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Double-cropping autumn-sown camelina with food crops and pelargonic acid application

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A R T I C L E I N F O

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A B S T R A C T

Double-cropping systems represent a sustainable strategy to produce feedstock for the biobased industry without reducing food security, while simultaneously improving farmer profitability. Camelina [*Camelina sativa* (L.) Crantz], given its adaptability and short growth cycle, can serve as a winter intermediate crop, replacing fallow periods and preceding the establishment of typical summer food crops of the Mediterranean cropping systems. A two-year study (2022–2024) was conducted at the Experimental Farm of the University of Bologna to evaluate the agronomic performance, resource use efficiency, and economic profitability of two camelina varieties (CCE117 and CCE44, Camelina Company Spain) double-cropped with grain sorghum (*Sorghum bicolor* L.) and sunflower (*Helianthus annus* L.). Pelargonic acid was for the first time applied to camelina to accelerate camelina desiccation and advance harvest maturity, thereby enabling earlier establishment of the following crop. The application of 14.5 L ha^{-1} pelargonic acid bioherbicide on half of camelina strips (Cam-PA) allowed for an earlier harvest (7–15 d,) when compared to harvesting camelina at physiological maturity (Cam-FM). Cam-PA achieved the highest seed yield (Cam-PA:1.26 Mg DM ha^{-1} vs. Cam-FM: 0.91 Mg DM ha^{-1}), but had a lower seed oil content (Cam-PA: 26.1% vs. Cam-FM: 30.4%). Sunflower following Cam-PA achieved an average seed yield of 1.83 Mg DM ha^{-1}, resulting in 47% higher total seed production of the double-cropping system than of a sole-sunflower system; this double-cropping system also yielded the highest system gross revenue, €1675 ha^{-1}. By contrast, the camelina-sorghum sequence produced nearly 90% less seed yield than sole-sorghum system, which highlights the need for earlier-maturing hybrids and suggests that double-cropping with sorghum may be feasible when implemented in silage or biogas production.

1. Introduction

Next-generation cropping systems should aim to provide high productivity, while reducing their environmental footprint, by combining conventional agriculture with sustainable practices. Double-cropping is an agronomic practice in which two crops are grown sequentially on the same land within a single year, by cultivating the second crop after the first one has been harvested (FAO definition). According to Heaton et al. (2013), double-cropping could represent a sustainable strategy for intensification of crop production, as it may reduce fluctuation in yield while simultaneously providing ecosystem services (Sindelar et al., 2017; Moore and Karlen, 2014; Yang et al., 2023).

In recent years, several studies have identified camelina [*Camelina sativa* (L.) Crantz], belonging to the *Brassicaceae* family, as a promising oilseed crop for integration into current European cropping systems (Leclère et al., 2018; Pagani et al., 2024; Zanetti et al., 2021). Camelina represents an alternative to oilseed rape (*Brassica napus* L. var. Oleifera) and due to its agronomic plasticity, can be cultivated on marginal land or included within mixed cropping systems (i.e., intercropping, relay-cropping), as recently reported by Pagani et al. (2024) and Raimondi et al. (2025). Moreover, numerous studies conducted in continental climates or the northern USA have demonstrated that camelina is well-suited for double-cropping systems (Berti et al., 2015; Ceriani et al., 2024; Gesch and Archer, 2013; Leclère et al., 2018). Camelina seeds are rich in polyunsaturated fatty acids (~ 50% of total oil), proteins (24.5–31.7%), and amino acids, both essential (e.g., leucine, valine, lysine) and non-essential (e.g., glutamic and aspartic acids, arginine, proline) (Bătrîna et al., 2020; Zubr, 2003). Additionally, camelina seeds

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exhibit high levels of antioxidant compounds (e.g., phenolic acids, flavonoids, tocopherols and xanthophyll), minerals (e.g., phosphorus, manganese, calcium and iron) and vitamins (e.g., B_3, B_1 and B_5) (Zanetti et al., 2021; Zubr, 2010). Camelina oil content ranges between 28% and 49% with α-linolenic acid (C18:3) comprising approximately 28 – 50% of total fatty acid composition, while linoleic acid (C18:2) contributes around 15 – 23% (Krzyżaniak et al., 2019; Kurasiak-Popowska et al., 2019). The camelina nutritional profile has earned recognition for human health-promotion effects, especially via anti-inflammatory activity and positive impact on gastro-intestinal function (Ibrahim and El Habbasha, 2015; Rode, 2002; Terpinc et al., 2012, Zubr, 2010). Camelina has also been explored for bio-based material production, including packaging films, resins, bio-lubricants, adhesives and cosmetic products (Gursoy et al., 2018;Kim et al., 2015; Ionescu et al., 2015; Labanauskas et al., 2017)). Currently, the growing interest in camelina is largely driven by the suitability of its oil for the bioenergy sector, with high potential for conversion into Sustainable Aviation Fuel (SAF) (D'Ascenzo et al., 2024; Taheripour et al., 2022). Whereas camelina oil could contribute to the decarbonization and long-term sustainability of the aviation transport sector, its meal also may serve as a valuable ingredient for livestock feed. The integration of camelina meal into ruminant and monogastric diets appears to be a viable option as well as into conventional protein sources such as soybean. The favorable amino acid composition and fatty acid profile of camelina make its meal an ideal nutritional source for sustainable livestock systems (Aziza et al., 2010; Colombini et al., 2013; Halmemies-Beauchet-Filleau et al., 2018; Singh et al., 2025).

According to Berti et al. (2015), one of the main requirements for implementing double-cropping systems is a sufficiently long growing season and available moisture to ensure the cultivation of a second crop between the cycles of the main crops. Therefore, identifying optimal and locally-adapted cropping sequences is crucial to ensure the inclusion of new crops into existing European cropping systems without affecting food production, ease of agronomic management, and financial feasibility for farmers. Among agronomic strategies to address time constraints of double-cropping systems, shortening the duration of the first crop cycle may expand the sowing window for the subsequent one, thereby supporting adequate productivity of both components of the system. With this regard, harvest aids, including pre-harvest desiccant herbicides, have been investigated as management options able to accelerate crop dry-down and enable earlier harvest, although potential trade-offs depend on crop species, development stage and environmental conditions at the application moment (Calviño et al., 2002; Cubins et al., 2023; Du et al., 2013; Sintim et al., 2016).

From 2022–2023, total oilseed crop production in Europe increased by 0.9 million tons, mainly driven by a 14.2% increase in soybean (*Glycine max* L.) and a 5.3% increase in sunflower (*Helianthus annuus* L.) (EUROSTAT, 2024). In particular, sunflower production is forecast to increase by 3% by 2035, contributing to the overall expansion of oilseed crop production in Europe (European Commission, 2025). In 2023, sunflower cultivation in Italy covered about 120,000 ha (FAOSTAT, 2025). Sunflower is recognized as a resilient crop, due to its well-known abiotic stress tolerance (Debaeke et al., 2017; Lamichhane et al., 2022). Furthermore, recent advances in sunflower breeding, such as improvements in heat and drought tolerance, water-use efficiency, and responsiveness to high atmospheric CO_2, have made this crop even more suitable for cultivation in the Mediterranean basin (Giannini et al., 2022). Moreover, the development of earlier-maturing sunflower varieties enables the integration of this crop into double-cropping systems, as already demonstrated when sunflower was sown after the harvest of winter cereals (Debaeke et al., 2017).

