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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

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ABSTRACT

Camelina is a multi-purpose oilseed crop for industrial bio-based applications. Recently, it has gained increasing attention mostly due to the possibility to grow with limited resources and in marginal environments, as well as to increase soil coverage and water retention, while reducing nitrogen leaching. The present study aimed to assess the viability of using camelina as an emerging oilseed crop for EU and African Mediterranean farmers. Several camelina spring genotypes were evaluated in a multi-location trial (Italy, Spain, Algeria, Morocco and Tunisia) in two growing seasons (2020–22). Although thermal time was very similar at all sites (~1300 GDD from sowing to harvest), the growing cycle length was about 60 days longer in Europe than in Africa, leading to a higher seed yield (~ 1.5-fold higher). Mean seed production in the African countries was 0.71 Mg ha^{-1} proving camelina to be adaptable even to very arid conditions. Under more favorable conditions (European countries) seed yields was up to 2 Mg ha^{-1}. Among genotypes, Alba generally exhibited the highest seed yield and seed weight, while CCE42 and CCE29 showed more stable productions over years and locations. Based on the results of the present study it is possible to conclude that the introduction of camelina into conventional Mediterranean cropping systems appeared as feasible option to improve crop diversification; however, the selection of best camelina varieties is essential to achieve sustainable productions, particularly for African countries.

1. Introduction

The Mediterranean region has been described as a geographic area characterized by a temperate climate with warm winters and hot and dry summers (del Pozo et al., 2019). Over the past few decades, this region has become known as a “climate change hotspot”, as evidenced by studies conducted by Giorgi (2006), Giorgi and Lionello (2008), and Lionello and Scarascia (2018), that showed a considerable year-to-year fluctuation in rainfall and temperatures. Alessandri et al. (2014) predicted that the arid climate will extend further into this region during the next century, causing the Mediterranean climate to expand northward into central and eastern Europe, resulting in a reduction in water availability for the agricultural sector. The negative effects of climate change are increasingly evident in the Mediterranean, particularly in the southern part, where more than 90% of the cultivated land is under rain-fed regimes (Potter et al., 2012; Schilling et al., 2012). Identifying economically sustainable rainfed agricultural systems is therefore more urgent and important than never. The negative effects of climate change on agriculture are generally exacerbated by global issues such as land use change, depletion of soil organic matter (Davidson and Janssens, 2006), water usage, and nutrient leaching, that are causing a progressive and alarming abandonment of extensive agricultural land (Aguilera et al., 2020; Doblas-Miranda et al., 2017). The agricultural research community is increasingly prioritizing the study of the impact of climate

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change in the Mediterranean region. This includes examining the phenomenon known as "Mediterraneanization" which refers to the spread of resilient Mediterranean crops into areas that are more susceptible to environmental changes (Hernández et al., 2017). To address this issue, it is necessary to identify alternative productive systems that are climate-resilient, including shifts due to global change. The introduction of camelina in the typical rotations should be able to complement the existing systems in the area, which heavily rely on cereals such as winter wheat (*Triticum durum*) and barley (*Hordeum vulgare*) as the sole crops. The adoption of Conservation Agriculture (CA) is promoted by FAO (Food and Agriculture Organization of the United Nations, 2020) as a response to sustainable land management, environmental protection, and climate change adaptation. The main principles of CA are: *i*) the use of permanent (all-year-long) soil coverage through the adoption of cover-crops replacing fallow periods (Guardia et al., 2016), thus reducing evapotranspiration and soil erosion (Langdale et al., s.d.), *ii*) the adoption of minimum tillage or zero-tillage systems, and *iii*) the diversification of the crops in traditional rotations, which can provide alternative productions to the farmers, enhancing their final income. In response to the limited options for oilseed crops sourcing locally multi-use vegetable oils (with rapeseed and sunflower accounting for 99% of oil produced in Europe), new oilseed crops are trying to be introduced in the Mediterranean basin to meet the growing demand of the biobased industry. Camelina [*Camelina sativa (L.) Crantz*], an herbaceous oilseed crop belonging to the *Brassicaceae* family, seems to satisfy all the three points mentioned above. It is an ancient crop having its origins in southeastern of Europe and Southwestern Asia (Larsson, 2013), more specifically from the Caucasus region (Brock et al., 2022). In Europe, its cultivation has become more interesting in the last twenty years because of its rusticity and adaptability to different environments (Zanetti et al., 2021). Thanks to the presence of winter and spring biotypes, camelina can be sown from autumn to early winter; moreover, thanks to its short growing cycle (up to 90 d from sowing to harvest in sown in spring, while autumn sowing can reach up to 200 d from sowing to harvest, Zanetti et al., 2017; Royo-Esnal andValencia Gredilla, 2018) it allows double cropping with common summer crops (such as soybean or maize). Camelina can be easily integrated in most conventional crop rotations replacing for example, fallow or cereals. There is evidence, moreover, that camelina is enhancing insects' biodiversity (Groeneveld and Klein, 2013) due to its early flowering compared with other common spring crops. Camelina seed yield is generally 1.2–3.4 Mg ha^{-1} (Masella et al., 2014; Zanetti et al., 2017; Royo-Esnal and Valencia Gredilla, 2018; Zanetti et al., 2021), while the oil content is about 40 % (Righini et al., 2016) and the protein content ranges from 27% to 32% (Gugel and Falk, 2006). Camelina oil has high concentrations of oleic and linoleic acid (14–16% and 15–23%, respectively) and α-linolenic acid (C18:3 31–40%) (Berti et al., 2016), thus resulting in a high-quality multipurpose feedstock (Zubr and Matthäus, 2002; Alberghini et al., 2022). The cold pressed camelina oil is also very rich in natural antioxidants, such as tocopherols, making this highly stable oil very resistant to oxidation and rancidity (Sampath, 2009). Non-food applications such as for bio-diesel or lubricants are other market prospects of vast global interest. Lastly, camelina seed meal after oil extraction can be used in different feed industries as a valuable ingredient for animal diet (Cullere et al., 2023). The scope of the present work is to evaluate the feasibility of camelina as a cash cover crop in the Mediterranean region, including northern African countries, such as Algeria, Morocco and Tunisia, and southern European ones, such as Italy and Spain. To the best of our knowledge, it is the first study on camelina on such an extended Mediterranean area.

2. Materials and methods

Seven different camelina spring genotypes (Table 1) were evaluated in a multi-location (2 locations in Europe and 3 locations in North Africa) multi-year (2020–2022) screening trial. All the varieties were provided by CCE (Camelina Company España). At least five genotypes were tested at each location; genotypes were selected based on their potential suitability to specific local conditions and their feasibility in the crop rotation. At all locations the experimental set up of the trial was similar: plot size of 10 – 15 m^2, row spacing between 0.13 and 0.20 m, depending on the local machinery availability, seeding rate of 600 seeds m^{-2}, and fertilization of 60 kg N ha^{-1} as urea, applied before stem elongation. Trials were all rainfed, and only in one case (Morocco in 2021) harvesting was not performed because of extreme drought during the growing cycle. Sowing was performed in autumn or beginning of winter using a plot drill according to best agronomical practices specifically for each location while harvesting was performed from mid-April to beginning of June depending on the test environment (Table 2). Pesticides and herbicides were not used during the growing season and weed control, when necessary, was performed manually. The experimental design was completely randomized blocks with three or four replicates, depending on the location. Soil characteristics and the main meteorological data for each test location are summarized in Table 2.

Table 1
County, location, tested camelina genotypes, and study years. All the camelina genotypes were supplied by CCE (Camelina Company España).

