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On Farm Camelina Performance on Salt-Affected Mediterranean Coastal Soils: Evidence from Northeastern Italy

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Abstract

Salinity is an emerging constraint for Mediterranean coastal agriculture, where shallow groundwater, seawater intrusion, and summer evapo-concentration generate relevant intra-seasonal variability in soil electrical conductivity. Camelina [*Camelina sativa* (L.) Crantz] has been proposed as a diversification oilseed for constrained environments, but its field performance under realistic, dynamic salinity in Mediterranean soils remains unexplored. This two season on farm study compared three commercial camelina lines at an inland non-saline site and a coastal saline–sodic site in northeastern Italy, combining agronomic measurements with phenology aligned monitoring of soil saturated paste electrical conductivity (ECe). At the saline site, ECe increased from 1.8 dS m^{-1} at the vegetative stage to 6.2 dS m^{-1} at seed filling, while camelina completed its cycle earlier than at the inland site. Despite similar aboveground and root biomass yield at flowering across lines, performance diverged during the reproductive phase. Two lines maintained similar seed yields (1.30 Mg ha^{-1}) at the coastal site compared with the inland site, whereas one line declined from 1.45 Mg ha^{-1} to 0.40 Mg ha^{-1}. Differences among lines in seed yield under salinity were accompanied by contrasting responses in seed oil composition. Oil yield at the saline site was more strongly associated with the increase in ECe from flowering to seed filling than with absolute ECe at seed filling. These results provide the first field-based evidence of line-specific salinity responses in camelina and highlight its potential to diversify moderately salt-affected Mediterranean coastal cropping systems, while emphasizing the need to account for temporal salinity dynamics in genotype selection and crop planning.

Keywords: *Camelina sativa*; dynamic salinity; saline agriculture; coastal soils; crop diversification; seed and oil yield

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1. Introduction

Salinization is an expanding constraint for agriculture worldwide, affecting an estimated 1.38 Mha and driving substantial losses in productivity and land value [1–3]. Climate-driven sea level rise, declining freshwater availability, and high evaporative demand are expected to intensify soil salinity in agricultural systems, with Mediterranean coastal areas being particularly exposed [4–6]. Although mapping programs often classify these lands as moderately saline [7], this average label masks pronounced temporal variability that complicates soil

management and crop selection [8,9]. In Mediterranean coastal soils, salinity can fluctuate markedly within a single growing season as shallow phreatic levels, episodic seawater intrusion, and strong summer evaporation interact to promote transient salt accumulation in the root zone [8,10]. The northern Adriatic lowlands of Italy exemplify these dynamics: long-term observations indicate brackish shallow aquifers and unstable freshwater lenses that predispose soils to seasonal salt build up [11,12]. Comparable hydrogeological settings occur along other Italian and southern European coastlines, underscoring a broader regional vulnerability to progressive coastal salinization [13–15]. Cropping systems in these environments largely rely on cereals [16], with barley often addressed as the reference glycophytic species for relative salt tolerance [17,18]. However, these assessments are typically derived under constant salinity conditions, even though coastal fields experience strong intra-seasonal variability [19–21]. Multi-scale studies demonstrate that time series, phenology aware monitoring captures salinity impacts on crops more effectively than single time measurements or legacy soil classifications [22,23]. Together, these findings highlight the need for smarter crop planning that integrates crop tolerance profiles with the temporal dynamics of salinity, alongside broader diversification of coastal cropping systems to strengthen resilience under variable salt conditions [22,24]. Diversification improves whole-farm yield stability, interrupts pest and disease cycles typical of cereal-heavy sequences, and maintains ground cover and residue that support soil structure and infiltration [25,26]. *Camelina sativa* (L.) Crantz, an oilseed crop of the *Brassicaceae* family, has emerged as a promising diversification option for constrained Mediterranean environments [27,28]. Its seed contains 30–40% oil suited to biofuel and oleochemical uses, while the protein-rich meal supports feed and biorefinery pathways [29,30]. Agronomically, camelina is characterized by a short and flexible growth cycle (85–220 days), along with low nutrient and water requirements and compatibility with small-grain machinery, making it well suited to rainfed systems where intensive management is not feasible [27,31]. Its phenology allows both effective integration into cereal-based rotations and insertion as a short cycle crop before summer species [32–34]. Under semi-arid and marginal conditions, camelina reliably sustains moderate but agronomically relevant yields, typically around 1–1.5 t ha^{-1} in Mediterranean trials, aligning with the broader 0.4–2.0 t ha^{-1} range reported across marginal rainfed sites across Europe and North America [35–38]. Because salinity in glycophytic crops acts primarily through osmotic restriction of water uptake [39], camelina's documented drought resilience [40] provides a physiological basis for considering its potential in saline-prone coastal systems. Early-stage responses further support this potential. Controlled environment studies have revealed substantial intraspecific variability in germination and seedling tolerance to moderate salinity, indicating exploitable genotype-specific differences [41,42]. However, these insights remain mostly confined to the initial phases of crop development. Evidence beyond the early developmental stages is limited, and the few full cycle evaluations available come largely from controlled environments using artificial substrates, fixed salinity levels, and narrow genotype sets. While these studies consistently document linear declines in yield with increasing electrical conductivity [43,44], they do not completely reflect the physical complexity or temporal variability characteristics of salinity in coastal soils, nor the management constraints faced by farmers. Consequently, current knowledge offers only a partial indication of camelina's realistic agronomic potential in salt-affected environments. To address this gap, the present study includes a two season on farm evaluation of commercial camelina lines at contrasting sites in northeastern Italy—one coastal saline–sodic site and one inland non-saline control site—combining agronomic measurements with phenology aligned soil salinity monitoring.

2. Materials and Methods

To assess the current on farm yield potential of camelina under salt-affected conditions, a field comparison of three commercial lines over two growing seasons at two contrasting sites in northeastern Italy—an inland control site (site C) and a coastal saline site (site S)—has been conducted.

2.1. Experimental Sites and Soil Characteristics

Field experiments were established at two locations. Site C was situated at the organic experimental farm of the University of Bologna, in Ozzano dell'Emilia, Bologna (44°44′ N, 11°49′ E). Site S was located at a coastal farmland managed by Cooperativa Agrisfera in Casalborsetti, Ravenna (44°34′ N, 12°16′ E), representing a naturally salt-affected coastal environment influenced by shallow groundwater and episodic seawater intrusion (Figure 1). At both sites, composite soil samples (0–20 cm) were collected before sowing in each season for physicochemical characterization (Table 1), performed by the accredited laboratory Tentamus Agriparadigma. At site C, soil was characterized by clay or sandy loam texture, sub-alkaline (pH 7.26–8.16), non-saline, and non-sodic, with low saturated paste extract electrical conductivity (ECe 0.93–1.04 dS m^{-1}) and low exchangeable sodium percentage (ESP 6.2–7.1%). Total organic carbon at site C ranged from 6.5 to 10.2 g kg^{-1} and total nitrogen from 0.96 to 1.24 g kg^{-1}. At site S, soil was consistently sandy, sub-alkaline, moderately saline, and sodic (pH 7.88–8.23, ECe 2.66–2.86 dS m^{-1}, ESP 17.4–17.9%). At site S, total organic carbon (4.0–7.1 g kg^{-1}) and total nitrogen (0.50–0.70 g kg^{-1}) resulted lower than at site C. In addition, at site S a monthly in-season salinity monitoring was carried out as follows: for each camelina line, five fixed sampling points were established, and soil samples were collected from the 0–20 cm layer and analyzed for ECe according to Italian Official Methods for Soil Chemical Analysis [45].

Figure 1. Saline–sodic soil at the coastal experimental site in northeastern Italy (site S), managed by Cooperativa Agrisfera (Casalborsetti, Ravenna).

2.2. Plant Material and Agronomic Management

Among genotypes previously evaluated under salinity at early growth stages [41], three commercially available camelina lines (54, 55, and 56) were selected to represent current farm scale material in the present study. Lines 54 and 55 are spring biotypes supplied by Camelina Company Spain (Madrid, Spain), whereas line 56 is a winter one, supplied by the Poznan University (Poznan, Poland). Trials were established in site C and site S across two growing seasons, sowing large strips of 2400 m^2 for each line and location. At both sites, camelina was autumn-sown (Table 2). However, agronomical management was conducted according to the host farm standard practices to reflect realistic conditions.

At site C, tillage consisted of moldboard plowing followed by harrowing. Before sowing, an organic fertilizer was applied at 500 kg ha^{-1} (GUANITO, NPK 6-15-2, Hello Nature Italia Srl, Verona, Italy). Sowing was carried out by means of a mechanical drill seeder (Damax 17, Damax Srl, Brescia, Italy) at 0.15 m row spacing, with a density of 7 kg seed ha^{-1}. At site S, minimum tillage with a rotary harrow was performed. Sowing was conducted using a pneumatic seeder (Gaspardo PINTA 450, Maschio Gaspardo Spa, Padova, Italy) at 0.13 m row spacing, with a density of 8 kg seed ha^{-1}. At the beginning of flowering (BBCH 600 [46]), a biomass sampling was conducted in five 1 m^2 areas in each strip, to characterize camelina vegetative growth prior to reproductive development. When camelina reached full physiological maturity (BBCH 809 [46]), five 2 m^2 areas in each strip were identified as the sampling areas to determine yield parameters. At site S, these harvest areas coincided with the fixed sampling points used for the ECe monitoring.