In addition to sunflower, sorghum (*Sorghum bicolor* L.) represents an ideal candidate for the double-cropping system, due to its short growth cycle and limited input need. The global cultivation of sorghum has declined in recent years, mostly due to intensive cultivation of other staple crops. In Italy, sorghum is cultivated on about 41,000 ha, corresponding to 15% of the total sorghum cultivation area in Europe (FAOSTAT, 2025). As a species native of tropical regions, sorghum serves as a strategic alternative to conventional cereals in the current context of climate change (Awika, 2017; Hossain et al., 2022; Przybylska-Balcerek et al., 2024). Sorghum's drought-resistance and heat tolerance make this crop suitable for cultivation in water-limited environments, especially compared to crops such as maize (*Zea mays* L.) (George et al., 2022). Interest in sorghum derives from its potential use in both livestock feed and human nutrition, as a result of its beneficial compounds, especially phenols including phenolic acids, 3-deoxyanthocyanins, and condensed tannins (Dicko et al., 2006; Khalid et al., 2022; Taylor et al., 2006; Zheng et al., 2023). Currently, sorghum breeding programs for cold tolerance and early maturity are developing new hybrids with the aim to increase its suitability for double-cropping systems (Schaffasz et al., 2019; Srinivasa Rao et al., 2014; Zheng et al., 2023).

The main objectives of the present study were: ***i)*** to evaluate the feasibility of two different varieties of camelina as winter intermediates preceding the establishment of sunflower and sorghum in Northern Italy; ***ii)*** to compare the performance of sunflower and sorghum in a "business as usual" cropping system, established after winter fallow, with the same crops sown after the harvest of camelina in a double-cropping system; ***iii)*** to evaluate the efficacy of a pelargonic acid bioherbicide, derived from vegetable oils to accelerate harvest maturity of camelina and enable earlier sowing of the two main summer crops, sunflower and sorghum.

2. Materials and methods

2.1. *Cultural practices and experimental design*

The field experiment was carried out at the Experimental Farm of the University of Bologna in Cadriano (Bologna, 44°33' lat. N, 11° 21' E, 32 m a.s.l.), Northern Italy, over two growing seasons (2022–2024). Before sowing, soil samples were collected each year to assess the physical-chemical characteristics (Table 1). The study site is characterized by a clay loam soil (29% sand, 30% clay, 41% slit) and a typical north Mediterranean climate, with hot and dry summers and mild and wet winters (Metzger at al., 2005). The previous crop was winter wheat (*Triticum aestivum*) in both growing seasons. The experiment was designed as a strip plot design, where each strip covered an area of 0.130 ha in 2022–2023 and 0.175 ha in 2023–2024. Two camelina varieties (CCE117 and CCE44, provided by Camelina Company, Spain) were planted in two strips each, and the remaining strips were left fallow until the establishment of the summer crops (sunflower and sorghum) in their typical sowing date (early spring) in the growing area (business as usual: Sun-BAU, Sor-BAU). When camelina was approaching maturity and seed residual moisture was about 35% (Walia et al., 2018), half of each camelina strip was sprayed with pelargonic acid to accelerate desiccation and advance harvest maturity (Cam-PA). The remaining part of the strips reached physiological maturity and were harvested at ~10% residual seed moisture (Cam-FM). Accordingly, four camelina treatments were defined combining the two camelina varieties (CCE117 or CCE44) and the two harvesting moments (PA or FM): CCE117-PA, CCE44-PA, CCE117-FM, and CCE44-FM. Subsequently, in the sub-plots

Table 1
Main soil physical/chemical conditions of the experimental trials in the two growing seasons (2022–24).

Year	Location	Soil texture	pH in H_2O (%)	Organic C (g/kg)	N tot (g/kg)	Available Nutrients (mg/kg of soil)	
						P	K
2022–23	Cadriano	Clay loam	7.89	13.1	1.48	47	232
2023–24			7.61	11.5	1.24	77	187

the different summer crops were randomly planted within each main plot and sown after camelina sprayed with the pelargonic acid formulation (Sun-PA, Sor-PA) or otherwise camelina that physiologically matured (Sun-FM, Sor-FM). To minimize the effects of field variability, 5 pseudo-replicates were randomly sampled within each sub-plot. A summary of the experimental layout, including camelina varieties, maturity treatments, and the subsequent summer food crops is reported in Fig. 1.

Prior to sowing, the soil was ploughed to a depth of 0.30 m and harrowed. Subsequently, 100 kg ha^{-1} of diammonium phosphate (18–46 NP) fertilizer was incorporated in the field before sowing. Both camelina varieties were sown on the same dates, October 19, 2022, and November 15, 2023, using a mechanical cereal seeder (Damax, DSG MT 3, Italy) at a seeding rate of 7 kg ha^{-1} (Table 2). The interrow distance was 0.15 m and the sowing depth was 5 mm. In February, nitrogen was applied as top-dressed fertilizer at a rate of 60 kg N ha^{-1} in the form of urea (N = 46%) at stem elongation stage. No chemical inputs (i.e., herbicide, pesticide, fungicide) or irrigation treatments were applied on camelina. On May 20, 2023, and May 26, 2024, when the seed residual moisture content of both camelina varieties reached ~35%, a desiccant containing pelargonic acid formulation (Ager-Bi Universal, Novamont S.p.A., Italy) was applied on half of each strip of maturing camelina. The application rate was 14.5 L ha^{-1} of Ager-Bi Universal (a.i. 718 g L^{-1}) diluted in 200 L ha^{-1} of water.

For the food crop variety selection, the early-maturing sorghum hybrids for grain production, namely 'Icebergg' (APSOVSEMENTI, Italy) and 'Pegasus' (KWS Italia, Italy) were tested in 2022–23 and 2023–24, respectively. In addition, the 'Arabesk' hybrid (R.V. Venturoli, Italy) was tested as a very-early-maturing hybrid only in 2023–24. Regarding sunflower, the high-oleic and early-maturing sunflower hybrid 'MAS 808.OL' (Mas Seeds Italia, Italy) was tested in 2022–23, whereas in 2023–24, 'SY Asperio CLP' (Syngenta Italia, Italy), a medium-cycle and Clearfield® hybrid was used. Sorghum and sunflower were sown at rates of 14 kg ha^{-1} and 6 kg ha^{-1}, respectively, in 0.45-m spaced rows, using a pneumatic precision seeder (Gaspardo, MAGICA, Italy). The sowing depth was set at 30 and 40 mm for sorghum and sunflower, respectively. The sowing dates of sorghum and sunflower are reported in Table 2. For Sun-BAU and Sor-BAU cropping systems, prior to sowing, soil was ploughed at a depth of 0.3 m. Meanwhile sorghum and sunflower following camelina (i.e., Sor-PA, Sun-PA, Sor-FM, Sun-FM) were directly sown into camelina stubble left in the field. In the first growing season (2022–23), continuous precipitation after the harvest of Cam-PA allowed establishing Sor-PA, Sor-FM, Sun-PA and Sun-FM on the same sowing date, as reported in Table 2. Table 3 summarizes the key agronomic practices adopted in each food crop system.