Country	Location	Geographic coordinates	Tested genotypes	Study year
Italy	Cadriano	44°33'N, 11°23'E	CCE26, CCE29, CCE42, CCE43, CCE44, ALBA	2020/21, 2021/22
Spain	Ciudad Real	39°16' N, 3°56' W	CCE26, CCE29, CCE 42, CCE43, CCE44, CCE117, ALBA	2020/21, 2021/22
Algeria	Sétif	36°09'N, 5°22'E	CCE26, CCE29, CCE42, CCE43, CCE44, CCE117, ALBA	2020/21, 2021/22
Morocco	Marchouch	33°36'N, 6°42' W	CCE26, CCE29, CCE 42, CCE43, CCE44, CCE117, ALBA	2020/21
Tunisia	Kef	36°07' N, 8°43' W	CCE26, CCE29, CCE 42, CCE43, CCE44, CCE117, ALBA	2020/21, 2021/22

2.1. Meteorological data

Main meteorological data, including air temperature (minimum and maximum) and precipitation at each location for the two growing seasons were collected from the NASA website (https://power.larc.nasa.gov/data-access-viewer/) and resumed in Table 2. Growing degree days (GDD) were calculated as follows for each location/growing season:

$$GDD = \sum\left[\frac{Tmax + Tmin}{2} - Tbase\right]$$

Where T_{max} and T_{min} are daily maximum and minimum air temperature respectively and T_{base} is the base temperature adopted for calculation, in this case 4°C (Gesch and Cermak., 2011). In days when the difference between the mean temperature and the Tbase was negative, GDD was assumed equal to 0.

2.2. Harvesting and post-harvest analysis

Harvesting was performed manually in all locations. Before harvesting, plant height was measured as mean stand of camelina canopy. Once the camelina reached their full maturity, a sampling central area of 6 m^2 was manually collected to determine the total biomass and seed yield. Residual moisture of the plants and seeds was determined on subsamples (~100 g) by oven-drying at 105°C until constant moisture levels. Seed yield is expressed on dry basis. Thousand seed weight was determined on a representative seed sample of each genotype by a seed

Table 2

Sowing and harvest dates, mean minimum (Tmin, °C) and maximum (Tmax, °C) temperature, cumulative precipitation (Prec, mm), GDD (Growing Degree Days), and cycle length (d) of the five study sites from sowing to harvest in the two study years.

Study year	Country	Sowing date	Harvest date	Tmin (°C)	Tmax (°C)	Prec (mm)	GDD*	Cycle length (d)
2020/21	Italy	22-Oct	2-Jun	4.7	14.8	223	1238	224
	Spain	17-Nov	25-May	4.5	15.9	232	1148	189
	Algeria	17-Dec	2-Jun	5.1	17.3	275	1135	168
	Tunisia	16-Dec	20-May	6.2	18.9	239	1242	161
	Morocco	22-Dec	15-May	9.3	20.5	429	1429	145
2021/22	Italy	21-Oct	13-Jun	5.5	15.5	458	1460	236
	Spain	18-Nov	10-Jun	5.2	17.4	228	1398	205
	Algeria	27-Dec	2-Jun	4.8	17.1	247	1003	158
	Tunisia	21-Nov	27-May	5.8	17.9	302	1307	188
	Morocco	21-Dec	-	10.0	23.1	162	-	-

* Tbase for GDD calculation 4°C (Gesch and Cermak., 2011).

counter machine. Plant density at harvest was measured on two 1-m rows in all plots.

2.3. Statistical analysis

Prior to analysis of variance (ANOVA), the homoscedasticity of data was verified performing Barlett's Test ($P \leq 0.05$). Two types of ANOVA were carried out: *i*) intra-location one-way ANOVA comparing the results of the different varieties; *ii*) inter-locations two-way ANOVA only for the common varieties across the different locations. In both ANOVAs "year" was considered as a random factor. When the analysis of variance was significant ($P \leq 0.05$), HSD Tukey's test was used to separate means. Then in the inter-location study, in order to evaluate yield stability of the different varieties Wricke's Ecovalence Stability Coefficient (Wricke, 1962) was used, which defines ecovalence as the contribution of each genotype to the GEI (genotype x environment interaction) sum of squares. The ecovalence or stability of the genotype is its interaction with the environments, squared and summed across environments, and express as:

$$W_i = \left[\overline{Y}_{ij} - \overline{Y}_{.i} - \overline{Y}_{.j} - \overline{Y}_{..}\right]^2$$

where $\overline{Y}_{ij}$ is the mean performance of the i genotype in the jth environment and $\overline{Y}_{.i}$, $\overline{Y}_{.j}$ are the genotype and environment mean deviations, respectively and $\overline{Y}_{.}$ is the overall mean. For this reason, genotypes with lower W_i values are more stable across environments.

3. Results and discussion

3.1. Meteorological data and camelina growth cycle

Meteorological data were analysed in both years at all locations. In the European countries minimum and maximum temperatures were consistent across the growing seasons. In the African countries the highest temperatures were recorded in Morocco in both growing seasons, while the lowest ones were recorded in Algeria due to the altitude of the trial site (928 m a.s.l). In general, a cumulative precipitation in the range of 220–300 mm from sowing to harvest was enough to guarantee the fulfilment of camelina water needs (Hergert et al., 2016), confirming this crop being suitable to arid and semi-arid environments. Only in Morocco during the second growing season, where only 162 mm was recorded during crop growth, camelina completely failed. In fact, the 2021/22 growing season in Morocco was characterized by very dry winter months, with the first precipitation occurring only in March, so camelina was never able to establish properly in the field, and this caused the failure of crop. In Italy high amount of precipitation was registered in the second growing season (2021/22) due to high precipitation occurred at the end of May, towards the end of the growing cycle, and this negatively impacted the camelina harvesting. The accumulation of GDD from sowing to harvest was more or less in line with reference values from the literature (Righini et al., 2016; Zanetti et al., 2021; Alberghini et al., 2022). Interestingly, the main differences across locations was the duration of camelina growth cycle (Table 2), which was the shortest in Morocco in 2020/21 with 145 d, and the longest in Italy in the 2021/22 (236 d from sowing to harvest). On average crop cycle in Europe was about 60 d longer than in the African countries, and it is worth mentioning that the prolongation of camelina cycle is positively related to the productive performance of the crop, as often reported by different authors (Righini et al., 2016; Zanetti et al., 2020). Despite camelina being a completely new crop for the African countries, it confirmed its wide environmental suitability since on the ten field experiments considered, only one (Morocco 2021/22) completely failed, in this location no adequate rains were received for nearly two and half months after germination of the crop. The severe drought affected crop growth and development and many of the plants died due to severe water stress. The rain received after mid-March 2022 was not able to save the crop, therefore, seed yield was not recorded.

3.2. Intra-location results and discussion

Concerning the intra-location analysis, at least five camelina genotypes were compared in each environment considering different productive parameters, depending on the data availability. The results of the ANOVA are reported on Table 3. Concerning the results for Europe, in Italy, final plant height, seed yield, and 1000-seed-weight were significantly influenced by the genotypes. The mean plant emergence was 130 plants m^{-2}, a value which can be considered adequate to guarantee a good soil coverage and competition against weeds to camelina grown in Northern Italy (Zanetti et al., 2020). Camelina final plant height was on average of the five genotypes 0.93 m, a value which is consistent with previous findings for the same growing environment (Zanetti et al., 2020). Among camelina genotypes, Alba and CCE43 were the tallest while CCE29 was the shortest. Interestingly, seed yield (Fig. 1A) seemed not directly influenced by emergence, but more to final plant height, so Alba resulted the most productive genotype (Fig. 1B) and CCE29 the least productive one. The mean seed yield of the trial was 1.72 Mg DM ha^{-1}, but only Alba yielded above 2 Mg DM ha^{-1}, which

Table 3

ANOVA results (F-values) of the intra-location trials.