Table 1. Physicochemical soil properties at sowing in Year 1 and Year 2 at the two experimental sites in northeastern Italy: site C (control; inland, Ozzano dell'Emilia, Bologna) and site S (saline; coastal, Casalborsetti, Ravenna).

		Site C		Site S	
Parameter	**Unit**	**Year 1**	**Year 2**	**Year 1**	**Year 2**
Clay	g kg^{-1}	200	140	50	75
Silt	g kg^{-1}	310	200	209	93
Sand	g kg^{-1}	490	660	741	832
pH		7.26	8.16	7.88	8.23
Total limestone	g kg^{-1}	81	161	120	67
Active limestone	g kg^{-1}	75	24	29	16
Total organic carbon	g kg^{-1}	10.2	6.5	7.1	4.0
Total nitrogen	g kg^{-1}	1.24	0.96	0.70	0.50
Exchangeable sodium percentage (ESP)	%	6.21	7.14	17.4	17.9
Electrical conductivity of saturated paste extract (ECe)	dS m^{-1}	1.04	0.93	2.86	2.66

Table 2. Crop cycle and weather conditions at the two experimental sites in northeastern Italy, site C (control) and site S (saline), in Year 1 and Year 2. Sowing and harvest dates are reported as dd/mm/yyyy. Cycle length is the number of days from sowing to harvest. T min and T max are the mean daily minimum and maximum air temperatures over the crop cycle. GDD is the accumulated growing degree days over the cycle, and GDD FF is the accumulated growing degree days from sowing to full flowering (BBCH 605) (base temperature = 4 °C). Prec is the cumulative precipitation during the entire camelina cycle. Prec FF is the cumulative precipitation from sowing to BBCH 605.

Site	**Year**	**Sowing**	**Harvest**	**Cycle Length (d)**	**T min**	**T max**	**GDD (°C)**	**GDD FF**	**Prec**	**Prec FF (mm)**
C	1	27/10/2022	12/06/2023	228	5.7	15.6	1518	551	625	262
	2	01/11/2023	27/05/2024	208	5.8	14.8	1520	545	230	161
S	1	09/11/2023	24/05/2024	197	6.4	14.6	1168	560	385	270
	2	20/11/2024	03/06/2025	195	6.5	14.5	1188	552	419	264

2.3. Meteorological Data

Meteorological data, including minimum and maximum daily air temperature and precipitation, were recorded throughout each growing season by a weather station located near-by each of the experimental sites (Table 2). Growing degree days (GDDs) were calculated from sowing to harvest and from sowing to full flowering (BBCH 605 [46]), according to the following equation:

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

where T max and T min are the maximum and minimum daily air temperatures, respectively, and T base for camelina was defined as 4 °C [47].

2.4. Measurements at Flowering Stage and at Harvest

A biomass sampling was conducted at full flowering (BBCH 605 [46]) at site C in Year 2 and in Years 1 and 2 at site S. All plants within five 1 m^2 areas in each strip were carefully excavated to allow separation of aboveground and belowground organs. Roots were gently washed with water to remove adhering soil. Fresh aboveground biomass and fresh root biomass were recorded separately. All plant material from both fractions was then oven-dried at 105 °C to constant mass to determine dry aboveground biomass and dry root biomass. Dry matter percentage of aboveground biomass and roots was calculated from the ratio between dry biomass and corresponding fresh biomass.

At harvest in all the sites and years, all plants within five 2 m^2 areas in each strip were cut at ground level and weighed fresh to determine fresh aboveground biomass yield. A subsample of plants for each sampling area was then oven-dried at 105 °C to constant mass to determine dry matter content, which was used to calculate dry aboveground biomass yield. The aboveground biomass of each area was subsequently threshed to separate seed and straw. Fresh seed weight of each area was recorded, and a seed subsample for each area was oven-dried at 105 °C to determine seed dry matter content, from which dry seed yield was calculated. Thousand seed weight (TKW) was determined using a Seed Counter S-25 (Data Technologies Ltd., Kibbutz Tzora, Israel), performing 3 technical replicates per each sample.

2.5. Oil Extraction from Camelina Seeds, Seed Oil Content and Composition Determination, Oil Yield Calculation

Oil was recovered from camelina seeds and gravimetrically determined following the procedure reported by Zanetti et al. (2022) [48]. Briefly, 1.5 g of previously ground seeds underwent a 2 h extraction in an in-line Soxhlet unit, using 60 mL of n-hexane as organic solvent. The extract was then filtered over anhydrous sodium sulphate. After solvent removal under reduced pressure in a rotary evaporator, the extracted oil was exactly weighed. Seed oil content was expressed as percentage (m/m) of seed dry matter. Solvents and reagents were analytical grade (Merck, Darmstadt, Germany). Oil yield was computed as the product of dry seed yield and seed oil content. To determine seed oil composition, extracted fatty acids were converted to methyl esters (FAMEs) and successively analyzed by gas chromatography with flame ionization detection (GC–FID) after a cold transmethylation procedure performed on camelina oil. Transmethylation and GC operating conditions were carried out as previously described [48]. Seed oil composition was evaluated only in Year 1 at site S and in Year 2 at site C.

2.6. Statistical Analysis of Data

Statistical analyses were performed using RStudio (2023.03.0+386 "Cherry Blossom" Release for Windows, version 4.3.2). For each yield parameter (dry aboveground biomass, dry seed yield, TKW, seed oil content, oil yield), a linear mixed-effects model was fitted, with Line, Site, and their interaction (Line × Site) as fixed effects and Year as random factor, using "lme4" package [49]. For biomass traits measured at flowering (dry aboveground biomass, dry root biomass, dry matter percentage of aboveground biomass, dry matter percentage in root biomass) and seed oil composition, linear models were fitted, with Line, Site, and their interaction (Line × Site) as factors. Year was not included in the models, as these data were not collected for two years at each site. ANOVA tables were obtained from the models, and, when effects were significant, model-estimated marginal means were compared with Tukey's HSD ($p \leq 0.05$) using "emmeans" package [50]. Model

assumptions were confirmed with Shapiro–Wilk test for normality and Levene test for homoscedasticity. For soil salinity dynamic at site S, monthly ECe values at each fixed sampling point were averaged within phenological stages: vegetative (BBCH 100-500 [46]), flowering (BBCH 501-609 [46]), and seed filling (BBCH 701-809 [46]). Stage effects were tested with a repeated measures linear mixed model, treating the sample points as the subject. Pairwise comparisons used Tukey's HSD ($P \leq 0.05$). Because an increase in ECe was observed only at the seed filling stage, a multiple linear regression was fitted at site S to evaluate the roles of absolute salinity and its relative change. Oil yield was regressed on ECe at filling and on the increase in ECe from flowering to filling (ΔECe). Association for each predictor was assessed from the regression coefficient (estimate ± SE) and *p*-value (Wald *t* test), while overall model fit was summarized by the *p*-value (F test), R^2, and adjusted R^2. Collinearity was checked via variance inflation factors and residual diagnostics (normality and homoscedasticity) were inspected.

3. Results

3.1. Crop Cycle Length, Meteorological Data, and Soil Electrical Conductivity

At site C, the camelina cycle lasted 228 d in Year 1 and 208 d in Year 2. The mean temperatures and accumulated growing degree days over full crop cycle (GDDs) were very similar across years (average T min 5.7–5.8 °C; average T max 14.8–15.6 °C; GDD 1518–1520 °C). Otherwise, precipitation totaled 625 mm in Year 1 vs. 230 mm in Year 2, corresponding to +40% and −48% compared with the site C long-term average (445 mm), indicating an uncommonly wet first season and a markedly dry second season (Table 2). At site S, the cycle length was 197 d in Year 1 and 195 d in Year 2; mean temperatures and GDDs were similar across years (average T min 6.4–6.5 °C; average T max 14.5–14.6 °C; GDD 1168–1188 °C); and precipitation ranged from 385 to 419 mm (aligned to site S long-term average of 415 mm) (Table 2). Overall, at site S, camelina had shorter cycle lengths and accumulated less GDDs than at site C under quite similar temperatures.

Accumulated growing degree days from sowing to full flowering (GDDs FF) were similar across sites and years, ranging from 545 to 560, and cumulative precipitation up to full flowering (Precipitation FF) varied within a relatively narrow range (161–270 mm) (Table 2).

At site S, soil salinity (ECe) increased progressively along camelina phenological stages: mean ECe rose from 1.8 dS m^{-1} at the vegetative stage to 2.6 dS m^{-1} during flowering, and peaked at 6.2 dS m^{-1} during seed filling stage (Figure 2). The seed filling stage showed significantly higher ECe than the vegetative stage, while the flowering stage was intermediate and not statistically different from the other stages (Figure 2).