Table 2
Sowing and harvest dates in both growing seasons of the study (2022–24) for camelina, sorghum and sunflower in the different cropping systems. Cam-PA = Camelina treated with pelargonic acid formulation; Cam-FM = Camelina Full Maturity; Sun-BAU = Sunflower Business As Usual; Sun-PA = Sunflower double-cropped with camelina treated with pelargonic acid formulation; Sun-FM = Sunflower double-cropped with camelina full maturity; Sor-BAU = Sorghum Business As Usual; Sor-PA = Sorghum double-cropped with camelina treated with pelargonic acid formulation; Sor-FM = Sorghum double-cropped with camelina full maturity.

	2022–23		2023–24	
Cropping system	Sowing date	Harvest Date	Sowing date	Harvest Date
Cam-PA	26 Oct	29 May	15 Nov	29 May
Cam-FM	26 Oct	6 Jun	15 Nov	14 Jun
Sun-BAU	5 Apr	25 Aug	9 Apr	3 Sep
Sun-PA	26 Jun	10 Oct	30 May	1 Oct
Sun-FM	26 Jun	10 Oct	26 Jun	19 Nov
Sor-BAU	6 Apr	25 Aug	9 Apr	3 Sep
Sor-PA	26 Jun	10 Oct	30 May	15 Oct
Sor-FM	26 Jun	10 Oct	26 Jun	19 Nov

2.2. Meteorological conditions

Daily meteorological data, including minimum and maximum air temperatures and precipitation, were monitored by the weather station located at the Experimental Farm of the University of Bologna in Cadriano (Bologna, Italy, 44°33' lat. N, 11°21' E, 32 m a.s.l) and reported in Table 4. Growing Degree Days (GDD) were calculated from sowing to harvest date for camelina, sunflower, and sorghum under each cropping system. The base temperatures applied were: 4°C for camelina, 6.7°C for sunflower, and 10°C for sorghum (Table 5) (Gerik et al., 2003; Gesch and Cermak, 2011; Schneiter and Miller, 1981).

2.3. Camelina seed yield and quality

Camelina was harvested at two different times: 1) after the application of pelargonic acid formulation (Cam-PA), and 2) at physiological maturity (Cam-FM). Both camelina varieties sprayed with pelargonic acid formulation (Cam-PA) were harvested on May 29, in 2023 and 2024. Camelina at physiological maturity (Cam-FM) was harvested on June 6, 2023, and June 14, 2024 (Table 2). Five areas (1 m^2 each) were harvested via manual cutting at soil level for each camelina variety (CCE117 and CCE44) within each treatment subplot (Cam-PA, Cam-FM) of every strip. Each sample was then threshed using a plot combine (Wintersteiger, Nursery Master, Austria) to determine seed yield (Mg DM ha^{-1}). Representative sub samples of seed and straw from each

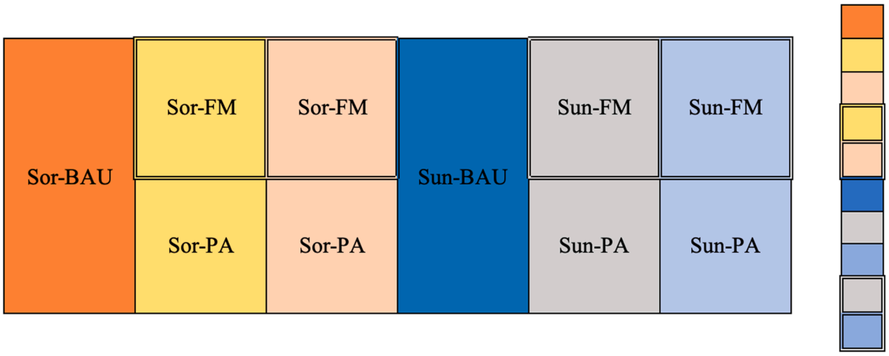

Fig. 1. Experimental design across the two growing seasons (2022–2023 and 2023–2024). The layout included two camelina varieties (i.e., CCE117 and CCE44), each managed under two maturity treatments (i.e., chemically desiccated with pelargonic acid formulation by Novamont (PA) or harvested at physiological maturity (FM), resulting in four camelina treatments: CCE117-PA, CCE44-PA, CCE117-FM, CCCE44-FM. Summer food crops (i.e., sorghum and sunflower) were established after the harvest of camelina sprayed with pelargonic acid formulation (Sor-PA, Sun-PA) or physiologically matured (Sor-FM, Sun-FM). "Business as usual" sole crops (Sor-BAU, Sun-BAU) were established in winter fallow strips.

Table 3
Summary of agronomic management practices applied to sorghum and sunflower in Sor-BAU, Sun-BA, Sor-PA, Sor-FM, Sun-PA, Sun-FM cropping systems, including basal fertilizer, top-dressing fertilizer, weed control, irrigation treatment in both growing seasons of the study (2022–24).

Agronomic practice	Sor-BAU	Sun-BAU	Sor-PA	Sor-FM	Sun-PA	Sun-FM
Pre-planting fertilization	100 kg ha^{-1} ammonium nitrate (34% N)					
Top-dressing fertilization	100 kg ha^{-1} urea (46% N)					
Weed control	1.25 L ha^{-1} Mondak 480 S (dicamba, 480 g a.i. L^{-1})	0.4 L ha^{-1} MAZA 4% SL (imaxamox, 40 g a.i. L^{-1})	1 L ha^{-1} of Primagram Gold (S-metoachlor, 312.5 g a.i. L^{-1}; terbuthylazine, 187.5 g a.i. L^{-1}) + Roundup Power 2.0 (glyphofosate, 360 g a.i. L^{-1})		1 L ha^{-1} Dual Gold (S-metolachlor, 960 g a.i. L^{-1}) + 2.5 L ha^{-1} Roundup Power 2.0 (glyphosate, 360 g a.i. L^{-1}).	
Irrigation	2 applications x 35 mm of water each (sprinkler system)					

Table 4
Monthly average temperature (°C) and cumulative precipitation (mm) recorded during the two growing seasons of the trial (2022–23 and 2023–24) compared with the long-term mean (2012–2021).