Country	Genotypes	Emergence (plants m^{-2})	Final plant height (m)	Seed yield (Mg DM ha^{-1})	1000-seed weight (g)
Italy	5	2.61^{ns}	8.61^{**}	6.54^{**}	8.32^{**}
Spain	7	0.81^{ns}	7.20^{**}	2.53^{**}	10.88^{**}
Algeria	7	6.33^{**}	0.96^{ns}	2.07^{ns}	2.21^{ns}
Morocco	7	1.09^{ns}	2.18^{ns}	0.83^{ns}	3.07^{**}
Tunisia	7	0.03^{ns}	0.96^{ns}	1.91^{ns}	8.77^{**}

** significant for $P \leq 0.05$

ns = not significant

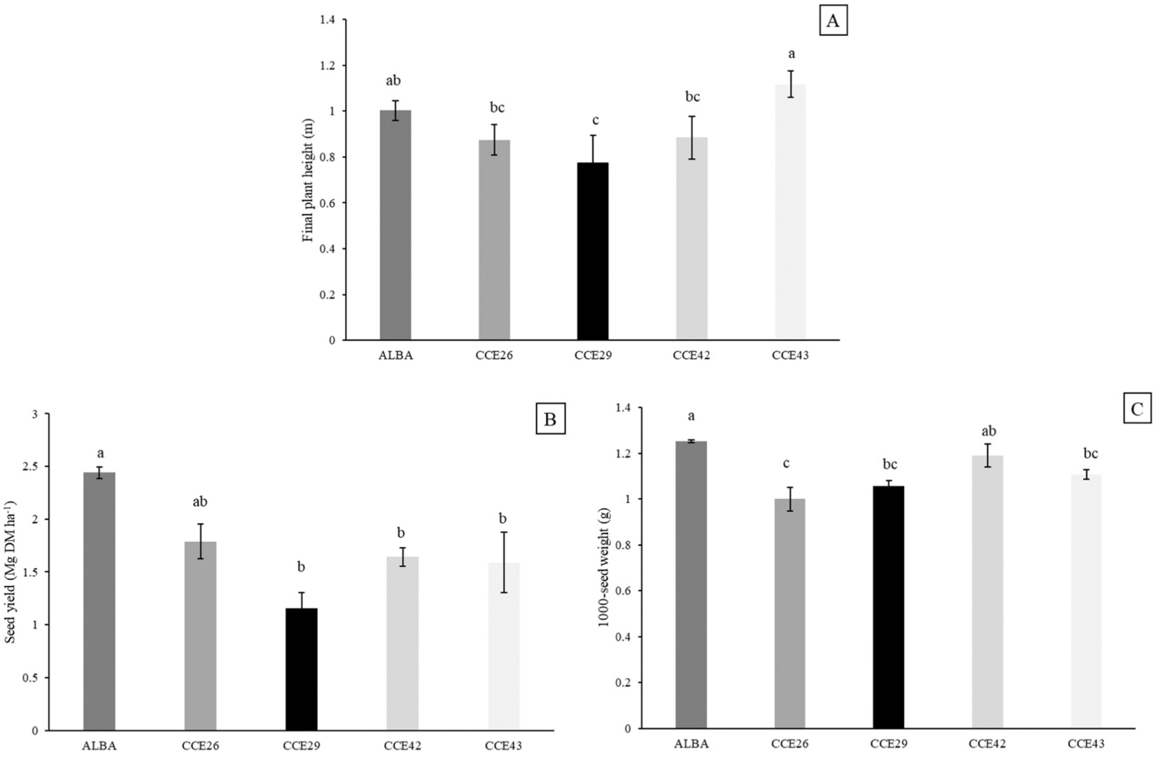

Fig. 1. Intra-location analysis in Italy. Main effect genotype on: A) Final plant height (m), B) Seed yield (Mg DM ha^{-1}), and C) 1000-seed weight (g) of 5 different camelina genotypes for two consecutive growing seasons (2020–2022). Different letters: significant different values ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

could be considered a target achievable production rate for spring camelina sown in autumn in northern Italy (Zanetti et al., 2021). Finally, 1000-seed weight, an “élite” trait for camelina breeding programs (Zanetti et al., 2017), was also influenced by genotype choice, with highest values obtained from Alba and CCE42 (Fig. 1C), compared with CCE26 and CCE29 which produced the lightest seeds. Alba was the best

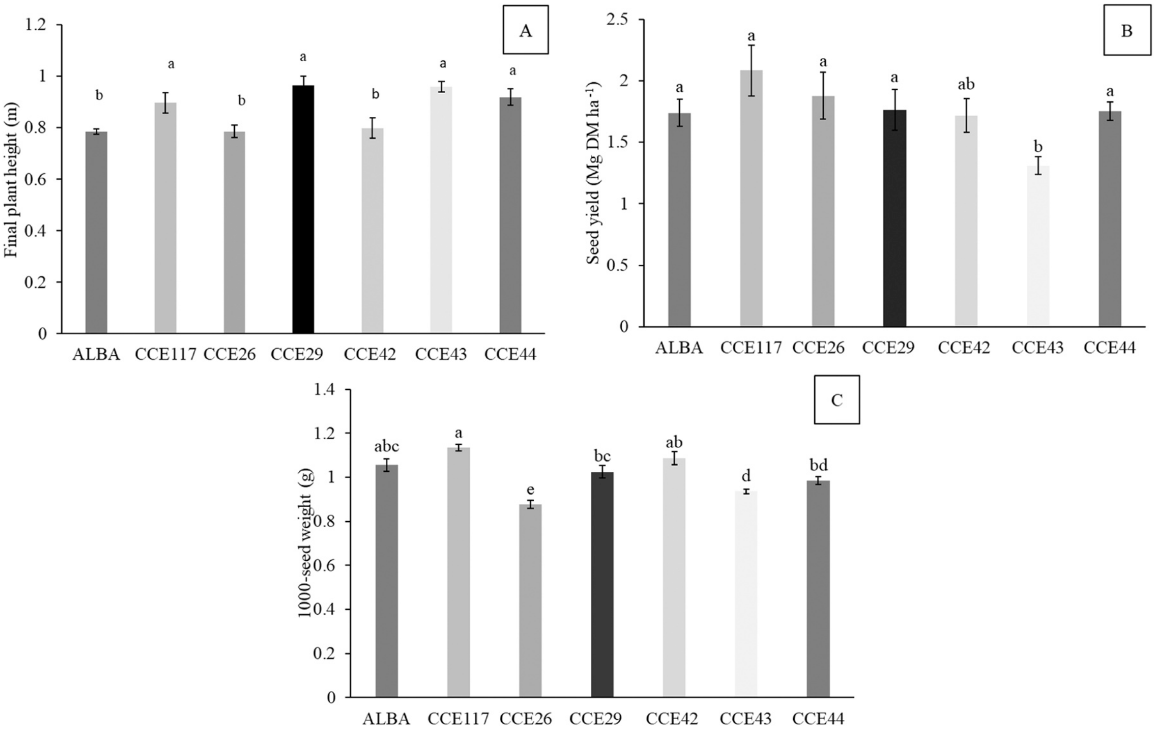

Fig. 2. Intra-location analysis for Spain. Main effect genotype on: A) Final plant height (m), B) Seed yield (Mg DM ha^{-1}), and C) 1000-seed weight (g) of 7 different camelina genotypes for two consecutive growing seasons (2020–20221). Different letters: significant different values ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