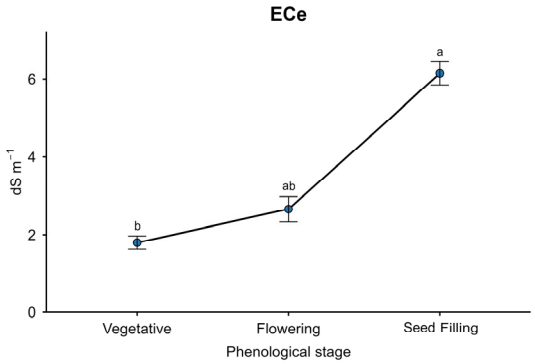

Figure 2. Mean electrical conductivity of soil saturated paste extract (ECe) measured at camelina vegetative, flowering, and seed filling stages at the saline site (S). Values represent the mean ECe across all measured areas within each phenological stage. Different letters represent significant differences among means at $P \leq 0.05$ (Tukey's HSD). Error bars represent standard errors.

3.2. Biomass Sampling at Flowering

To characterize crop growth prior to the reproductive phase, aboveground and belowground biomass traits were assessed at full flowering (BBCH 605). However, at site C, these data were collected only in Year 2. Linear models indicated the significant main effects of Line and Site for most traits, whereas the Line × Site interaction was not significant for any variable (Table 3). Dry aboveground biomass at flowering resulted in being significantly affected by both Line and Site (Table 3). Across lines, line 55 and line 54 exhibited higher aboveground biomass than line 56, which showed the lowest values (Figure 3A). Across lines, dry aboveground biomass was significantly higher at site C than at site S (Figure 4A). Dry root biomass at flowering differed significantly among lines and between sites (Table 3). Line 55 showed the highest root biomass, while lines 54 and 56 had lower and comparable values (Figure 3C). In contrast to aboveground biomass, dry root biomass resulted in being significantly higher at site S than at site C (Figure 4C). The dry matter percentage of aboveground biomass at flowering was significantly affected by both Line and Site (Table 3). Line 54 showed the highest aboveground dry matter percentage, line 55 the lowest, and line 56 an intermediate value (Figure 3B). Across lines, the aboveground dry matter percentage was significantly higher at site S compared with site C (Figure 4B). By contrast, the dry matter percentage of root biomass at flowering was not significantly affected by Line, Site, or their interaction (Table 3).

Table 3. ANOVA table (F-values) of traits measured at flowering (BBCH 605), from linear models including Line, Site, and their interaction (Line × Site) as factors. Evaluated dependent variables include dry aboveground biomass (AGB ff), dry root biomass at flowering (Root ff), dry matter percentage of aboveground biomass (D.M. AGB ff), dry matter percentage of root biomass (D.M. Root ff). Significance levels are indicated as follows: "*", for significance at $P \leq 0.05$; "**", for significance at $P \leq 0.01$; "ns", not significant ($P > 0.05$).

	AGB ff		**Root ff**		**D.M. AGB ff**		**D.M. Root ff**	
Line	8.05	**	4.56	*	3.67	*	0.51	ns
Site	10.04	**	4.90	*	31.40	**	3.07	ns
Line × Site	0.36	ns	0.84	ns	0.16	ns	0.79	ns

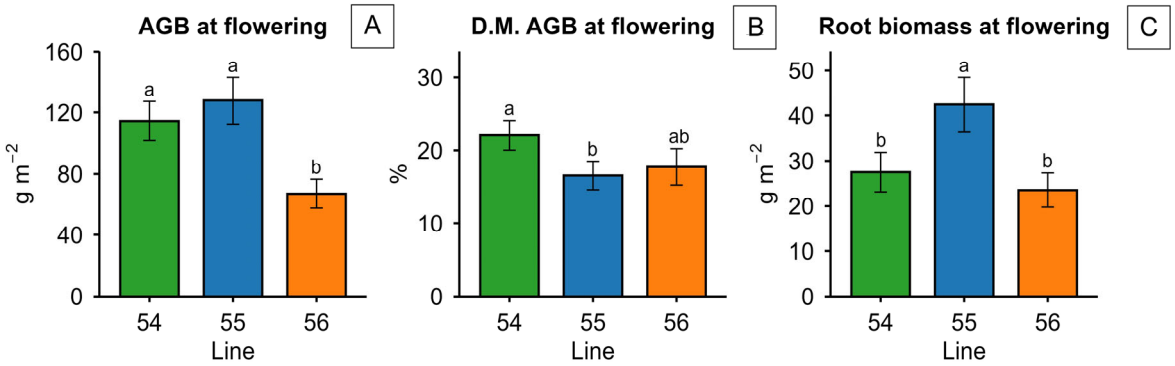

Figure 3. (**A**) Aboveground dry biomass (AGB), (**B**) aboveground dry matter percentage (D.M. AGB), and (**C**) dry root biomass measured at full flowering (BBCH 605) as affected by Line. Different letters denote significant differences among means at $P \leq 0.05$ (Tukey's HSD). Error bars represent standard errors.

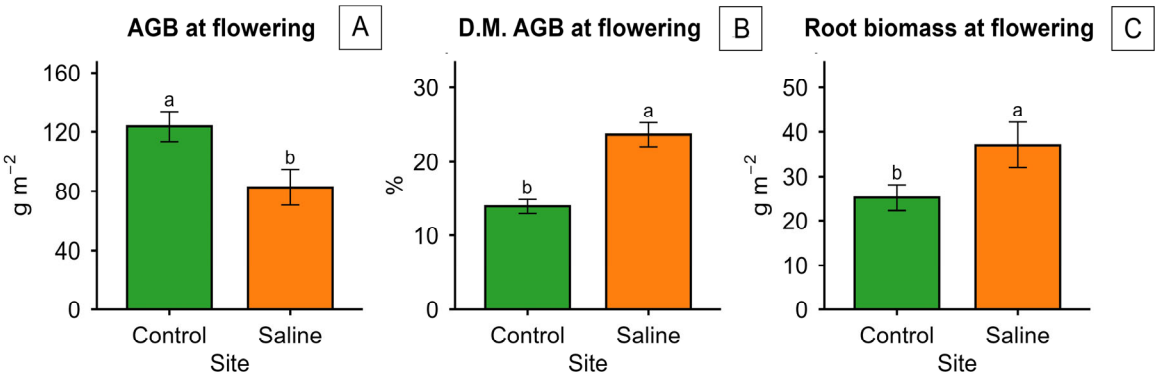

Figure 4. (**A**) Aboveground dry biomass (AGB), (**B**) aboveground dry matter percentage (D.M. AGB), and (**C**) dry root biomass measured at full flowering (BBCH 605) as affected by Site. Different letters denote significant differences among means at $P \leq 0.05$ (Tukey's HSD). Error bars represent standard errors.

3.3. Agronomic Performance

To evaluate camelina's productive performance, aboveground dry biomass yield, dry seed yield, TKW, seed oil content, and oil yield were surveyed at physiological maturity. No significant effect of Line or Site was observed in seed oil content and oil yield, whereas dry aboveground biomass yield, dry seed yield, and TKW reported a significant Line × Site interaction (Table 4). At site C, line 54 reported an aboveground dry biomass yield of 3.5 Mg ha^{-1}, significantly lower than line 55 and line 56, which had similar values averaging 6.1 Mg ha^{-1} (Figure 5). At site S, no significant differences were observed in aboveground biomass among lines, with an average aboveground biomass of 8.7 Mg ha^{-1} (Figure 5). Across sites, line 54 and line 55 reported a significant increase in aboveground biomass at site S compared with site C, passing from 3.5 and 6.3 Mg ha^{-1} at site C to 8.2 and 9.5 Mg ha^{-1} at site S, respectively. Line 56 did not differ between sites (Figure 5). At site C, line 55 produced an average dry seed yield of 1.85 Mg ha^{-1}, significantly higher than line 54 (1.15 Mg ha^{-1}). Line 56 showed an intermediate seed yield of 1.55 Mg ha^{-1}, not significantly different from the other camelina lines (Figure 6). At site S, line 55 and line 54 reported similar seed yields (1.25 and 1.30 Mg ha^{-1}), whereas line 56 produced only 0.40 Mg ha^{-1}, a significantly lower seed yield than both the other lines (Figure 6). Compared with site C, seed yield in line 56 was reduced at site S, while line 54 and line 55 did not differ significantly between sites (Figure 6). At site C, lines 54 and 55 reported similar TKW (1.35 and 1.40 g) and both exceeded line 56 (1.15 g) (Figure 7). At site S, line 54 showed the highest TKW (1.20 g) compared with lines 55 and 56, which did not differ from each other (1.05 and 1.10 g) (Figure 7). Across sites, TKW declined at site S compared with site C in line 54 and line 55, whereas line 56 did not report significant differences between sites (Figure 7). A multiple linear regression model was fitted to evaluate the effect on oil yield at site S using ECe at the seed filling stage and the change in ECe from the flowering to seed filling stages (ΔECe) as predictors (Table 5). The model resulted in being significant ($P < 0.001$), explaining 60% of the variance ($R^2 = 0.64$; adjusted $R^2 = 0.60$). ΔECe showed a significant negative relation with oil yield (estimated coefficient = -72.29 ± 27.22, $P = 0.0166$), whereas ECe at seed filling resulted in being not significant (estimated coefficient = 4.86 ± 50.78, $P = 0.925$) (Table 5).