	Average temperature (°C)			Precipitation (mm)		
Month	2022–23	2023–24	2012–2021	2022–23	2023–24	2012–2021
November	10.0	9.0	9.8	111.4	39.2	38.5
December	6.4	6.1	4.4	64.6	11.8	75.1
January	5.8	4.0	3.5	51.8	70.0	50.3
February	5.4	8.6	6.0	14.2	34.4	53.7
March	10.7	11.8	9.0	29.0	37.0	64.9
April	12.2	14.3	13.6	31.4	32.2	43.5
May	17.2	18.1	17.8	276.2	15.4	27.5
June	23.0	23.0	23.1	55.6	42.8	40.7
July	26.5	27.1	25.6	16.0	44.4	55.4
August	25.3	26.6	24.9	23.0	165.0	52.4
September	22.3	20.4	20.2	15.6	136.4	83.4
October	18.0	16.9	15.1	56.0	111.6	38.2

Table 5
Growing degree days (GDD) and days from sowing to harvest of camelina (Cam-Pa and Cam-FM), sunflower (Sun-BAU, Sun-PA and Sun-FM) and sorghum (Sor-BAU, Sor-PA, Sor-FM) over the two growing seasons 2022–24.

Growing season	Crop	Cropping system	GDD	Crop cycle duration (d)
2022–23	Camelina[a]	Cam-PA	1282	215
		Cam-FM	1419	223
	Sunflower[b]	Sun-BAU	2053	142
		Sun-PA	1513	106
		Sun-FM	1513	106
	Sorghum[c]	Sor-BAU	1586	141
		Sor-PA	1159	106
		Sor-FM	1159	106
2023–24	Camelina[a]	Cam-PA	1266	196
		Cam-FM	1546	212
	Sunflower[b]	Sun-BAU	2324	147
		Sun-PA	2185	124
		Sun-FM	2206	146
	Sorghum[c]	Sor-BAU	1818	147
		Sor-PA	1862	138
		Sor-FM	1688	146

T base: a) 4°C (Gesch and Cermak, 2011), b) 6.7°C (Schneiter and Miller, 1981); c) 10°C (Gerik et al., 2003).

randomly harvested area were oven-dried for 24 h at 105°C until constant weight to determine the residual moisture content.

Thousand seed weight was determined on a representative seed sample for each treatment combination of camelina variety and harvesting stage (CCE44-PA, CCE117-PA, CCE44-FM, CCE117-FM) only in the growing seasons 2023–24. The Seed Counter S-25 machine by DATA Technologies (Tsor'a, Israel) was used to measure the 1000-seed weight at the Research and Analysis Laboratory (LaRAS) of the University of Bologna. The weight of camelina seeds was determined using a METTLER TOLEDO PC180 precision balance (Milan, Italy).

Seed oil extraction was performed following the procedure described by Zanetti et al. (2022) on representative samples of 1.5 g of ground camelina seeds for each treatment combination (CCE44-PA, CCE117-PA, CCE44-FM, CCE117-FM) using and Soxhlet extractor and n-hexane as organic solvent (60 mL, 2 h).

2.4. *Summer food crops production data*

Sorghum and sunflower were hand-harvested, sampling 5 areas (1 m^2 each) within each cropping system. The various cropping systems were harvested within three time windows: 1) Sor-BAU, and Sun-BAU were harvested between late August and early September, 2) Sor-PA and Sun-PA were harvested in October, and 3) Sor-FM and Sun-FM were harvested between October and November, as reported in Table 2. Capitula and panicles were manually removed from the whole biomass and threshed mechanically using a plot combine (Wintersteiger, Nursery Master, Austria). Seeds obtained were oven-dried at 105°C to a constant weight, then moisture content was collected, and finally seed yield (Mg DM ha^{-1}) was determined.

2.5. *System productivity and resource use efficiency*

The total production of the different double-cropping systems was evaluated over the two growing seasons (2022–24). Total production was estimated as the sum of the average seed yield of camelina + sorghum, and camelina + sunflower, express in mass (Mg DM ha^{-1}) (Yadav et al., 2005). For a more comprehensive comparison of production of the different cropping systems, the Summer Crop Equivalent Yield (SCEY) was estimated following Iboyi et al. (2023). With this method, camelina seed yield or "winter fallow" yield, which are non-summer crops, were converted into summer crop (i.e., sorghum, sunflower) equivalent yield (SCEY) using the market prices of summer crops observed by Bologna Borsa Merci e Prezzi (Camera di Commercio di Bologna, 2024) and reported in Table 7. SCEY formula used was the following:

$$\text{SCEY} = \text{Yield X} + (\text{Yield Y x Price Y}) \ / \ \text{Price X}$$

where X represents summer food crops (i.e., sorghum, sunflower), while Y indicates camelina or winter fallow.

Water use efficiency (WUE) was estimated as the ratio between seed yield (kg ha^{-1}) and crop water requirements (Et_c) for the summer food crops within each cropping system during the study period (Gao et al., 2019; Liu et al., 2022; Wu et al., 2024). As WUE was calculated using average yield values, no statistical analysis was performed. Crop water requirements (Et_c) were obtained by multiplying the crop coefficient (K_c) by the potential evapotranspiration (Et_0, mm d^{-1}). The crop coefficient (K_c) of sorghum and sunflower were determined according to crop phenology and divided in four growth stages: initial, crop development, mid-season and late season. Crop coefficient was assumed constant during the initial and mid-season stages. In contrast, during the crop development and late season, K_c was linearly interpolated between the value at the end of the previous stage and the value at the beginning of the following stage, as reported by FAO (FAO, 1998). The potential Et_0 was evaluated according to the Penmen-Monteith equation as follow:

$$Et_0 = \frac{0.408 \quad \Delta \quad (R_n - G) + \gamma[900/(T + \quad 273)]U_2 \quad (e_s - e_a)}{\Delta + \gamma \quad (1 + 0.34U_2)}$$

where Et_0 is the daily crop evapotranspiration rate (mm d^{-1}), Δ is the slope of the saturation vapor pressure curve (kPa $^{\circ}C^{-1}$), R_n is the net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa $^{\circ}C^{-1}$), T is the daily average temperature (°C), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturated vapor pressure (kPa), and e_a is the actual air vapor pressure (kPa).

Land use efficiency (LUE, %) was evaluated according to Yadav et al. (2005) by dividing the total duration of crop cycle included in monoculture and double-cropping systems by the duration of a growing season (365 d).

Finally, system gross revenue (€ ha^{-1}) was estimated only for the best performing camelina variety, CCE117, for all the different double cropping systems (i.e., Cam-Sor-PA, Cam-Sor-FM, Cam-Sun-PA, Cam-Sun-FM), as well as for the food crops in the business-as-usual scenarios (i.e., Sor-BAU and Sun-BAU), and the cropping systems including the summer food crops. The estimation was based on the mean seed yields recorded over the 2022–24 growing seasons and their corresponding market prices. Average prices of the component crops were derived from Bologna Borsa Merci e Prezzi (Camera di Commercio di Bologna, 2024) for sorghum (205 € Mg^{-1}) and sunflower (436 € Mg^{-1}). Camelina price was assumed to be 600 € Mg^{-1}, based on the average market value of camelina seeds grown as intermediate crop in Europe.