genotype for Italy producing higher seed yield coupled with larger seed weight. In Spain, the genotype significantly influenced final plant height, seed yield, and the 1000-seed weight (Table 3). In general, CCE29, CCE43 and CCE44 produced taller plants than the other genotypes (Fig. 2A). When analysing seed yield (Fig. 2B), most of the tested genotypes showed similar results, only CCE43 and CCE117 differentiated significantly, with the latter being more productive than CCE43. The mean seed yield reported in the variety trial was 1.75 Mg DM ha^{-1}, a value in line with previous findings for this area (Montero-Muñoz et al., 2023), and demonstrating that the selected genotypes were well adapted to the Spanish environment characterized by an arid climate with low precipitation and high temperatures, mostly at the end of the growing cycle. Significant differences for 1000-seed weight were surveyed (Fig. 2C), with CCE117 reporting the highest value (1.13 g) and CCE26 the lowest (0.87 g). The overall mean for 1000-seed weight was about 1 g, a value often reported in the literature as the reference for camelina (Zanetti et al., 2021). Despite both Italy and Spain being located in the southern part of Europe, the responses of some common genotypes were quite contrasting, particularly in terms of morphological rather than productive traits, in fact e.g. Alba produced the tallest plants in Italy compared with the others, but this did not occur in Spain. On the other hand, Alba was at both locations among the top performers for seed yield and 1000-seed weight. Nevertheless, CCE29, which was the worst performer in Italy for the surveyed parameters, showed an average productive performance in Spain.

Concerning the trials conducted in northern Africa, there is little research on camelina as a new oilseed in this environment so far, despite the fact that *Camelina microcarpa (Andrz. ex DC.) Bonnier*, a near relative of *Camelina sativa (L.) Crantz*, can be easily found as a wild plant in the high plains of Algeria (Guendouz et al., 2022). In the three countries included in the present research, Algeria, Morocco, and Tunisia, it was the first experience ever of camelina cultivation, thus the present results are of enormous interest for the future diffusion of camelina in such areas of Mediterranean Africa. In Algeria, only camelina emergence was influenced by the different genotypes (Table 3). Alba (Fig. 3) showed the highest emergence attesting on 308 plants m^{-2}, while CCE43 showed the lowest value with only 170 plants m^{-2}. Interestingly without reporting significant differences among the seven genotypes compared, camelina final plant height was 0.79 m, the mean seed yield was 0.72 Mg DM ha^{-1}, with almost double production in the first growing season than in the second, presumably in relation to a more suitable meteorological condition. Camelina 1000-seed weight was on average 0.95 g, a value quite similar to that reported in Spain. In Morocco, the parameters were analysed only for the first growing season, since in the second camelina failed due to extreme drought at establishment. The mean emergence was 190 plants m^{-2}, the final plant height was on average 0.94 m, and the seed yield was 0.51 Mg DM ha^{-1}, without any significant differences among the seven camelina genotypes. The only surveyed parameter significantly influenced by genotype in Morocco was 1000-seed weight (Table 3). Alba and CCE117 produced the heaviest seeds, with a mean value of 1.24 g (Fig. 4), and CCE26 reported the lightest seeds, with a mean of 0.83 g. Finally, the trial conducted in Tunisia showed significant differences between varieties only for 1000-seed weight (Table 3). The mean values for plant emergence, and final plant height were on average 241 plants m^{-2} and 0.68 m, respectively. Seed yield was on average 0.74 Mg DM ha^{-1}, ranging from 0.53 Mg DM ha^{-1} for Alba, to0.87 Mg DM ha^{-1} for CCE42. In general, seed yields in Tunisia were comparable to that achieved in Algeria and higher than in Morocco, but lower than the ones reported in the European countries in this study. Nevertheless, the 1000-seed weight was on average 1.05 g, which was the third highest value in the present study after Italy and Morocco. The genotype CCE42 was again the heaviest among the seven tested in Tunisia (1.13 g), CCE44, CCE117, Alba and CCE29 showed intermediate values ranging from 1.09 g to 1.04 g, and CCE26 resulted in the genotype with the lightest seeds (0.91 g) (Fig. 5).

3.3. Inter-location results and discussion

Four genotypes including Alba, CCE26, CCE29 and CCE42, were in common to all the experiments across locations, so an inter-location analysis of their productive results has been carried out. Table 4 reports the ANOVA results for the main surveyed parameters, considering the effect of the environment (E), of the genotype (G), and their interaction (G X E). The growing environment was significant for all the surveyed parameters, while genotype affected only seed yield and 1000-seed weight (Table 4). Plant emergence (plants m^{-2}) was significantly affected by the environment (Fig. 6) with the highest rate in Spain (461 plants m^{-2}) and the lowest rate in Italy (138 plants m^{-2}). Plant height was affected by the interaction G x E (Fig. 7). Camelina plants were the shortest in Tunisia (~0.57 m) and the tallest in Morocco (~0.93 m). In Italy and Spain, the highest variation in plant height among genotypes was registered. Interestingly, in Italy Alba was the tallest (~ 1 m) and CCE29 the shortest (0.77 m), whereas in Spain it was the opposite, (~0.78 and 0.97 m, Alba and CCE29, respectively). In the African countries, plant height ranged from 0.93 m in Morocco to 0.59 m in Tunisia. Camelina seed yield (Mg DM ha^{-1}) was considerably affected

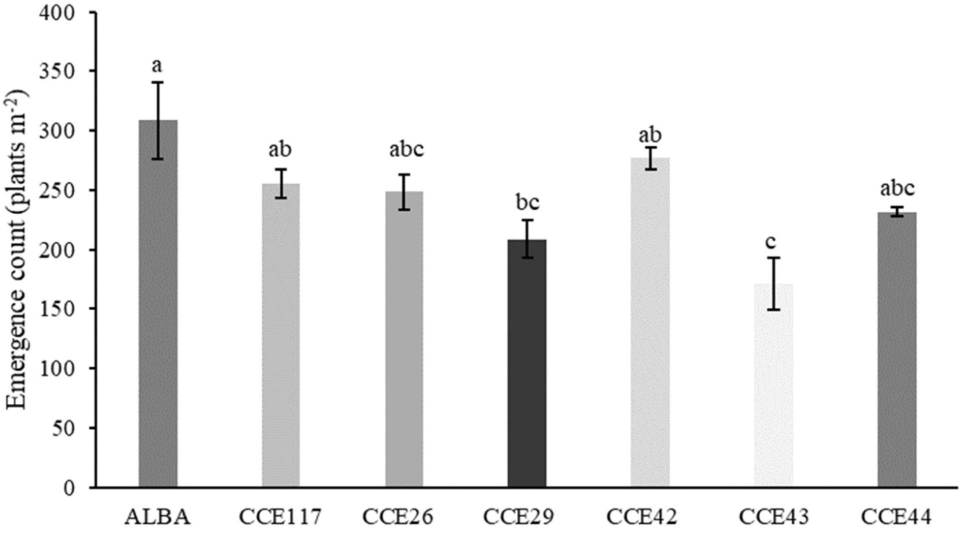

Fig. 3. Intra location analysis in Algeria. Main effect genotype for emergence count (plants m^{-2}) of 7 different camelina genotypes for two consecutive growing seasons (2020–2022). Different letters: significant different values ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