Table 4. ANOVA table (F-values) of yield data, from linear mixed-effects models including Line, Site, and their interaction (Line × Site) as fixed effects, and Year as a random effect. Evaluated dependent variables include dry aboveground biomass yield (AGB), dry seed yield (seed yield), Thousand Kernel Weight (TKW), seed oil content (oil content), oil yield. Significance levels are indicated as follows: "*", for significance at $P \leq 0.05$; "**", for significance at $P \leq 0.01$; "ns", not significant ($P > 0.05$).

	AGB		Seed Yield		TKW		Oil Content		Oil Yield	
Line	9.54	**	8.36	**	27.59	**	0.98	ns	2.36	ns
Site	5.95	ns	2.68	ns	4.64	ns	0.94	ns	0.50	ns
Line × Site	3.25	*	5.00	*	13.44	**	3.16	ns	1.78	ns

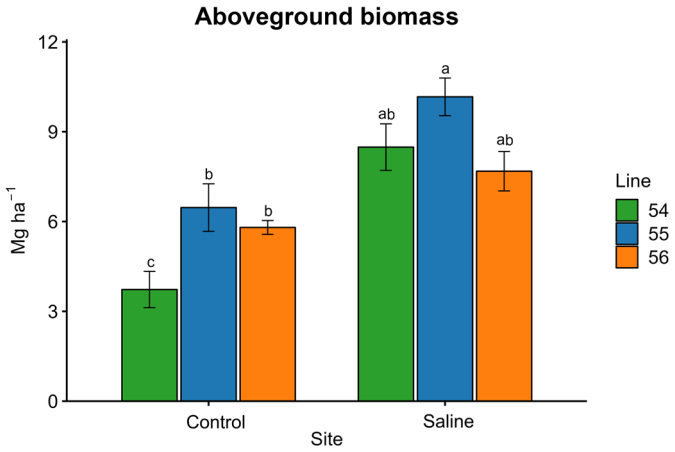

Figure 5. Dry aboveground biomass yield in response to the interaction effect Line × Site, from a linear mixed-effects model with Line, Site, and their interaction as fixed effects, and Year as a random effect. Different letters denote significant differences among means at $P \leq 0.05$ (Tukey's HSD). Error bars represent standard errors.

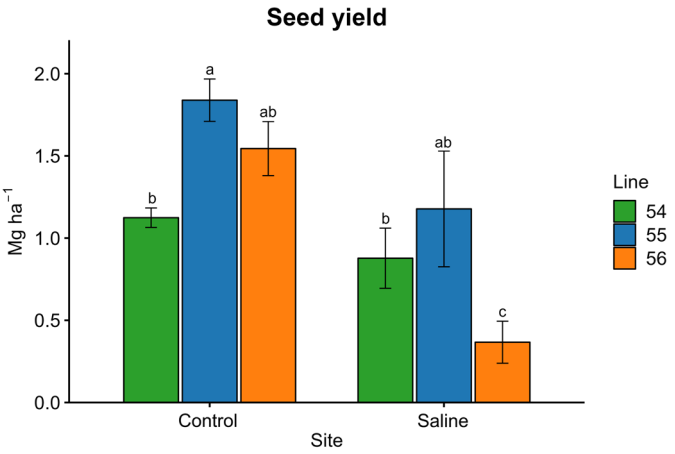

Figure 6. Dry seed yield in response to the interaction effect Line × Site, from a linear mixed-effects model with Line, Site, and their interaction as fixed effects, and Year as a random effect. Different letters denote significant differences among means at $P \leq 0.05$ (Tukey's HSD). Error bars represent standard errors.

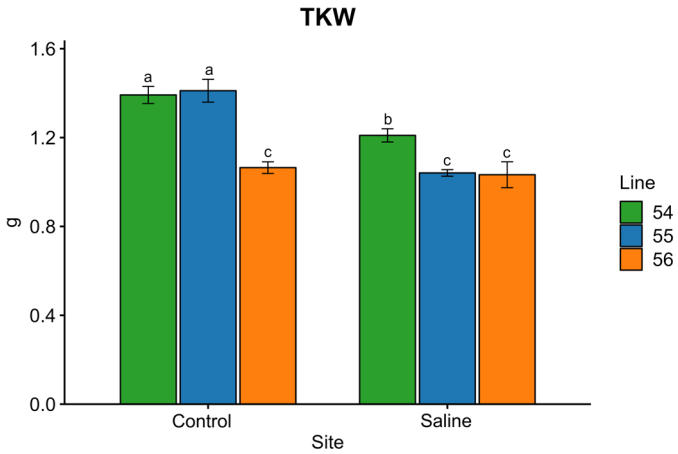

Figure 7. Thousand Kernel Weight (TKW) in response to the interaction effect Line × Site, from a linear mixed-effects model with Line, Site, and their interaction as fixed effects, and Year as a random effect. Different letters denote significant differences among means at $P \leq 0.05$ (Tukey's HSD). Error bars represent standard errors.

Table 5. Multiple linear regression of oil yield at site S on electrical conductivity of soil saturated paste extract measured during seed filling (ECe) and on the change in ECe from flowering to seed filling (ΔECe). The table reports coefficient estimates (±standard errors) and *p*-values. Model fit statistics, reported on the bottom, include the overall F and its *p*-value, the coefficient of determination (R^2), and the adjusted R^2. Significance levels are indicated as follows: "*", for significance at $P \leq 0.05$; "**", for significance at $P \leq 0.01$; "ns", not significant ($P > 0.05$).

	Coefficient Estimate	**Standard Error**	***P*-Value**	
Intercept	495.27	234.18	0.0495	*
ECe	4.86	50.78	0.9249	ns
ΔECe	−72.29	27.22	0.0166	*

F-statistic: 15.22 on 2 and 17 DF, *P*-value: 0.0001625 **, R^2: 0.64, adjusted R^2: 0.60.

3.4. Seed Oil Composition

Seed oil fatty acid composition was evaluated only in Year 1 at site S and in Year 2 at site C. The content of the main camelina fatty acids showed clear line-specific responses to Site, as indicated by the significant Line × Site interactions for oleic acid (C18:1), linoleic acid (C18:2), and eicosenoic acid (C20:1), and for the saturated (SFA), monounsaturated (MUFA), and polyunsaturated (PUFA) fractions (Table 6). By contrast, linolenic acid (C18:3) and erucic acid (C22:1) did not show a significant effect of Site nor a significant Line × Site interaction (Table 6). Oleic acid increased at site S in lines 55 and 56 compared with site C, whereas no significant differences between sites were observed in line 54 (Figure 8A). Conversely, linoleic acid increased in line 54 at site S compared with site C, while it decreased in line 55 and no significant differences were detected between sites in line 56 (Figure 8B). Eicosenoic acid showed higher values at site S relative to site C in lines 55 and 56, whereas a reduction under saline conditions was observed in line 54 (Figure 8C). The contrasting line-specific responses observed for individual fatty acids were reflected in the distribution of fatty acid classes (Figure 9). Saturated fatty acids (SFAs) did not differ significantly between sites in line 54, while they increased at site S in line 55, and decreased in line 56, compared with site C (Figure 9A). Monounsaturated fatty acids (MUFAs) showed an increase at site S relative to site C in line 55 and line 56, whereas MUFA content decreased in line 54 (Figure 9B). Conversely, polyunsaturated fatty acids (PUFAs) declined at site S compared to site C in lines 55 and 56, while line 54 exhibited a significant increase under saline conditions (Figure 9C).

Table 6. ANOVA table (F-values) of main fatty acids and fatty acid aggregated classes, from linear models including Line, Site, and their interaction (Line × Site) as factors. Evaluated dependent variables include stearic acid (C18:0), oleic acid (C18:1), linoleic acid (C18:2), linolenic (C18:3), eicosenoic acid (C20:1), erucic acid (C22:1), saturated fatty acids (SFAs), monounsaturated fatty acids (MUFAs), polyunsaturated fatty acids (PUFAs). Significance levels are indicated as follows: "*", for significance at $P \leq 0.05$; "**", for significance at $P \leq 0.01$; "ns", not significant ($P > 0.05$).