2.6. *Statistical analysis*

All statistical analyses were performed by using "RStudio" statistical software. Before analysis of variance (ANOVA), the homoscedasticity of data was verified by performing Levene's test ($P \leq 0.05$). Three different ANOVA were carried out: *i)* Two-way ANOVA on camelina data, with variety (CCE117, CCE44) and treatment (Cam-PA, Cam-FM) considered as "fixed factor", including their interaction (variety x treatment); *ii)* One-way ANOVA on food crops data, considering the "cropping system" in which sorghum and sunflower were included as the sole independent variable; *iii)* One-way ANOVA to assess differences in system gross revenue among cropping systems. When the ANOVA resulted significant ($P \leq 0.05$), Fisher's Least Significant Difference test was performed to separate means.

3. Results

3.1. *Meteorological data and crop cycle growth*

Monthly meteorological data (minimum and maximum temperatures and precipitation) of the 2022–24 growing seasons were compared to the long-term reference period (2012–2021) as reported in Table 4. During the 2022–23 season, the average temperature was 0.8°C higher than the long-term (2012–2021) mean value. The 2023–24 growing season was even warmer, with an increase of 1.1°C compared with the long-term data. During winter months, temperatures were generally above the long-term average, especially in December (+2.0°C in 2022 and +1.7°C in 2023), February (+2.6°C in 2024), and March (+1.7°C in 2023 and +2.7°C in 2024). Also, autumn months were generally warmer than the long-term data, in particular September (+2.1°C in 2022), and October both in 2023 (+2.9°C) and 2024 (+1.8°C). The meteorological trend throughout the study was predominantly dry, with below-average precipitation observed in both growing seasons. However, some months showed unusual precipitation patterns. For instance, in November 2022, 111 mm of precipitation were recorded, exceeding the 10-year average which reports only 38 mm. In May 2023, extreme precipitation events with 249 mm of rain led to field flooding. In 2024 the wettest months were August (165 mm), September (136 mm), and October (112 mm).

Regarding the observed camelina growth cycle, the period from sowing to harvest at the physiological maturity lasted 223 d in 2022–23, and 212 d in 2023–24 (Table 5). In terms of Growing Degree Days (GDD), Cam-FM completed its cycle in 1419 GDD in 2022–23 and 1546 GDD in 2023–24. Cam-PA was harvested 6 and 16 d earlier than Cam-FM in 2023 and 2024, respectively. Consequently, in terms of GDD, Cam-PA accumulated 1282 GDD and 1266 GDD in the 2022–23 and 2023–24 growing seasons, respectively (Table 5).

The duration of sorghum and sunflower growth cycles is reported in Table 5. The duration of the Sor-BAU cycle was consistent during the two growing seasons, lasting 141 d in 2022–23 and 147 d in 2023–24. By contrast, a marked difference was observed in terms of GDD accumulated, which corresponded to 1586 and 1818 GDD in 2022–23 and 2023–2024, respectively. For sunflower, the Sun-BAU cycle lasted 142 d in 2022–23 and 147 d in 2023–24, corresponding to 2053 and 2324 GDD, respectively. For both summer food crops in each cropping system, higher GDD values were recorded in 2023–24, likely due to the higher average temperatures during spring/summer months, especially in April (+2.1°C), May (+0.9°C), and August (+1.3°C) in comparison with 2022–23 (Table 5). In addition, Table 6 shows meteorological data (minimum, mean, and maximum temperature and cumulative precipitation) and GDD for sorghum and sunflower within each cropping system tested during 2023–24. Data are reported separately for the periods from sowing to flowering and from flowering to harvest. During the first growing stages, Sor-FM and Sun-FM recorded the highest temperatures (Tmax: 33°C), comparable to those observed in Sor-BAU and Sun-BAU after the flowering stage. By contrast, after Sun-BAU and Sor-BAU sowing, lower temperatures and limited precipitation were recorded. Sor-PA received the highest amount of precipitation during the maturation stage (~340 mm). Notably, precipitation was intense after the post-flowering stage for all cropping systems. Regarding GDD, crops sown in April (Sor-BAU, Sun-BAU) accumulated less GDD from planting to flowering compared to the following growth stages. By contrast, Sor-FM, Sun-PA, and Sun-FM accumulated lower GDD during the post-flowering stages rather than the pre-flowering period.

3.2. *Camelina seed yield and quality*

The two camelina varieties produced statistically significant different seed yields (Fig. 2). CCE 117 obtained the highest seed yield,

Table 6
Tmin (°C), Tavg (°C), Tmax (°C), precipitation (mm), and Growing Degree Days (GDD) from sowing to flowering and from flowering to harvest of sorghum and sunflower included in different cropping systems tested at the Experimental Farm of Bologna in 2023–24.

Phenological stage	Cropping system	Tmin (°C)	Tavg (°C)	Tmax (°C)	Precipitation (mm)	GDD
From sowing to flowering	Sor-BAU	12.3	18.1	24.2	69	602
	Sor-PA	17.8	24.4	31.0	89	779
	Sor-FM	20.1	26.8	33.7	179	992
	Sun-BAU	12.3	18.1	24.2	69	845
	Sun-PA	18.3	24.9	31.6	89	1167
	Sun-FM	20.0	26.7	33.7	209	1402
From flowering to harvest	Sor-BAU	19.9	26.4	33.2	230	1216
	Sor-PA	17.4	22.8	28.9	340	1083
	Sor-FM	13.2	17.3	22.2	279	696
	Sun-BAU	19.9	26.4	33.2	230	1479
	Sun-PA	18.0	23.5	29.6	301	1018
	Sun-FM	12.2	16.0	20.6	248	804

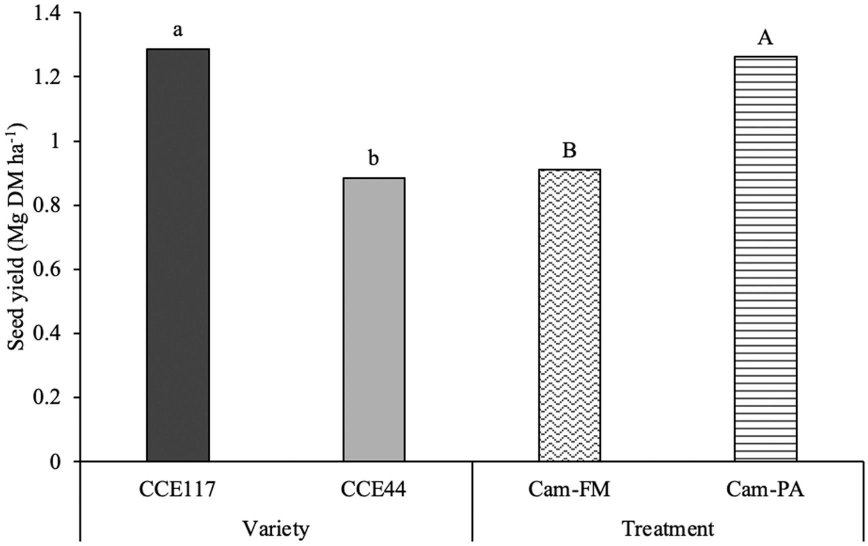

Fig. 2. Camelina seed yield (Mg DM ha^{-1}) obtained at the Experimental Farm of the University of Bologna for two consecutive growing seasons (2022–2024) in response to the main factors: variety (i.e., CCE 117 and CCE 44), and application of pelargonic acid (i.e., camelina sprayed with pelargonic acid formulation, Cam-PA, vs. camelina at full maturity, Cam-FM). Different letters: statistically different mean values within the same main factor ($P \leq 0.05$, LSD test).