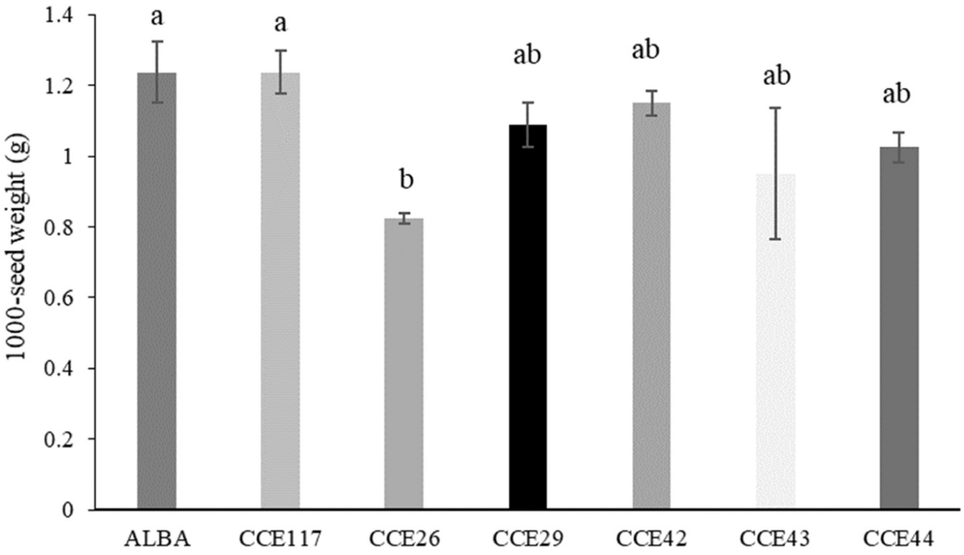

Fig. 4. Intra-location analysis in Morocco. Main effect genotype for 1000-seed weight (g) of 7 different camelina genotypes for one growing season (2020–2021). Different letters: significant different values ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

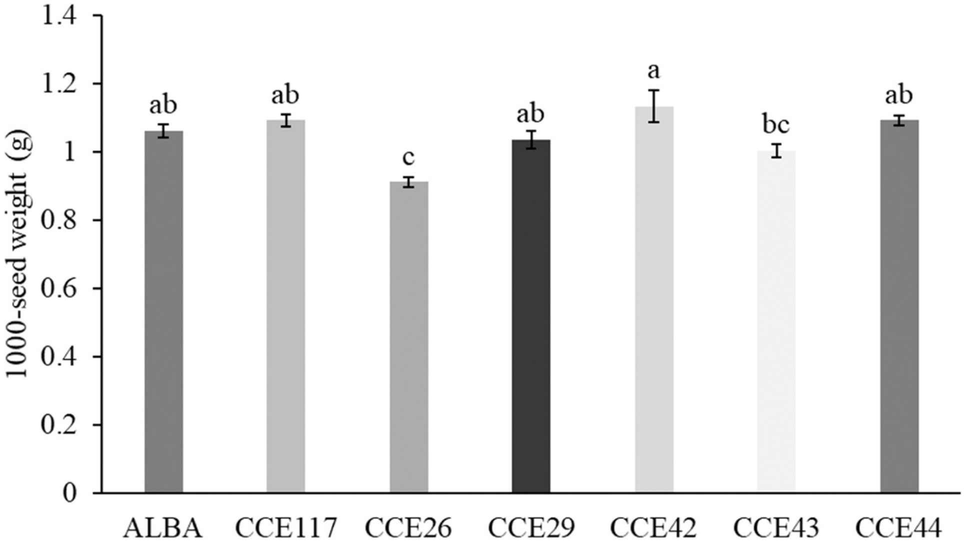

Fig. 5. Intra-location analysis in Tunisia. Main effect genotype on 1000-seed weight of seven different camelina genotypes in for two consecutive growing seasons (2020–2022). Different letters: significant different values ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

Table 4
ANOVA results (F-values) of the inter-location analysis for: emergence, final plant height, seed yield and 1000-seed weight, in response to the main factors: G= genotype, E= environment and the G x E =genotype x environment interaction.

Source of variation	Emergence (plants m^{-2})	Plant height (m)	Seed yield (Mg DM ha^{-1})	1000-seed weight (g)
G	0.89^{ns}	0.89^{ns}	84.4^{**}	7.79^{**}
E	48.8^{**}	56.2^{**}	3.34^{**}	34.2^{**}
G X E	0.48^{ns}	3.68^{**}	4.12^{**}	1.77^{ns}

** significant for $P \leq 0.05$
^{ns} = not significant

by the interaction G x E (Fig. 8), higher seed yields being generally observed in Europe than Africa. Alba showed the highest yield in Italy (2.43 Mg DM ha^{-1}) and CCE29 the lowest one (1.16 Mg DM ha^{-1}), confirming the same trend of plant height. In Spain, no significant differences were surveyed among varieties (1.77 Mg DM ha^{-1}, on average). Those values are in line with Royo-Esnal and Valencia-Gredilla (2018) who reported mean seed yield values between 0.6 and 2.4 Mg DM ha^{-1} in the Mediterranean climate of southern Spain. Likely, because of significantly lower precipitation amount during the early camelina growing period and the shorter cycle length (~ 2 months shorter), the African countries had significant lower seed yield potentials than the European ones. Furthermore, when analysing the coefficient of variation (CV) for seed yield for the European and African countries, it resulted 0.26 and 0.44, respectively, thus confirming not only a lower productive potential but also a higher variation across seasons and sites in Northern Africa. On a country-based analysis the CV for seed yield resulted the lowest in Spain (0.24), followed by Italy (0.30), Tunisia (0.35), and Algeria (0.44). The CV for Morocco (0.38) referred only one growing season, so it is probably not as reliable. The future spread of camelina cultivation across Mediterranean African countries will probably permit it to reduce this range of variation, identifying target areas within each country more suitable to camelina

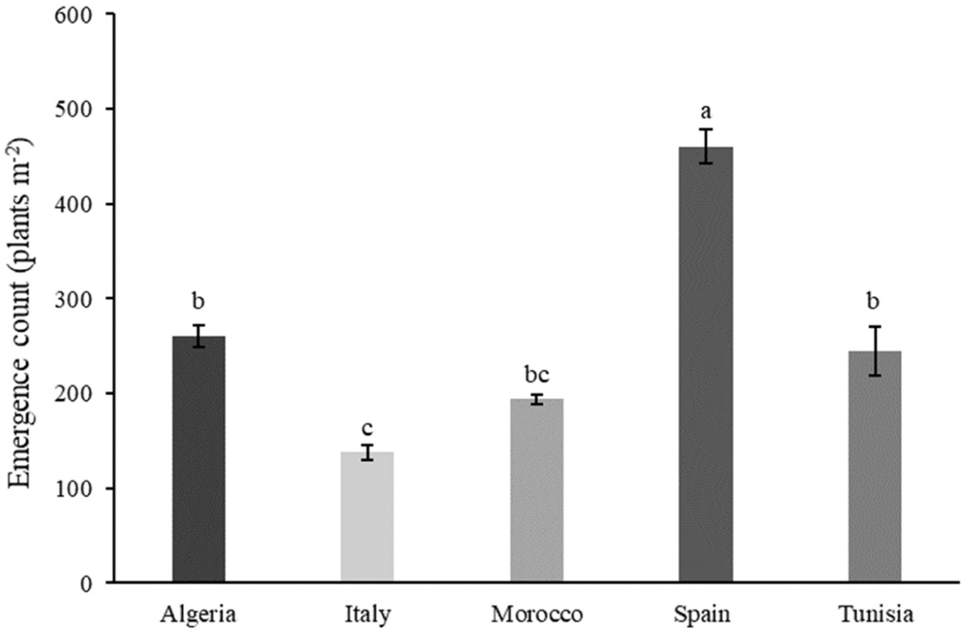

Fig. 6. Inter-location results for emergence count (plants m^{-2}) of 4 camelina lines at 5 different locations for two consecutive growing seasons (2020–22, except for Morocco, where only 2020–21 was included in the analysis). Main effect: environment. Different letters: significant different values ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