	C18:1		C18:2		C18:3		C20:1		C22:1		SFA		MUFA		PUFA	
Line	20.45	**	1.46	ns	11.74	**	7.66	**	0.22	ns	8.24	**	21.25	**	32.25	**
Site	15.12	**	0.39	ns	2.30	ns	2.11	ns	1.38	ns	0.01	ns	12.18	**	14.27	**
Line × Site	11.76	**	8.68	**	0.98	ns	10.70	**	1.68	ns	6.35	**	26.85	**	35.46	**

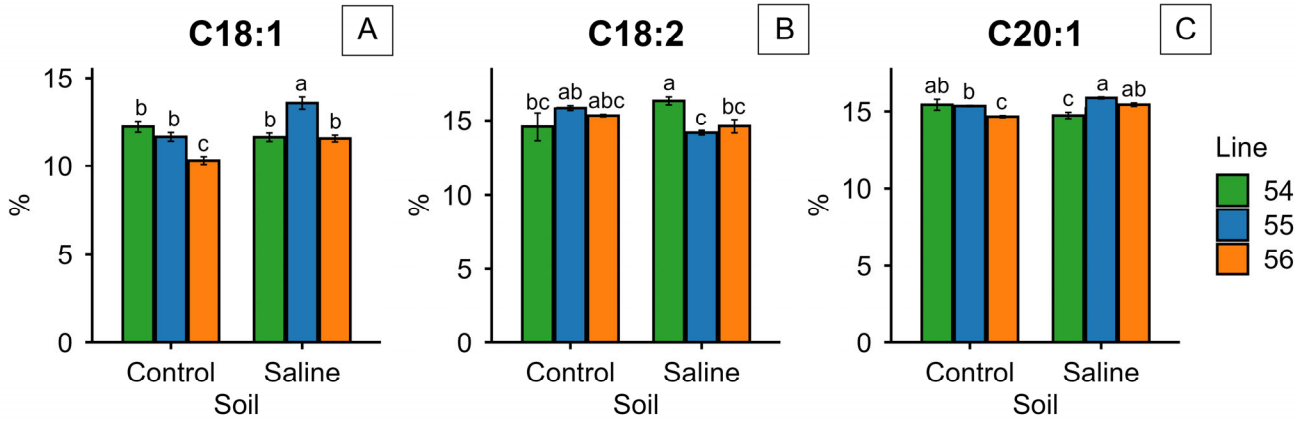

Figure 8. (**A**) Oleic acid (C18:1), (**B**) linoleic acid (C18:2), and (**C**) eicosenoic acid (C20:1) contents expressed as percentage of seed oil content, as affected by the interaction between Line and Site. Different letters denote significant differences among Line × Site combinations at $P \leq 0.05$ (Tukey's HSD). Error bars represent standard errors.

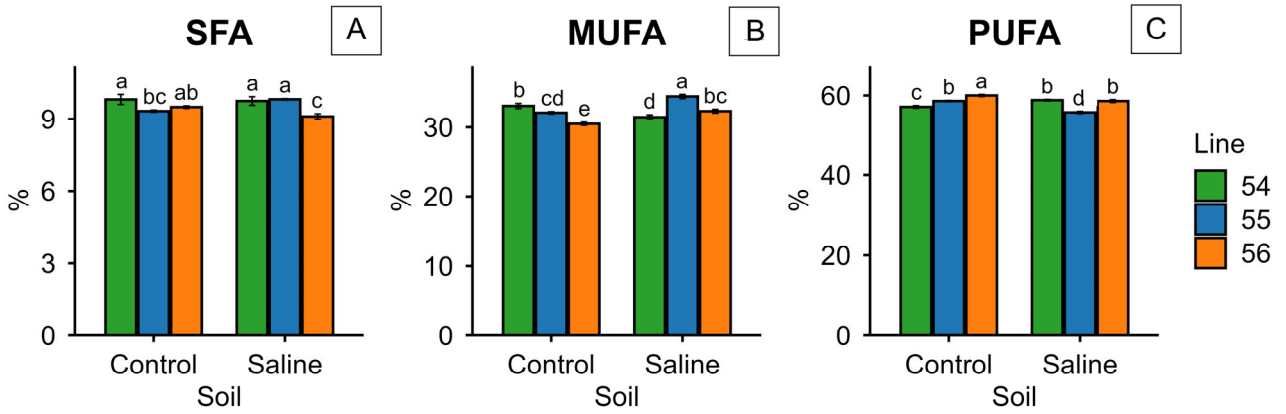

Figure 9. (**A**) Saturated fatty acid (SFA), (**B**) monosaturated fatty acid (MUFA), and (**C**) polyunsaturated fatty acid (PUFA) contents expressed as percentage of seed oil content, as affected by the interaction between Line and Site. Different letters denote significant differences among Line × Site combinations at $P \leq 0.05$ (Tukey's HSD). Error bars represent standard errors.

4. Discussion

Several alternative crops, including oilseeds, have been proposed for salt-affected Mediterranean coastal systems based on studies conducted under controlled conditions. However, the absence of on farm field evidence under realistic, heterogeneous salinity hampers diversification and resilience, sustaining dependence on a few well-characterized species for reliable yields. To address this gap and test whether controlled condition

patterns translate to farm scale performance, a two season, on farm comparison of three commercial camelina lines was conducted at contrasting sites in northeastern Italy: an inland non-saline control farm (site C) and a coastal saline–sodic farm (site S). The coastal area hosting site S has been the focus of water and soil quality monitoring [11,51]. At site S, the soil has been previously classified as an Endogleyic (Salic) Cambisol, indicating periodic saturation and reducing conditions with seasonal salt accumulation in near surface horizons [51]. A hydrogeologic long-term study confirmed the intrinsically salt-prone setting at site S: the phreatic water table was very shallow, the coastal aquifer saline, and the freshwater–saltwater interface layer < 0.50 m below sea level, implying a thin and unstable freshwater lens [11]. Consistent with these findings, the saturated paste electrical conductivity (ECe) at that site during the present study rose from 1.8 dS m^{-1} at the camelina vegetative stage to 2.6 dS m^{-1} at flowering, peaking at 6.2 dS m^{-1} during seed filling (Figure 2). Indeed, at the beginning of the flowering stage, camelina at the saline site was characterized by lower aboveground biomass, higher root biomass, and increased aboveground dry matter concentration in all lines compared with the control site (0.05, reflecting widely reported, non-specific osmotic adjustment responses [39]. Line-specific differences in performance emerged only later in the crop cycle, as soil salinity further increased during seed filling. This highlights a central point for agriculture in saline conditions and site-specific management: one-time sampling, as used in many mapping programs, can misclassify fields by missing seasonal salinity peaks [22,52]. For coastal agriculture, phenology-coupled monitoring is therefore a more informative basis for management than static soil classification, in line with recent studies showing that time series vegetation signals and proximal sensing outperform single date maps or legacy soil classes for salinity stress diagnosis [23,52]. In the present study, the late season ECe peak at seed filling likely shortened the camelina cycle at site S compared with site C (Table 2). This resulted in a contrast with the controlled environment studies in *Brassica napus*, where salinity delayed flowering and shifted subsequent stages later, thereby extending the crop cycle [53,54]. While salinity can delay flowering [55,56], a longer cycle follows only when physiological maturity is also postponed, a response mostly reported under stable soil moisture and temperatures typical of controlled conditions [57,58]. By contrast, under real field conditions, especially coastal or seasonally dry sites, salinity increase is driven by post winter evapo-concentration. Thus, the ECe peak often co-occurs with heat and drought stress, factors known to accelerate senescence and advance physiological maturity [8,59]. Accordingly, the interpretations of phenological adjustments under salinity should explicitly account for co-occurring abiotic stresses, as salinity often interacts with other environmental constraints. [60–62]. Seed yields at site C, observed in the present study, for the three camelina lines (1.15, 1.85, and 1.55 Mg ha^{-1} for lines 54, 55, and 56, respectively; Figure 6) were consistent with field performance reported in previous camelina trials across Italy and Europe (1.3–3.3 Mg ha^{-1}) [31,38,63]. At site S, where ECe reached 6.2 dS m^{-1} during seed filling, seed yield responses were line-dependent: lines 54 and 55 maintained values similar to site C (1.25–1.30 Mg ha^{-1}), whereas line 56 declined sharply from 1.55 Mg ha^{-1} at site C to 0.40 Mg ha^{-1} at site S (Figure 6). Field evidence from other oilseed crops at comparable salinity provides a useful benchmark for contextualizing camelina's potential in salt-affected soils. In sunflower (*Helianthus annuus*), seed yield reductions were observed above 4.8 dS m^{-1}, with losses of approximately 5% per additional dS m^{-1} [64]. Safflower (*Carthamus tinctorius*) at 6 dS m^{-1} showed a lower seed yield and harvest index compared with non-saline conditions [65]. Screenings of sesame (*Sesamum indicum*) and linseed (*Linum usitatissimum*) at 5–8 dS m^{-1} likewise reported significant seed yield reductions relative to non-saline controls, with magnitude depending on genotype and site [66,67]. By contrast, oilseed rape (*Brassica napus*) maintained seed yield up to 10–12 dS m^{-1} [68], and a semi-