with an average value of 1.29 Mg DM ha^{-1}, compared with CCE44 which had an average seed yield of 0.88 Mg DM ha^{-1}. Among the

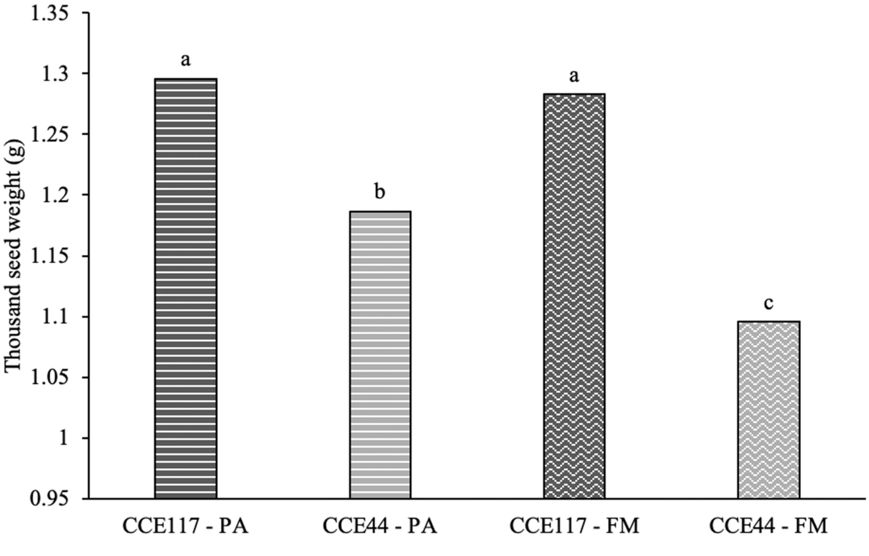

Fig. 3. Thousand seed weight (g) of two camelina varieties subjected to two different treatments: sprayed with pelargonic acid formulation (CCE 117-PA and CCE 44-PA) and full maturity (CCE 117-FM and CCE 44-FM) grown at the Experimental Farm of the University of Bologna in 2023–2024 growing season. A significant interaction between variety and treatment was detected. Different letters: statistically different mean values ($P \leq 0.05$, LSD test).

different treatments, Cam-PA had the highest seed yield (1.26 Mg DM ha^{-1}), in comparison with Cam-FM (0.91 Mg DM ha^{-1}) (Fig. 2).

Camelina 1000-seed weight (TSW) resulted as significantly affected by the interaction between variety and treatment, as shown in Fig. 3. CCE117 showed the highest TSW values, irrespective of the pelargonic acid application (CCE117-PA: 1.30 g vs. CCE117-FM: 1.28 g). Nevertheless, when analyzing the seed oil content (% DM), no significant differences were detected between the two varieties, with a mean value of 27.9% DM. On the contrary, the application of pelargonic acid (Fig. 4a) significantly reduced the seed oil content, (Cam-PA vs. Cam-FM reporting 26.1% vs. 30.4% seed oil content, respectively). Finally, oil yield (kg DM ha^{-1}) differed among varieties, with CCE117 and CCE44 recording 400 kg DM ha^{-1} and 287 kg DM ha^{-1}, respectively, whereas no significant differences were observed between Cam-PA and Cam-FM, which showed an average oil yield of 343 kg DM ha^{-1} (Fig. 4b).

3.3. Summer food crops seed yield

Regarding summer food crop yield, the productivity of sorghum was significantly affected by cropping system. Sor-BAU achieved an average seed yield of 6 Mg DM ha^{-1}, while Sor-PA or Sor-FM reached significantly lower seed yields, corresponding to 0.68 Mg DM ha^{-1} in Sor-PA and 0.86 Mg DM ha^{-1}in Sor-FM (Fig. 5). For sunflower, the seed yield obtained by Sun-BAU was statistically comparable to the productivity of Sun-PA (Fig. 6). However, Sun-FM seed yield was significantly lower (0.75 Mg DM ha^{-1}, $P \leq 0.05$).

3.4. System productivity and resource use efficiency

The cumulative seed yields of the tested double-cropping systems are reported in Fig. 7, obtained by adding camelina treatment yields to their corresponding summer crop yields. Sor-BAU, sown at the optimal sowing date, achieved the highest cumulative seed yield value compared with the double-cropping system with camelina, under both harvest treatments Sor-PA and Sor-FM, for which cumulative seed yield was reduced by 64% and 74%, respectively. When considering sunflower, the highest cumulative seed yield was observed in Cam-Sun-PA cropping system. The cumulative seed yield of Cam-PA + Sun-PA system was 47% higher than in the Sun-BAU system. On the contrary, the Cam-FM + Sun-FM system resulted in 21% lower cumulative seed yield than the BAU system.

System productivity, indicated by SCEY and reported in Table 7, was the highest for Sor-BAU (6000 kg ha^{-1}), followed by Cam-Sor-PA and Cam-Sun-PA, which obtained 4035 kg ha^{-1} and 3430 kg ha^{-1}, respectively. Excluding Sor-BAU, the highest SCEY values were achieved when camelina was included in the system, replacing fallow . In particular, the inclusion of Cam-PA in cropping systems led to the highest SCEY values. Finally, Sun-BAU produced the lowest SCEY of around 2100 kg ha^{-1}.

In both growing seasons, the highest WUE was achieved by Sor-BAU (~ 7 kg ha^{-1} mm^{-1}, Table 7). This value decreased when sorghum followed the harvest of Cam-PA and Cam-FM, as reported in Table 8. In 2022–2023, Sun-PA and Sun-FM achieved a WUE of 4.59 kg ha^{-1} mm^{-}1, recording a higher WUE in comparison with Sun-BAU which achieved 1.97 kg ha^{-1} mm^{-1}. By contrast, in the 2023–2024 growing season, Sun-BAU showed the highest WUE value corresponding to 3.04 kg ha^{-1} mm^{-1}, while the WUE for Sun-PA and Sun-FM were 2.85 and 1.96 kg ha^{-1} mm^{-1}, respectively (Table 8).