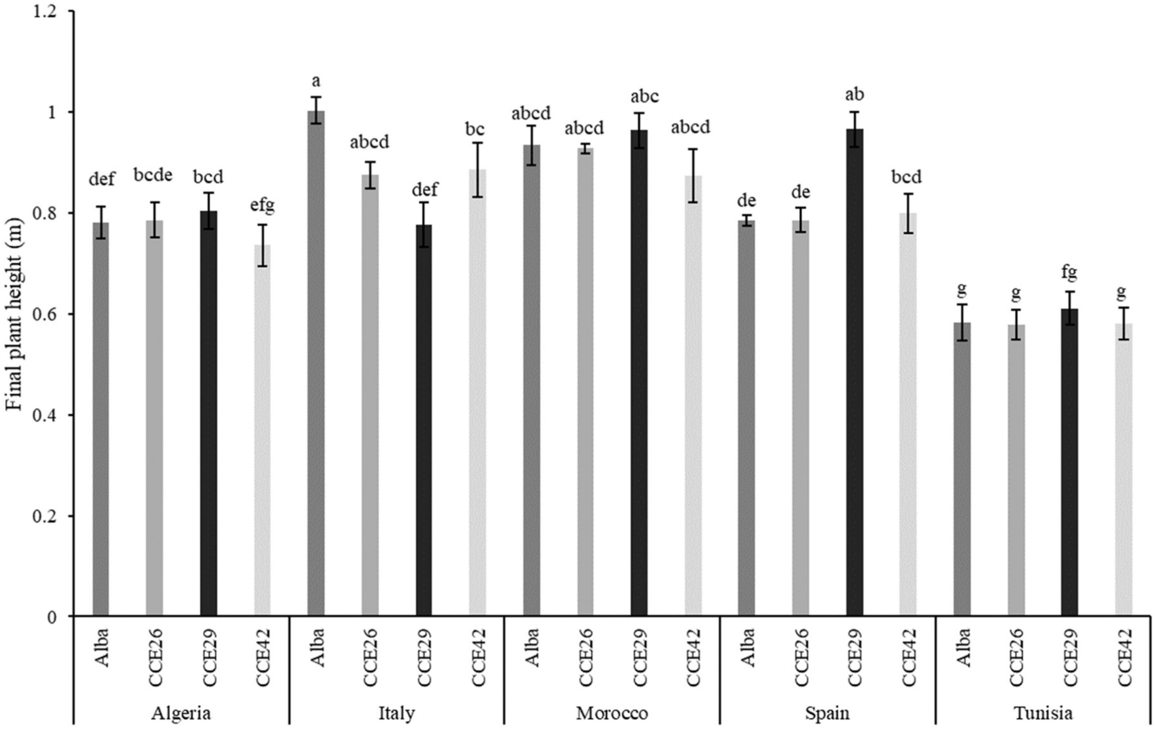

Fig. 7. Inter-location results for final plant height (m) of 4 camelina lines at 5 different locations for two consecutive growing seasons (2020–2022, except for Morocco, where only 2020–21 was included in the analysis). Interaction effect: environment x genotype. Different letters: significant different values ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

cultivation, a process which is already being done in Europe and Northern America. In any case, the calculated CV are in line with those found in a similar study across different European countries carried out almost 10 years ago (Zanetti et al., 2017), demonstrating that camelina, besides being widely adaptable, is also highly influenced by growing conditions. Finally, in order to evaluate more in depth, the seed yield variation of the common genotypes, tested in the different environments, a stability analysis was carried out as suggested by Wricke (1962), by means of the ecovalence value. The genotype CCE 26 resulted the most stable across locations reporting an ecovalence value of 0.108 followed by CCE42, and Alba had the lowest (Table 5). Thousand seed weight was significantly influenced by the main effect: genotype and environment (Table 4). Across countries, it ranged from 0.98 to 1.12 g, in Algeria and Italy, respectively (Fig. 9A), those values are in

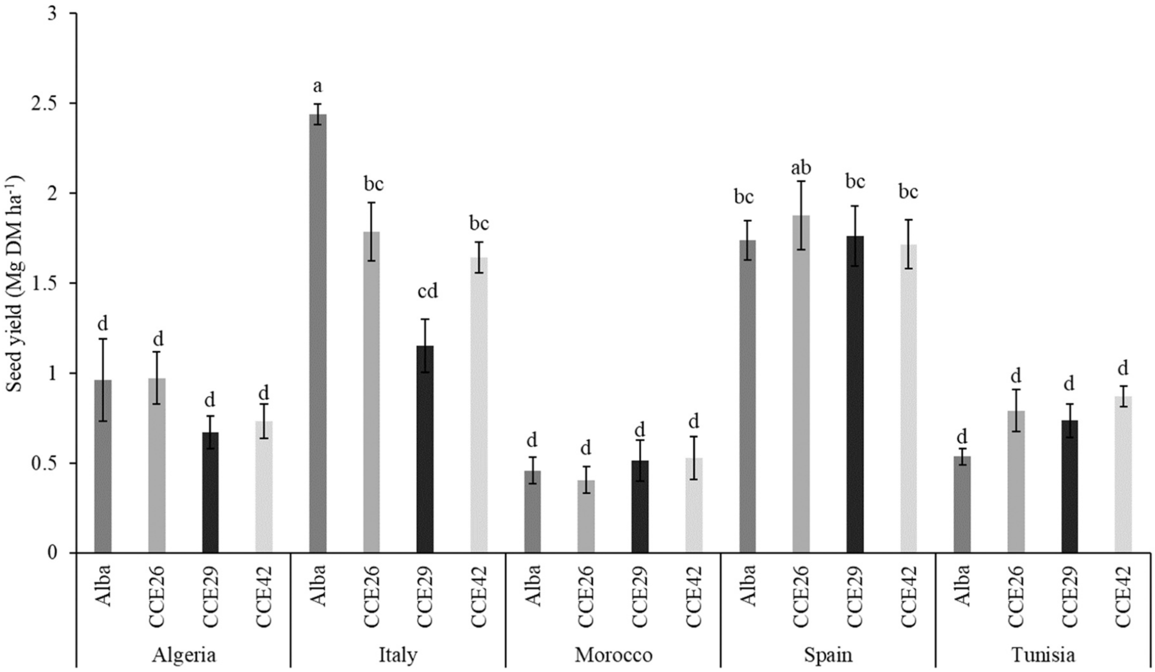

Fig. 8. Inter-location results for seed yield (Mg DM ha^{-1}) of 4 camelina lines at 5 different locations for two consecutive growing seasons (2020–22, except for Morocco, where only 2020–21 was included in the analysis). Interaction effect: environment x genotype. Different letters: significant different values ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

Table 5
Wrickes' ecovalence values for the common camelina genotypes (Alba, CCE26, CCE29, CCE42) across the five study environments.