controlled environment comparison placed camelina below *B. napus* in terms of salinity tolerance [43]. Overall, at 6 dS m^{-1}, camelina's most tolerant lines appeared competitive with sunflower, safflower, sesame, and linseed, but likely less tolerant than oilseed rape on a strict salinity-threshold basis. All the oilseed crop field studies, however, reported salinity as a single seasonal value rather than aligning it with crop phenology. Resolving phase-specific responses to salinity is therefore essential and may reveal a competitive advantage for camelina in Mediterranean coastal systems: its short and flexible cycle could be managed by moving sowing dates and aiming at avoiding salinity peaks during sensitive stages. Importantly, in the present study, the rate of salinity increase from flowering to seed filling, rather than the absolute ECe at seed filling, emerged as a significant negative predictor of oil yield (Table 5). This indicates that a rising salinity trend during sensitive phenological phases can be more damaging than a high but stable soil salinity level. Dynamic depth × time salinity modeling, successfully used in arid land cotton to predict and manage yield [69], could be adapted to oilseeds to capture phase-specific salinity dynamics. In the present study, the decrease in TKW observed for lines 54 and 55 at site S (Figure 7) suggested that, under rising salinity, reproductive sinks weakened and seed filling was curtailed more than seed number. Similar patterns of reduced biomass allocation to siliques and seeds and relatively greater allocation to vegetative organs under salinity have been reported in *B. napus*, where salt stress inhibited assimilate transport into reproductive tissues [70]. At the same time, both lines 54 and 55 showed increased aboveground biomass at site S compared with site C (Figure 5), consistent with a compensatory growth strategy in which vegetative development is maintained or enhanced despite the constraints on reproductive allocation. Moderate salinity levels have been shown to stimulate vegetative biomass in *B. napus* seedlings, whereas stronger salinity and late stress preferentially reduce seed size and weight, a pattern also documented for camelina under reproductive heat stress [71,72]. Taken together, these observations supported the interpretation that, in lines 54 and 55, stress primarily limited the filling process rather than silique formation, while compensatory vegetative growth helped buffer yield stability. Despite the apparent similarities between line 54 and line 55, a closer inspection of yield components and oil composition suggests different responses under saline conditions. Although seed yield differences were not statistically significant, seed yield at site S declined by 23.5% in line 54 and by 36.2% in line 55 relative to site C (Figure 6). Similarly, TKW at site S declined by 11.1% in line 54 and by 25.0% in line 55 relative to site C (Figure 7). This consistent pattern suggested that seed filling was less constrained in line 54, whereas line 55 experienced a stronger limitation. The contrasting oil composition responses supported this interpretation. Under saline conditions, line 55 shifted toward higher oleic and eicosenoic acid contents and higher monounsaturated fatty acids, whereas line 54 showed increased linoleic acid and higher polyunsaturated fatty acids (Figures 8 and 9). In camelina and other oilseed crops, the MUFA–PUFA balance is strongly determined during seed filling. During this phase, oleic acid is progressively desaturated to linoleic and linolenic acids by desaturases, whose activity depends on temperature, assimilate supply, and effective filling duration [72,73]. Experimental studies in *B. napus* and camelina have shown that late season stress, including salinity and heat, commonly reduces net desaturation, resulting in increased oleic acid and reduced polyunsaturated fatty acids when seed filling is shortened or metabolically constrained [63,74]. Similarly, salinity has been reported to increase oleic acid while decreasing linoleic and linolenic acids in *C. tinctorius* [75]. Within this framework, the MUFA-oriented response of line 55 resulted in being consistent with a stronger constraint on filling metabolism or effective filling duration compared with line 54. However, explicit quantification of flowering duration, filling duration, and thermal exposure during seed development would be essential to test this hypothesis. The line-specific yield responses

observed in the present study align closely with previous controlled-environment results obtained at germination and seedling stages on the same camelina genotypes [41]. In that study, lines 54 and 55 were assigned to a functional cluster characterized by slower but ultimately high germination under salinity, combined with strong seedling establishment and early root vigor, whereas line 56 had rapid germination but poor seedling vigor. These early differences interestingly anticipated the field outcomes of the present study: under the late season salinity rise at site S, lines 54 and 55 were able to keep stable seed yields, whereas line 56 experienced a marked reduction, mirroring its weaker seedling tolerance (Figure 6). These convergent patterns across early-stage screening and field performance reinforced the functional clustering previously established and indicated that early traits such as seedling vigor under salinity can be informative proxies for field resilience under heterogeneous and dynamic stress conditions. However, extending this approach to a broader panel of genotypes and salinity profiles will be essential to confirm the generality of these relationships and to guide breeding towards camelina ideotypes adapted to salt-affected Mediterranean systems. At the same time, the present on farm study was not designed to resolve the physiological mechanisms underlying line-specific responses, such as ion homeostasis or oxidative stress regulation, which require controlled experimental conditions. The consistent divergence observed among lines under dynamic salinity nonetheless strongly suggests that differences in these processes contribute to field performance, highlighting the need for complementary controlled environment studies.

5. Conclusions

This two season on farm study demonstrated that camelina can be a current viable oilseed crop for moderately salt-affected Mediterranean coastal systems, ensuring seed yields of about 1.2–1.3 Mg ha^{-1} even where soil ECe peaked near 6 dS m^{-1}. Yield stability under these conditions depended strongly on the genotype, with performance differences consistent with functional clusters previously identified based on germination and seedling vigor responses to salinity. Beyond yield stability, genotypes differed in their ability to preserve seed lipid metabolism at the saline site. Salinity monitoring at the saline site revealed that the increase in ECe from flowering to seed filling, rather than absolute electrical conductivity, was a significant driver of oil yield reduction, emphasizing the importance of interpreting field salinity as a dynamic, phase-dependent stress. Overall, these findings provided the first field-based validation of line-specific salinity responses in camelina and highlight its potential to diversify cropping systems on salt-prone Mediterranean soils, while underscoring the need for further multi-site testing across broader salinity gradients and camelina lines.

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References

1. Ivushkin, K.; Bartholomeus, H.; Bregt, A.K.; Pulatov, A.; Kempen, B.; de Sousa, L. Global Mapping of Soil Salinity Change. *Remote Sens. Environ.* **2019**, *231*, 111260. [CrossRef]
2. Qadir, M.; Quillérou, E.; Nangia, V.; Murtaza, G.; Singh, M.; Thomas, R..; Drechsel, P.; Noble, A.D. Economics of Salt-Induced Land Degradation and Restoration. *Nat. Resour. Forum* **2014**, *38*, 282–295. [CrossRef]
3. Food and Agriculture Organization of the United Nations. *Global Status of Salt-Affected Soils: Main Report*; FAO: Rome, Italy, 2024.
4. Libutti, A.; Cammerino, A.R.B.; Monteleone, M. Risk Assessment of Soil Salinization Due to Tomato Cultivation in Mediterranean Climate Conditions. *Water* **2018**, *10*, 1503. [CrossRef]
5. Wang, J.; Ding, J.; Lizaga, I.; Singh, A.; Tarolli, P. The Rising Threat of Subsoil Salinization in Drylands. *Int. Soil Water Conserv. Res.* **2025**, *13*, 1044–1045. [CrossRef]
6. Daliakopoulos, I.N.; Tsanis, I.K.; Koutroulis, A.; Kourgialas, N.N.; Varouchakis, A.E.; Karatzas, G.P.; Ritsema, C.J. The Threat of Soil Salinity: A European Scale Review. *Sci. Total Environ.* **2016**, *573*, 727–739. [CrossRef] [PubMed]
7. Schillaci, C.; Scarpa, S.; Yunta, F.; Lipani, A.; Visconti, F.; Szatmári, G.; Balog, K.; Koganti, T.; Greve, M.; Bondi, G.; et al. Empirical Estimation of Saturated Soil-Paste Electrical Conductivity in the EU Using Pedotransfer Functions and Quantile Regression Forests: A Mapping Approach Based on LUCAS Topsoil Data. *Geoderma* **2025**, *454*, 117199. [CrossRef]
8. Shokri, N.; Hassani, A.; Sahimi, M. Multi-Scale Soil Salinization Dynamics From Global to Pore Scale: A Review. *Rev. Geophys.* **2024**, *62*, e2023RG000804. [CrossRef]
9. Li, H.; Liu, X.; Hu, B.; Biswas, A.; Jiang, Q.; Liu, W.; Wang, N.; Peng, J. Field-Scale Characterization of Spatio-Temporal Variability of Soil Salinity in Three Dimensions. *Remote Sens.* **2020**, *12*, 4043. [CrossRef]
10. Ghirardelli, A.; Straffelini, E.; Park, E.; D'Agostino, V.; Masin, R.; Tarolli, P. Global Impact of Seawater Intrusion on Coastal Agriculture. *Environ. Res. Lett.* **2024**, *20*, 013005. [CrossRef]
11. Giambastiani, B.M.S.; Kidanemariam, A.; Dagnew, A.; Antonellini, M. Evolution of Salinity and Water Table Level of the Phreatic Coastal Aquifer of the Emilia Romagna Region (Italy). *Water* **2021**, *13*, 372. [CrossRef]
12. Ghirardelli, A.; Straffelini, E.; Cucchiaro, S.; Tarolli, P. The Impact of Seawater Intrusion in the Summer Season: A Remote Sensing Assessment of Crop Greening in the Po River Delta (Italy). In *Proceedings of the Biosystems Engineering Promoting Resilience to Climate Change—AIIA 2024—Mid-Term Conference*; Sartori, L., Tarolli, P., Guerrini, L., Zuecco, G., Pezzuolo, A., Eds.; Springer Nature: Cham, Switzerland, 2025; pp. 50–57.
13. Burbulea, R.; Marchina, C.; Bartoletta, S.; Manoni, A.; Tarolli, P. Analysis of Soil Salinization Induced by Seawater Intrusion on the Coastal Agriculture of Lazio Region (Italy). In Proceedings of the EGU General Assembly 2025, Vienna, Austria, 27 April–2 May 2025.
14. Cruz, J.V.; Andrade, C. Groundwater Salinization in Graciosa and Pico Islands (Azores Archipelago, Portugal): Processes and Impacts. *J. Hydrol. Reg. Stud.* **2017**, *12*, 69–87. [CrossRef]
15. Rodríguez-Santalla, I.; Navarro, N. Main Threats in Mediterranean Coastal Wetlands. The Ebro Delta Case. *J. Mar. Sci. Eng.* **2021**, *9*, 1190. [CrossRef]
16. Calatrava, J.; Álvaro-Fuentes, J.; Martínez-Granados, D.; Franco-Luesma, S.; Gómez-López, M.D. Stakeholders' Preferences for Sustainable Agricultural Practices in Mediterranean Cereal Cropping Systems. *Sustainability* **2025**, *17*, 4219. [CrossRef]
17. Maas, E.V.; Hoffman, G.J. Crop Salt Tolerance—Current Assessment. *J. Irrig. Drain. Div.* **1977**, *103*, 115–134. [CrossRef]
18. Grieve, C.M.; Grattan, S.R.; Maas, E.V. Plant Salt Tolerance. In *Agricultural Salinity Assessment and Management*; Wallender, W.W., Tanji, K.K., Eds.; ASCE Manuals and Reports on Engineering Practice; American Society of Civil Engineers: Reston, VA, USA, 2012; pp. 405–459.
19. Passioura, J.B. The Perils of Pot Experiments. *Funct. Plant Biol.* **2006**, *33*, 1075–1079. [CrossRef]
20. Negrão, S.; Schmöckel, S.M.; Tester, M. Evaluating Physiological Responses of Plants to Salinity Stress. *Ann. Bot.* **2017**, *119*, 1075–1079. [CrossRef]
21. Plessis, A. Abiotic Stress Experiments Need a Reality Check to Improve Translation to the Field. *J. Exp. Bot.* **2023**, *74*, 1741–1744. [CrossRef]
22. Corwin, D.L.; Scudiero, E. Chapter One—Review of Soil Salinity Assessment for Agriculture across Multiple Scales Using Proximal and/or Remote Sensors. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2019; Volume 158, pp. 1–130.
23. Zhang, T.-T.; Qi, J.-G.; Gao, Y.; Ouyang, Z.-T.; Zeng, S.-L.; Zhao, B. Detecting Soil Salinity with MODIS Time Series VI Data. *Ecol. Indic.* **2015**, *52*, 480–489. [CrossRef]