Furthermore, land-use efficiency (LUE) was affected by the growing season. The highest LUE was obtained by double-cropping system in which summer food crops followed Cam-FM in 2022–2023 (~ 90%) and in 2023–2024 (~ 98%). In both growing seasons, sorghum and sunflower grown in monoculture (Sor-BAU and Sun-BAU) recorded the lowest LUE (~ 40%), completing the growth cycle in approximately 140 d (Table 9).

Finally, system gross revenue differed significantly among cropping systems (Table 10). The highest economic return was observed in Cam-Sun-PA, which reached €1675 ha^{-1}, whereas Sor-BAU and Cam-Sun-FM showed intermediate performance and did not differ significantly from each other. Lower revenues were recorded for Cam-Sor-PA and Sun-BAU which obtained €1017 ha^{-1} and €912.9 ha^{-1}, respectively. Finally, Cam-Sor-FM resulted in the lowest economic return of €888 ha^{-1}.

4. Discussion

Camelina short growth cycle makes it a promising option that enables double-cropping before the establishment of typical summer food crops in the Mediterranean basin, especially sunflower. According to previous studies, the growth cycle of camelina sown in autumn ranged from 220 to 236 d in Italy, between 163 and 221 d in Spain, and up to 291 d in Poland (Berzuini et al., 2024; Czarnik et al., 2017; Masella et al., 2014; Royo-Esnal and Valencia-Gredilla, 2018). In the present study, the application of pelargonic acid desiccant allowed for an even shorter growth cycle, with Cam-PA harvested about 20 d earlier than in previous studies conducted in the same environment. Moreover, the application of pelargonic acid not only enabled an earlier harvest, but also allowed Cam-PA to significantly increase the seed yield (1.26 Mg DM ha^{-1}) in comparison with Cam-FM. Overall, the present production results were lower compared with those reported for autumn-sown camelina in other studies carried out in Italy and Europe (Berzuini et al., 2024; Ghidoli et al., 2023; Masella et al., 2014; Royo-Esnal and Valencia-Gredilla, 2018; Zanetti et al., 2017). Quinlan and Goslee (2025) demonstrated that excessive precipitation and wet soil significantly limit camelina

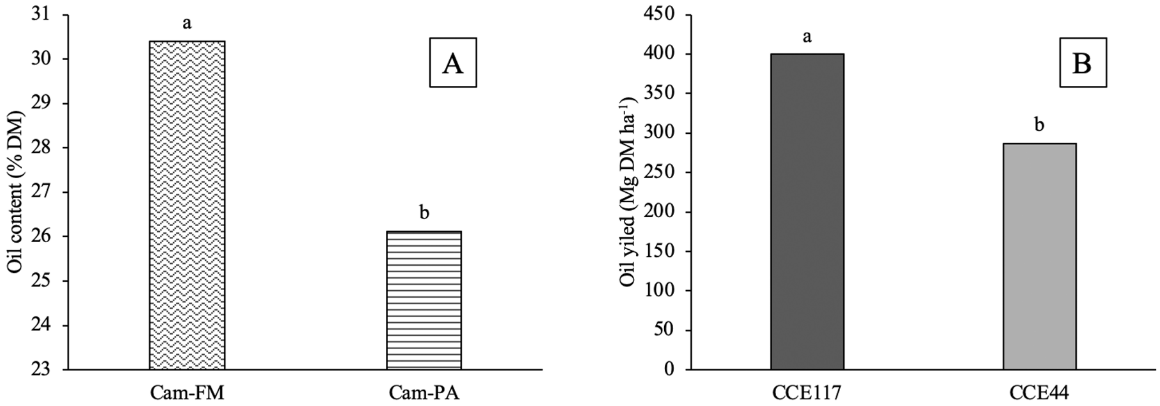

Fig. 4. A) Camelina seed oil content (% DM) in response to the application of pelargonic acid formulation (Cam-PA) compared with camelina harvested at full maturity (Cam-FM) for two consecutive growing seasons (2022–24). B) Camelina oil yield (kg DM ha^{-1}) in response to variety (CCE117 and CCE44) for two consecutive growing seasons (2022–2024). Different letters: statistically different mean values ($P \leq 0.05$, LSD test).

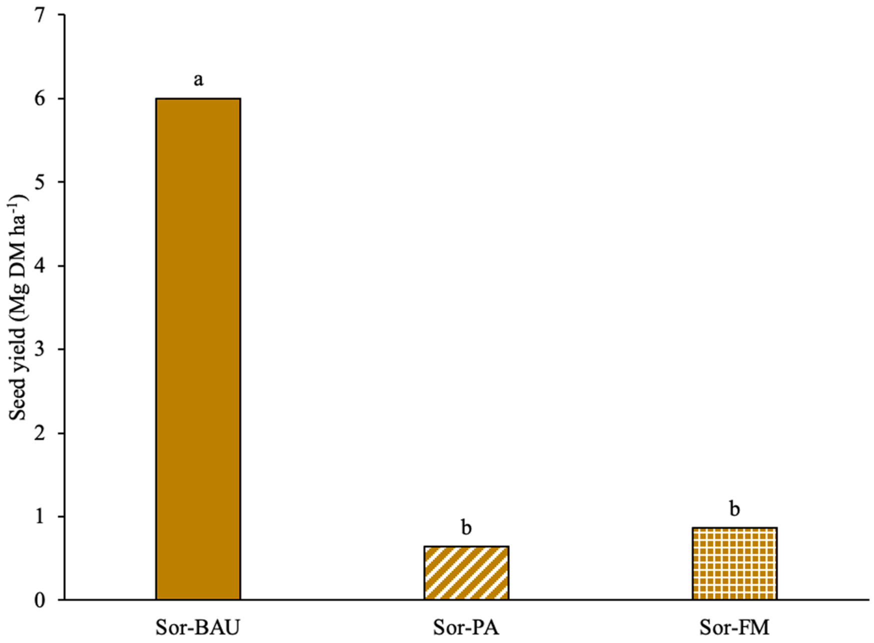

Fig. 5. Seed yield (Mg DM ha^{-1}) of sorghum grown at the Experimental Farm of the University of Bologna for two consecutive growing seasons (2022–24) in the "Business as usual" (Sor-BAU) in comparison with sorghum established after camelina sprayed with pelargonic acid formulation (Sor-PA) and after the harvest of camelina at full physiological maturity (Sor-FM). Different letters: statistically different mean values ($P \leq 0.05$, LSD test).

