUC. This is also supported by recent findings reported by Friedlingstein et al. (2025), indicating that emissions related to anthropogenic land use change are substantially higher than previously estimated.

Berti et al. (2025) reported that, according to U.S. standards (which require a 50% reduction in CO_2 equivalent emissions compared to conventional aviation fuel), feedstock production emissions must remain below 30–35 g CO_2 eq MJ^{-1} for a biofuel to qualify as SAF. Oilseeds heating values can be affected by many factors, from agronomic management to environmental conditions and crop genotype. If the same seed heating value reported in Berti et al. (2025) is assumed (25 MJ kg^{-1} of seeds), cradle-to-gate emissions from our study vary approximately from 28 g CO_2 eq MJ^{-1} in control, to 29 g CO_2 eq MJ^{-1} in 60_40, to 36 g CO_2 eq MJ^{-1} in 60_0. So, the first two fertilization strategies offered an adequate feedstock for SAF under U.S. standards, while the third one appears to be within the upper limit of acceptability. However, if the reduction threshold is set to 65% compared to conventional fossil fuel, as required by the EU Renewable Energy Directives (European Parliament 2018), none of the scenarios meets SAF feedstock criteria. Similarly, when including iLUC in the assessment, all three fertilization strategies produce feedstock with an impact exceeding the limits for SAF production for either EU or the US standards (from 95 g CO_2 eq MJ^{-1} in 60_40, to 214 g CO_2 eq MJ^{-1} in control). The EU has introduced the regulatory category of low-iLUC risk feedstock for biofuel production, with specific certification criteria (EU 2022/996). A central element of this framework is compliance with additionality criteria, verified through certification schemes demonstrating that specific agricultural practices lead to production gains beyond business-as-usual scenarios. In our study, sulfur fertilization of camelina resulted in feedstock with a lower iLUC impact than conventional fertilization practices. Nevertheless, although these improvements move in the desired direction, they remain insufficient to achieve fully satisfactory environmental performance. Given recent advances in camelina breeding programs, newly developed genotypes may exhibit improved responsiveness to agronomic inputs. It would therefore be interesting to investigate whether commercially available camelina varieties, beyond the 'Calena' genotype studied here, exhibit enhanced responsiveness to sulfur fertilization further reducing iLUC-related emissions.

In a regional scale study, Moeller et al. (2017) observed that the introduction of camelina in semiarid agroecosystems can improve the energy return compared to traditional biofuel crops. In our research, the energetic characteristics of the crop were not analytically evaluated. However, in Jankowski and Sokólski (2021) have reported that the effect of sulfur fertilization in spring camelina can vary from no effect to a positive effect on heating value, depending on N rates. Though since in our study sulfur application reduced substantially the energetic input to produce 1 Mg seed, it can be assumed that the overall energy gains and energy efficiency (Dubis et al. 2020) of the system was improved by supplying sulfur fertilizer at the reported rate.

5 | Conclusion

From the agronomic perspective, camelina is confirmed as a suitable crop for Mediterranean climates under relatively low-input conditions. Fertilization with industrially recovered gypsum proved to be an effective agronomic lever to enhance camelina productivity, without adverse effects on seed quality parameters, indicating that this waste stream could find valorization in agriculture to improve cropping systems efficiency. The combined application of 60 kg N ha^{-1} and 40 kg S ha^{-1}

maximized seed yield, indicating that sulfur nutrition can mitigate yield limitations typically observed in low-S soils. However, precise fertilization recommendations must be tailored to the specific pedoclimatic conditions of each cultivation site.

LCA showed that sulfur fertilization significantly reduced the environmental impact of camelina production under the tested conditions. Nevertheless, the results also indicate that camelina cannot be regarded as an intrinsically low iLUC crop, as its environmental performance is strongly dependent on agronomic management, yield level, and site productivity. Accordingly, the sustainability of camelina-based biofuel systems is closely linked to optimized fertilization strategies and input efficiency.

In line with current recommendations for cultivating biofuel crops on marginal lands, future research should focus on multisite experiments to assess the robustness of these findings across contrasting pedoclimatic conditions and productivity levels, and to further clarify the physiological mechanisms underlying S–N interactions in camelina. Moreover, recent advances in camelina breeding programs suggest that newly developed varieties may exhibit improved responses to agronomic inputs, potentially enhancing both productivity and environmental performance. Multilocation trials would also allow an experimental evaluation of how iLUC varies in response to changes in agronomic inputs and NPP_0, highlighting the main drivers for iLUC reduction.

Author Contributions

C. Nicolella: supervision, writing – review and editing, project administration, validation. **A. Rossi:** conceptualization, investigation, writing – original draft, methodology, writing – review and editing, software, formal analysis, data curation, visualization. **I. Galasso:** investigation, methodology, formal analysis, writing – original draft, writing – review and editing. **S. Tavarini:** conceptualization, funding acquisition, writing – original draft, validation, writing – review and editing, project administration, supervision, resources. **L. G. Angelini:** conceptualization, funding acquisition, writing – review and editing, resources, supervision, project administration. **C. Clemente:** investigation, writing – original draft, writing – review and editing, data curation. **S. E. Vlaeminck:** writing – review and editing, supervision. **M. Spiller:** conceptualization, writing – original draft, methodology, validation, writing – review and editing, software, supervision, data curation, resources. **J. Santolin:** writing – review and editing, methodology, data curation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Inventory data for the production of 1 Mg of camelina seeds under three tested fertilization strategies. **Table S2:** Characteristics (weight and rated power) of machinery used during field operations, along with diesel consumption and working time. **Table S3:** Materials and energy required to produce 1 kg of gypsum granules (< 1% humidity). **Table S4:** Tuscany energetic mix as reported by the transmission system operator*. **Table S5:** Average emissions per kW produced by geothermal power plants, processed from the reports of the regional environmental monitoring agency for 2022* and 2023**.