Genotype	Algeria	Italy	Morocco	Spain	Tunisia	Ecovalence (W_i)	Ecovalence (% W_i)	Rank
ALBA	0.0016	0.627	-0.144	-0.161	-0.324	2.18	48.9	4
CCE26	0.0721	0.0349	-0.138	0.0384	-0.00787	0.108	2.41	1
CCE29	0.0256	-0.621	0.226	0.177	0.192	2.03	45.4	3
CCE42	-0.0993	-0.0409	0.0553	-0.0543	0.139	0.148	3.31	2

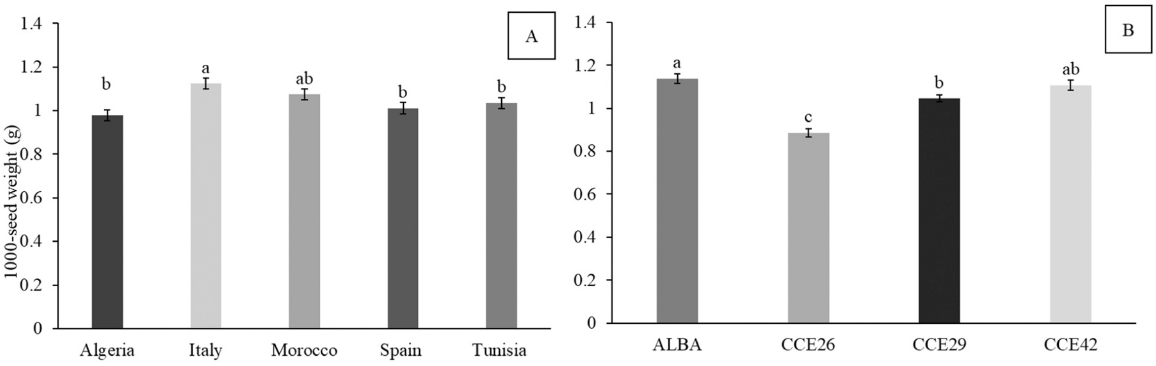

Fig. 9. Inter-location results for 1000-seed weight (g) of 4 camelina lines at 5 different locations for two consecutive growing seasons (2020–22, except for Morocco, where only 2020–21 was included in the analysis). Main effects: A) environment, and B) genotype. Different letters: significant different values ($P \leq 0.05$, HSD Tukey test). Vertical bars: standard error.

line to available literature (Berti el al., 2016; Zanetti et al., 2021). The CV for 1000-seed weight was the lowest among all the surveyed parameters (0.14), confirming the already reported lower susceptibility of this trait to environmental conditions, being presumably more under genetic control, as already evidenced in previous multi-location studies on camelina (Zanetti et al., 2017). Among tested genotypes Alba exhibited larger 1000-seed weight (Fig. 9B), while CCE26 showed the lowest value (0.89 g). Vollmann et al. (2007) indicated that genotypes with higher 1000-seed weight showed the lowest seed yield, however in this study Alba showed seed yields higher than the average (1.26 Mg DM ha^{-1} vs 1.08 Mg DM ha^{-1}, Alba vs. the grand mean of all the other genotypes, respectively) and 1000-seed weight (1.14 g vs. 1.01 g, Alba vs. the grand mean of all the other genotypes, respectively), thus contrasting the findings obtained in the previous study.

4. Conclusions

Camelina is a minor oilseed crop, which is attracting the interest of

Mediterranean farmers for its suitability to dry climates. Despite different studies reported the productive potential of the crop in different European countries, for the first time it was tested also in the southern shore of the Mediterranean sea, in African countries, such as Algeria, Morocco, and Tunisia. In the present study the potential of several genotypes of camelina under different European and African Mediterranean environments, and camelina confirmed to be generally well suited to the Mediterranean, a region which is predominantly vulnerable to the impacts of warming. Out of ten considered field trials only one failed, a fact that further testifies the high suitability and resilience of this crop. For the future development of camelina, from an industrial perspective, not only the potential yield of genotypes should be considered, but also their yield stability over years and environments. In this respect, CCE42 and CCE26 were the most stable genotypes in term of seed yield, while Alba had on average the highest seed yield and seed weight, across all test location. The productivity of CCE42 and CCE26 was only 11% and 5%, respectively lower than the commercial variety Alba; therefore, these varieties can be considered as promising varieties currently. Nevertheless, if the G x E results will be consistent in future years, Alba may continue to maintain superior yields, particularly in Italy, while CCE26 seems more promising in Spain, and CCE29 appears very poorly adapted to Italy while in all the other test countries it performed on average with all the other lines. Interestingly CCE42 was identified as an average and stable performer across all locations, and like Alba, it was characterized by heavier seeds, a quality trait highly important for farmers and processors, making the sowing and seed pressing phases easier.

CRediT authorship contribution statement

Andrea Monti: Writing – review & editing, Supervision, Funding acquisition. **Sara Berzuini:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Federica Zanetti:** Writing – original draft, Formal analysis. **Imen Trabelsi:** Writing – review & editing, Data curation. **Abderrahmane Hannachi:** Writing – review & editing, Data curation. **Sripada M Udupa:** Writing – review & editing, Data curation. **Barbara Alberghini:** Formal analysis, Data curation. **Paloma Leon:** Writing – review & editing, Data curation. **Javier Prieto:** Writing – review & editing, Data curation. **Yuri Herrera:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Federica zanetti reports financial support was provided by Partnership for Research and Innovation in the Mediterranean Area. Andrea Monti reports a relationship with Horizon Europe that includes: funding grants. Yuri Herrera reports a relationship with Horizon Europe that includes: funding grants. Imen Trabelsi reports a relationship with Horizon Europe that includes: funding grants. Sripada Udupa reports a relationship with Horizon Europe that includes: funding grants. Abderrahmane Hannachi reports a relationship with Horizon Europe that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Aguilera, E., Diaz-Gaona, C., Garcia-Laureano, R., Reyes-Palomo, C., Guzmán, G.I., Ortolani, L., Sanchez-Rodriguez, M., Rodriguez-Estevez, V., 2020. Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. Agric. Syst. 181 https://doi.org/10.1016/j.agsy.2020.102809.

Alberghini, B., Zanetti, F., Corso, M., Boutet, S., Lepiniec, L., Vecchi, A., Monti, A., 2022. Camelina [*Camelina sativa* (L.) Crantz] seeds as a multi-purpose feedstock for bio-based applications. Ind. Crop. Prod. 182 https://doi.org/10.1016/j.indcrop.2022.114944.

Alessandri, A., De Felice, M., Zeng, N., Mariotti, A., Pan, Y., Cherchi, A., Lee, J., Wang, B., Ha, K., Ruti, P., Artale, V., 2014. Robust assessment of the expansion and retreat of Mediterranean climate in the 21st century. Sci. Rep. 4 (1), 7211 https://10.1038/srep07211.

Berti, M., Gesch, R., Eynck, C., Anderson, J., Cermak, S., 2016. Camelina uses, genetics, genomics, production, and management. Ind. Crop. Prod. 94, 690–710. https://doi.org/10.1016/j.indcrop.2016.09.034.

Brock, J.R., Ritchey, M.M., Olsen, K.M., 2022. Molecular and archaeological evidence on the geographical origin of domestication for *Camelina sativa*. Am. J. Bot. 109 (7), 1177–1190. https://doi.org/10.1002/ajb2.16027.