24. Jamal, M.d.R.; Kristiansen, P.; Kabir, M.d.J.; Lobry de Bruyn, L. Cropping Systems Intensification and Diversification: Risk, Vulnerability and Adaptation in Southwest Coastal Bangladesh. *Int. J. Sustain. Dev. World Ecol.* **2022**, *29*, 677–694. [CrossRef]
25. Volsi, B.; Higashi, G.E.; Bordin, I.; Telles, T.S. The Diversification of Species in Crop Rotation Increases the Profitability of Grain Production Systems. *Sci. Rep.* **2022**, *12*, 19849. [CrossRef]
26. Baldwin-Kordick, R.; De, M.; Lopez, M.D.; Liebman, M.; Lauter, N.; Marino, J.; McDaniel, M.D. Comprehensive Impacts of Diversified Cropping on Soil Health and Sustainability. *Agroecol. Sustain. Food Syst.* **2022**, *46*, 331–363. [CrossRef]
27. Berti, M.; Gesch, R.; Eynck, C.; Anderson, J.; Cermak, S. Camelina Uses, Genetics, Genomics, Production, and Management. *Ind. Crops Prod.* **2016**, *94*, 690–710. [CrossRef]
28. Zanetti, F.; Alberghini, B.; Marjanović Jeromela, A.; Grahovac, N.; Rajković, D.; Kiprovski, B.; Monti, A. Camelina, an Ancient Oilseed Crop Actively Contributing to the Rural Renaissance in Europe. A Review. *Agron. Sustain. Dev.* **2021**, *41*, 2. [CrossRef]
29. Alberghini, B.; Zanetti, F.; Corso, M.; Boutet, S.; Lepiniec, L.; Vecchi, A.; Monti, A. Camelina [*Camelina sativa* (L.) Crantz] Seeds as a Multi-Purpose Feedstock for Bio-Based Applications. *Ind. Crops Prod.* **2022**, *182*, 114944. [CrossRef]
30. Mondor, M.; Hernández-Álvarez, A.J. *Camelina sativa* Composition, Attributes, and Applications: A Review. *Eur. J. Lipid Sci. Technol.* **2022**, *124*, 2100035. [CrossRef]
31. Zanetti, F.; Peroni, P.; Pagani, E.; von Cossel, M.; Greiner, B.E.; Krzyżaniak, M.; Stolarski, M.J.; Lewandowski, I.; Alexopoulou, E.; Stefanoni, W.; et al. The Opportunities and Potential of Camelina in Marginal Land in Europe. *Ind. Crops Prod.* **2024**, *211*, 118224. [CrossRef]
32. Gregg, S.; Coulter, J.A.; Strock, J.S.; Liu, R.; Garcia y Garcia, A. Double-Cropped Winter Camelina with and without Added Nitrogen: Effects on Productivity and Soil Available Nitrogen. *Agriculture* **2022**, *12*, 1477. [CrossRef]
33. Gesch, R.W.; Archer, D.W. Double-Cropping with Winter Camelina in the Northern Corn Belt to Produce Fuel and Food. *Ind. Crops Prod.* **2013**, *44*, 718–725. [CrossRef]
34. Schillaci, C.; Perego, A.; Acutis, M.; Botta, M.; Tadiello, T.; Gabbrielli, M.; Barsali, T.; Tozzi, F.; Chiaramonti, D.; Jones, A. Assessing Marginality of Camelina (*C. sativa* L. Crantz) in Rotation with Barley Production in Southern Europe: A Modelling Approach. *Agric. Ecosyst. Environ.* **2023**, *357*, 108677. [CrossRef]
35. Avola, G.; Sortino, O.; Gresta, F. Low-Input Cultivation of Camelina (*Camelina sativa* (L.) Crantz) in a Mediterranean Semi-Arid. *Environ. Ital. J. Agron.* **2021**, *16*, 1728. [CrossRef]
36. Campbell, M.C.; Rossi, A.F.; Erskine, W. Camelina (*Camelina sativa* (L.) Crantz): Agronomic Potential. in Mediterranean Environments and Diversity for Biofuel and Food Uses. *Crop Pasture Sci.* **2013**, *64*, 388–398. [CrossRef]
37. Hergert, G.W.; Margheim, J.F.; Pavlista, A.D.; Martin, D.L.; Isbell, T.A.; Supalla, R.J. Irrigation Response and Water Productivity of Deficit to Fully Irrigated Spring Camelina. *Agric. Water Manag.* **2016**, *177*, 46–53. [CrossRef]
38. Berzuini, S.; Zanetti, F.; Alberghini, B.; Leon, P.; Prieto, J.; Herreras Yambanis, Y.; Trabelsi, I.; Hannachi, A.; Udupa, S.; Monti, A. Assessing the Productivity Potential of Camelina (*Camelina sativa* L. Crantz) in the Mediterranean Basin: Results from Multi-Year and Multi-Location Trials in Europe and Africa. *Ind. Crops Prod.* **2024**, *219*, 119080. [CrossRef]
39. Munns, R.; Tester, M. Mechanisms of Salinity Tolerance. *Annu. Rev. Plant Biol.* **2008**, *59*, 651–681. [CrossRef]
40. Alberghini, B.; Vicino, M.; Zanetti, F.; Silvestre, S.; Haslam, R.; Zegada-Lizarazu, W.; Monti, A. Assessing Different Physiological, Seed Yield and Quality Responses of Camelina Lines to Drought. *Ind. Crops Prod.* **2025**, *234*, 121528. [CrossRef]
41. Mastroberardino, R.; Zanetti, F.; Monti, A. Exploring Intraspecific Variation in Salinity Tolerance at Germination and Seedling Development Stages in *Camelina sativa*. *Front. Plant Sci.* **2025**, *16*, 1713651. [CrossRef]
42. Luo, Z.; Szczepanek, A.; Abdel-Haleem, H. Genome-Wide Association Study (GWAS) Analysis of Camelina Seedling Germination under Salt Stress Condition. *Agronomy* **2020**, *10*, 1444. [CrossRef]
43. Steppuhn, H.; Falk, K.C.; Zhou, R. Emergence, Height, Grain Yield and Oil Content of Camelina and Canola Grown in Saline Media. *Can. J. Soil Sci.* **2010**, *90*, 151–164. [CrossRef]
44. Stasnik, P.; Vollmann, J.; Großkinsky, D.K.; Jonak, C. Leaf Carbohydrate Metabolic Enzyme Activities Are Associated with Salt Tolerance and Yield Stability in the Climate-Resilient Crop Camelina Sativa. *Plant Stress.* **2024**, *14*, 100629. [CrossRef]
45. *Italia Decreto Ministeriale 13 Settembre 1999*; Italian Ministry: Rome, Italy, 1999.
46. Martinelli, T.; Galasso, I. Phenological Growth Stages of *Camelina sativa* According to the Extended BBCH Scale. *Ann. Appl. Biol.* **2011**, *158*, 87–94. [CrossRef]
47. Gesch, R.W. Influence of Genotype and Sowing Date on Camelina Growth and Yield in the North Central U.S. *Ind. Crops Prod.* **2014**, *54*, 209–215. [CrossRef]
48. Zanetti, F.; Angelini, L.G.; Berzuini, S.; Foschi, L.; Clemente, C.; Ferioli, F.; Vecchi, A.; Rossi, A.; Monti, A.; Tavarini, S. Safflower (*Carthamus tinctorius* L.), a winter multipurpose oilseed crop for the Mediterranean region: Lessons learnt from on-farm trials. *Ind. Crops Prod.* **2022**, *184*, 115042. [CrossRef]
49. Bates, D.; Mächler, M.; Bolker, B.; Walker, S. Fitting Linear Mixed-Effects Models Using Lme4. *J. Stat. Softw.* **2015**, *67*, 1–48. Available online: https://www.jstatsoft.org/article/view/v067i01 (accessed on 4 December 2025). [CrossRef]

50. Lenth, R.V.; Piaskowski, J.; Banfai, B.; Bolker, B.; Buerkner, P.; Giné-Vázquez, I.; Hervé, M.; Jung, M.; Love, J.; Miguez, F.; et al. *Emmeans: Estimated Marginal Means, Aka Least-Squares Means*; The Comprehensive R Archive Network, 2025. Available online: https://cran.r-project.org/package=emmeans (accessed on 4 December 2025).
51. Vittori Antisari, L.; Speranza, M.; Ferronato, C.; De Feudis, M.; Vianello, G.; Falsone, G. Assessment of Water Quality and Soil Salinity in the Agricultural Coastal Plain (Ravenna, North Italy). *Minerals* **2020**, *10*, 369. [CrossRef]
52. Bandak, S.; Movahedi-Naeini, S.A.; Mehri, S.; Lotfata, A. A Longitudinal Analysis of Soil Salinity Changes Using Remotely Sensed Imageries. *Sci. Rep.* **2024**, *14*, 10383. [CrossRef] [PubMed]
53. Dai, R.; Zhan, N.; Geng, R.; Xu, K.; Zhou, X.; Li, L.; Yan, G.; Zhou, F.; Cai, G. Progress on Salt Tolerance in Brassica Napus. *Plants* **2024**, *13*, 1990. [CrossRef]
54. Wang, L.; Zuo, Q.; Zheng, J.; You, J.; Yang, G.; Leng, S. Salt Stress Decreases Seed Yield and Postpones Growth Process of Canola (*Brassica napus* L.) by Changing Nitrogen. and Carbon. *Characters. Sci. Rep.* **2022**, *12*, 17884. [CrossRef]
55. Lee, Z.; Kim, S.; Choi, S.J.; Joung, E.; Kwon, M.; Park, H.J.; Shim, J.S. Regulation of Flowering Time by Environmental Factors in Plants. *Plants* **2023**, *12*, 3680. [CrossRef]
56. Ryu, J.Y.; Lee, H.-J.; Seo, P.J.; Jung, J.-H.; Ahn, J.H.; Park, C.-M. The Arabidopsis Floral Repressor BFT Delays Flowering by Competing with FT for FD Binding under High Salinity. *Mol. Plant* **2014**, *7*, 377–387. [CrossRef]
57. Passioura, J.B. Translational Research in Agriculture. Can We Do It Better? *Crop Pasture Sci.* **2020**, *71*, 517–528. [CrossRef]
58. Poorter, H.; Fiorani, F.; Stitt, M.; Schurr, U.; Finck, A.; Gibon, Y.; Usadel, B.; Munns, R.; Atkin, O.K.; Tardieu, F.; et al. The Art of Growing Plants for Experimental Purposes: A Practical Guide for the Plant Biologist. *Funct. Plant Biol.* **2012**, *39*, 821–838. [CrossRef] [PubMed]
59. Aboelsoud, H.M.; Habib, A.; Engel, B.; Hashem, A.A.; El-Hassan, W.A.; Govind, A.; Elnashar, A.; Eid, M.; Kheir, A.M.S. The Combined Impact of Shallow Groundwater and Soil Salinity on Evapotranspiration Using Remote Sensing in an Agricultural Alluvial Setting. *J. Hydrol. Reg. Stud.* **2023**, *47*, 101372. [CrossRef]
60. Zandalinas, S.I.; Sengupta, S.; Fritschi, F.B.; Azad, R.K.; Nechushtai, R.; Mittler, R. The Impact of Multifactorial Stress Combination on Plant Growth and Survival. *New Phytol.* **2021**, *230*, 1034–1048. [CrossRef] [PubMed]
61. Tricker, P.J.; ElHabti, A.; Schmidt, J.; Fleury, D. The Physiological and Genetic Basis of Combined Drought and Heat Tolerance in Wheat. *J. Exp. Bot.* **2018**, *69*, 3195–3210. [CrossRef]
62. Qaseem, M.F.; Qureshi, R.; Shaheen, H. Effects of Pre-Anthesis Drought, Heat and Their Combination on the Growth, Yield and Physiology of Diverse Wheat (*Triticum aestivum* L.) Genotypes Varying in Sensitivity to Heat and Drought Stress. *Sci. Rep.* **2019**, *9*, 6955. [CrossRef]
63. Righini, D.; Zanetti, F.; Martínez-Force, E.; Mandrioli, M.; Toschi, T.G.; Monti, A. Shifting Sowing of Camelina from Spring to Autumn Enhances the Oil Quality for Bio-Based Applications in Response to Temperature and Seed Carbon Stock. *Ind. Crops Prod.* **2019**, *137*, 66–73. [CrossRef]
64. Zeng, W.; Xu, C.; Wu, J.; Huang, J. Sunflower Seed Yield Estimation under the Interaction of Soil Salinity and Nitrogen Application. *Field Crops Res.* **2016**, *198*, 1–15. [CrossRef]
65. Bassil, E.S.; Kaffka, S.R. Response of Safflower (*Carthamus tinctorius* L.) to Saline Soils and Irrigation. *Agric. Water Manag.* **2002**, *54*, 81–92. [CrossRef]
66. Khan, M.S.U.; Rahman, M.M.; Basak, A.R.; Angon, P.B.; Ritu, S.A.; Kobir, M.; Islam, M.R. Evaluation of Different Sesame Varieties Cultivated under Saline Conditions in the Southwestern Coastal Region of Bangladesh. *Crop Des.* **2025**, *4*, 100093. [CrossRef]
67. Dubey, S.; Bhargava, A.; Fuentes, F.; Shukla, S.; Srivastava, S. Effect of Salinity Stress on Yield and Quality Parameters in Flax (*Linum usitatissimum* L.). *Not. Bot. Horti Agrobot.* **2020**, *48*, 954–966. [CrossRef]
68. Francois, L.E. Growth, Seed Yield, and Oil Content of Canola Grown under Saline Conditions. *Agron. J.* **1994**, *86*, 233–237. [CrossRef]
69. Gao, Y.; Chang, L.; Zeng, M.; Hu, Q.; Hui, J.; Jiang, Q. Quantitative Relationship Model between Soil Profile Salinity and Soil Depth in Cotton Fields Based on Data Assimilation Algorithm: Forecasting Cotton Field Yields and Profits. *Front. Plant Sci.* **2024**, *15*, 1519200. [CrossRef]
70. Wang, L.; Lin, G.; Li, Y.; Qu, W.; Wang, Y.; Lin, Y.; Huang, Y.; Li, J.; Qian, C.; Yang, G.; et al. Phenotype, Biomass, Carbon and Nitrogen Assimilation, and Antioxidant Response of Rapeseed under Salt Stress. *Plants* **2024**, *13*, 1488. [CrossRef]
71. Chen, B.; Bian, X.; Tu, M.; Yu, T.; Jiang, L.; Lu, Y.; Chen, X. Moderate Salinity Stress Increases the Seedling Biomass in Oilseed Rape (*Brassica napus* L.). *Plants* **2023**, *12*, 1650. [CrossRef]
72. Smith, B.E.; Lu, C. Heat Stress during Reproductive Stages Reduces Camelina Seed Productivity and Changes Seed Composition. *Heliyon* **2024**, *10*, e26678. [CrossRef]
73. Schulte, L.R.; Ballard, T.; Samarakoon, T.; Yao, L.; Vadlani, P.; Staggenborg, S.; Rezac, M. Increased Growing Temperature Reduces Content of Polyunsaturated Fatty Acids in Four Oilseed Crops. *Ind. Crops Prod.* **2013**, *51*, 212–219. [CrossRef]

74. Obour, A.K.; Obeng, E.; Mohammed, Y.A.; Ciampitti, I.A.; Durrett, T.P.; Aznar-Moreno, J.A.; Chen, C. Camelina Seed Yield and Fatty Acids as Influenced by Genotype and Environment. *Agron. J.* **2017**, *109*, 947–956. [CrossRef]
75. Yeilaghi, H.; Arzani, A.; Ghaderian, M.; Fotovat, R.; Feizi, M.; Pourdad, S.S. Effect of Salinity on Seed Oil Content and Fatty Acid Composition of Safflower (*Carthamus tinctorius* L.) Genotypes. *Food Chem.* **2012**, *130*, 618–625. [CrossRef]