Cullere, M., Singh, Y., Pellattiero, E., Berzuini, S., Galasso, I., Clemente, C., Dalle Zotte, A., 2023. Effect of the dietary inclusion of *Camelina sativa* cake into quail diet on live performance, carcass traits, and meat quality. Poult. Sci. 102 (6), 102650 https://doi.org/10.1016/j.psj.2023.102650.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440 (7081), 165–173. https://doi.org/10.1038/nature04514.

del Pozo, A., Brunel-Saldias, N., Engler, A., Ortega-Farias, S., Acevedo-Opazo, C., Lobos, G.A., Jara-Rojas, R., Molina-Montenegro, M.A., 2019. Climate change impacts and adaptation strategies of agriculture in Mediterranean-Climate Regions (MCRs). Sustainability 11 (10), 2769. https://doi.org/10.3390/SU11102769.

Doblas-Miranda, E., Alonso, R., Arnan, X., Bermejo, V., Brotons, L., De las Heras, J., Estiarte, M., Hódar, J.A., Llorens, P., Lloret, F., 2017. A review of the combination among global change factors in forests, shrublands and pastures of the Mediterranean Region: beyond drought effects. Glob. Planet. Change 148, 42–54. https://doi.org/10.1016/j.gloplacha.2016.11.012.

Gesch, R.W., Cermak, S.C., 2011. Sowing date and tillage effects on fall-seeded camelina in the northern corn belt. J. Agron. 103 (4), 980–987. https://doi.org/10.2134/agronj2010.0485.

Giorgi, F., 2006. Climate change hot-spots. Geophys. Res. Lett. *33* (8), L08707 https://doi.org/10.1029/2006GL025734.

Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. Glob. Planet. Change 63 (2), 90–104. https://doi.org/10.1016/j.gloplacha.2007.09.005.

Groeneveld, J.H., Klein, A., 2013. Pollination of two oil-producing plant species: Camelina (*Camelina sativa* L. Crantz) and pennycress (*Thlaspi arvense* L.) double-cropping in Germany. Glob. Change Biol. Bioenergy 6, 242–251. https://doi.org/10.1111/gcbb.12122.

Guardia, G., Abalos, D., García-Marco, S., Quemada, M., Alonso-Ayuso, M., Cárdenas, L. M., Dixon, E.R., Vallejo, A., 2016. Effect of cover crops on greenhouse gas emissions in an irrigated field under integrated soil fertility management. Biogeosciences 13 (18), 5245–5257. https://doi.org/10.5194/bg-13-5245-2016.

Guendouz, A., Hannachi, A., Benidir, M., Fellahi, Z., Frih, B., 2022. Agro-biochemical characterisation of *Camelina sativa*: a review. Agric. Rev. 43 (3), 278–287. https://doi.org/10.18805/ag.RF-230.

Gugel, R.K., Falk, K.C., 2006. Agronomic and seed quality evaluation of Camelina sativa in western Canada. Can. J. Pl. Sci. 86, 1047–1058.

Hergert, G.W., Margheim, J.F., Pavlista, A.D., Martin, D.L., Isbell, T.A., Supalla, R.J., 2016. Irrigation response and water productivity of deficit to fully irrigated spring camelina. Agric. Water Manag. 177, 46–53. https://doi.org/10.1016/j.agwat.2016.06.009.

Hernández, L., Sánchez de Dios, R., Montes, F., Sainz-Ollero, H., Cañellas, I., 2017. Exploring range shifts of contrasting tree species across a bioclimatic transition zone. Eur. J. For. Res. 136 (3), 481–492. https://doi.org/10.1007/s10342-017-1047-2.

Larsson, M., 2013. Cultivation and processing of *Linum usitatissimum* and *Camelina sativa* in southern Scandinavia during the Roman Iron Age. Veg. Hist. Archaeobot. *22*, 509–520, 10.1007/s00334-0 13-04 13-3.

Lionello, P., Scarascia, L., 2018. The relation between climate change in the Mediterranean region and global warming. Reg. Environ. Change 18 (5), 1481–1493. https://doi.org/10.1007/s10113-018-1290-1.

Masella, P., Martinelli, T., Galasso, I., 2014. Agronomic evaluation and phenotypic plasticity of *Camelina sativa* growing in Lombardia, Italy. Crop Pasture Sci. 65 (5), 453–460. https://doi.org/10.1071/CP14025.

Montero-Muñoz, I., Mostaza-Colado, D., Capuano, A., Mauri Ablanque, P.V., 2023. Seed and straw characterization of nine new varieties of *Camelina sativa* (L.) Crantz. Land 12 (2), 328. https://doi.org/10.3390/land12020328.

Potter, C., Klooster, S., Genovese, V., 2012. Net primary production of terrestrial ecosystems from 2000 to 2009. Clim. Change 115, 365–378. https://doi.org/10.1007/s10584-012-0460-2.

Righini, D., Zanetti, F., Monti, A., 2016. The bio-based economy can serve as the springboard for camelina and crambe to quit the limbo. OCL 23 (5), D504. https://doi.org/10.1051/ocl/2016021.

Royo-Esnal, A., Valencia-Gredilla, F., 2018. Camelina as a rotation crop for weed control in organic farming in a semiarid Mediterranean climate. Agriculture 8 (10), 156. https://doi.org/10.3390/agriculture8100156.

Sampath, A., 2009. Chemical Characterization of Camelina Seed Oil", MSc Thesis, Submitted to Graduate School-New Brunswick, Rutgers, The State University of New Jersey, USA. https://rucore.libraries.rutgers.edu/rutgers-lib/25894/PDF/1/play/.

Schilling, J., Freier, K.P., Hertig, E., Scheffran, J., 2012. Climate change, vulnerability and adaptation in North Africa with focus on Morocco. Agric. Ecosyst. Environ. 156, 12–26. https://doi.org/10.1016/j.agee.2012.04.021.

Vollmann, J., Moritz, T., Kargl, C., Baumgartner, S., Wagentristl, H., 2007. Agronomic evaluation of camelina genotypes selected for seed quality characteristics. Ind. Crop. Prod. 26 (3), 270–277. https://doi.org/10.1016/j.indcrop.2007.03.017.

Wricke, G., 1962. Uber eine methode zur erfassung der okologischen streubreite in feldversucen. *Z.* Pflanzenzucht. 47, 92–96.

Zanetti, F., Eynck, C., Christou, M., Krzyżaniak, M., Righini, D., Alexopoulou, E., Stolarski, M.J., Van Loo, E.N., Puttick, D., Monti, A., 2017. Agronomic performance and seed quality attributes of Camelina (*Camelina sativa* L. crantz) in multi-environment trials across Europe and Canada. Ind. Crop. Prod. 107, 602–608. https://doi.org/10.1016/j.indcrop.2017.06.022.

Zanetti, F., Gesch, W., R., Walia, K., M., Johnson, M.F.J., Monti, A., 2020. Winter camelina root characteristics and yield performance under contrasting environmental conditions. Field Crops Res. 252, 107794 https://doi.org/10.1016/j.fcr.2020.107794.

Zanetti, F., Alberghini, B., Marjanović, J., Grahovac, A., Rajković, N., Kiprovski, D., Monti, A, B., 2021. Camelina, an ancient oilseed crop actively contributing to the rural renaissance in Europe. A review. Agron. Sustain. Dev. 41, 1–18. https://doi.org/10.1007/s13593-020-00663-y.

Zubr, J., Matthäus, B., 2002. Effects of growth conditions on fatty acids and tocopherols in *Camelina sativa* oil. Ind. Crop. Prod. 15 (2), 155–162. https://doi.org/10.1016/S0926-6690(01)00106-6.