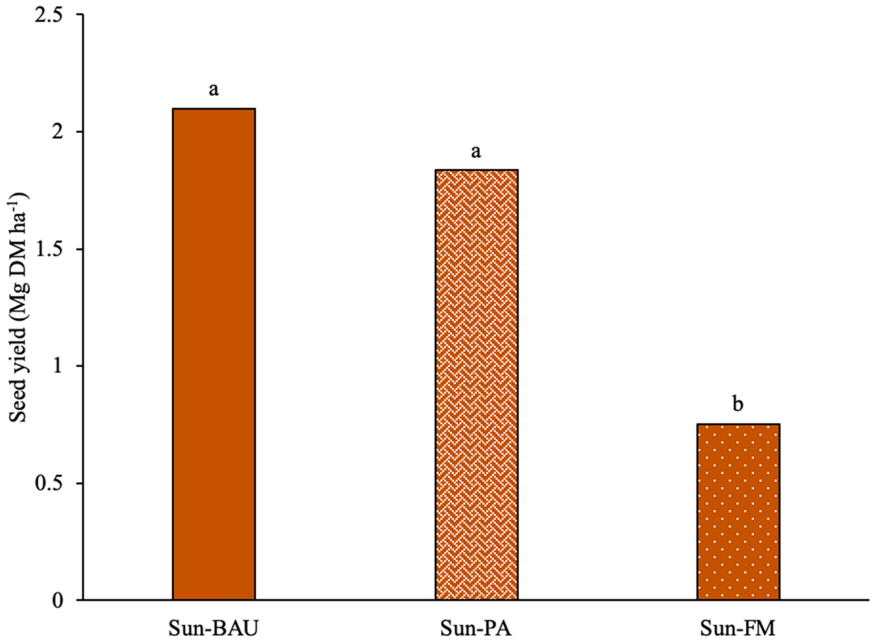

Fig. 6. Seed yield (Mg DM ha^{-1}) of sunflower grown at the Experimental Farm of the University of Bologna for two consecutive growing seasons (2022–2024) in the "Business as usual" (Sun-BAU) in comparison with sunflower established after camelina sprayed with pelargonic acid formulation (Sun-PA) and after camelina at full maturity (Sun-FM). Different letters: statistically different mean values ($P \leq 0.05$, LSD test).

growth, which is consistent with the conditions experienced during the growing seasons that comprise this study. Mediterranean climatic conditions allow spring camelina to be sown either in autumn or spring, with autumn sowing generally associated with higher productivity (Angelini et al., 2020; Czarnik et al., 2018; Zubr, 1997). Indeed, the spring camelina variety CCE117 demonstrated to be the most suitable option for the study site. The same varieties (CCE117 and CCE44) tested in the present experiment were previously evaluated in Spain where they achieved higher seed yield (Berzuini et al., 2024). Results from the present study were likely influenced by different experimental conditions, as they were obtained in open-field conditions in large strip plantings rather than in small plots, as is most commonly reported in the available literature. Nevertheless, in line with the present results, CCE44 showed lower productivity compared with CCE117 in Spain, despite the differences in pedo-climatic conditions (Berzuini et al., 2024). Additionally, variety CCE117 confirmed its superior performance, regardless of the agronomic management, producing heavier seeds, as indicated by a higher 1000-seed weight, and corroborating the findings of Berzuini et al. (2024). In contrast, variety CCE44 had significantly reduced seed weight when harvested at full maturity than after pelargonic acid

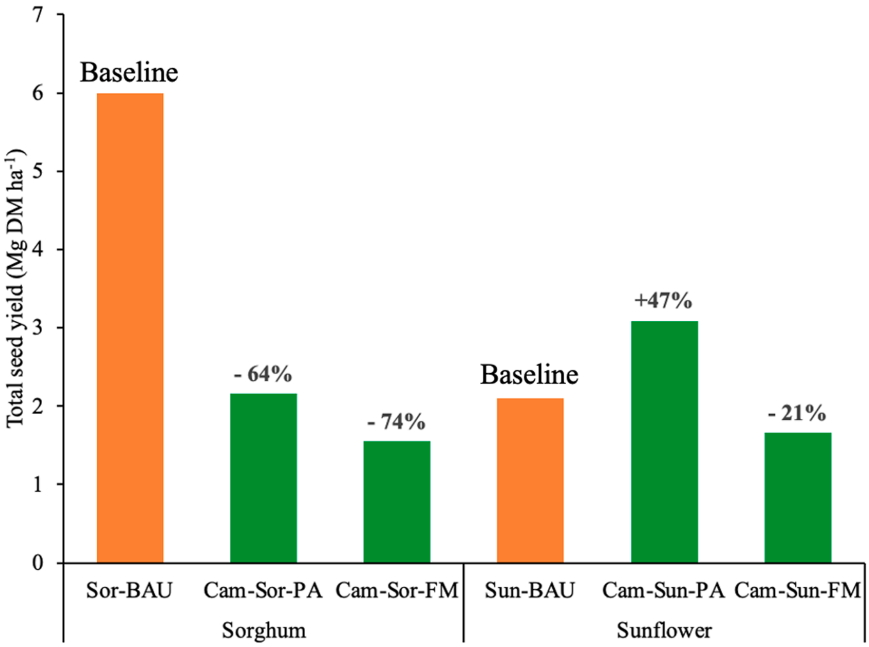

Fig. 7. Cumulative seed yield (Mg DM ha^{-1}) achieved by sorghum and sunflower in the business as usual (Sor-BAU, Sun-BAU) compared with the cumulative seed yields (i.e. camelina + sorghum or sunflower) obtained in the double-cropping systems sown after those grown after camelina sprayed with pelargonic acid formulation Cam-Sor-PA; Cam-Sun-PA) or after camelina at full maturity (Cam-Sor-FM; Cam-Sun-FM) across two growing seasons (2022–24) at Bologna experimental farm.

Table 7

Summer Crop Equivalent Yield (kg ha^{-1}) of all the cropping systems tested at the Experimental Farm of Bologna in 2022–24.

Cropping system	SCEY (kg ha^{-1})
Sor-BAU	6000
Cam-Sor-PA	4035
Cam-Sor-FM	3231
Sun-BAU	2100
Cam-Sun-PA	3430
Cam-Sun-FM	1867

Table 8

Crop evapotranspiration (Et$_c$, mm) and Water Use Efficiency (WUE, kg ha^{-1} mm^{-1}) of sorghum and sunflower included in different cropping systems tested at the Experimental Farm of the University of Bologna in 2022–23 and 2023–24.

Growing season	Cropping system	Et$_c$ (mm)	WUE (kg ha^{-1} mm^{-1})
2022–23	Sor-BAU	920	7.35
	Sor-PA	638	1.82
	Sor-FM	638	1.82
	Sun-BAU	799	1.97
	Sun-PA	392	4.59
	Sun-FM	392	4.59
2023–24	Sor-BAU	899	6.25
	Sor-PA	720	0.52
	Sor-FM	437	1.98
	Sun-BAU	863	3.04
	Sun-PA	654	2.85
	Sun-FM	383	1.96

(CCE44-PA: 1.18 g vs. CCE44-FM: 1.09 g, $P \leq 0.05$). Vollmann et al. (2007) suggested that larger-seeded camelina genotypes, such as CCE117, might be characterized by a lower seed oil content. In the present 2-year trial, no significant differences in seed oil content were detected between different camelina varieties, however CCE117 achieved a significantly higher oil yield in comparison with CCE44 (400 kg DM ha^{-1} vs. 287 kg DM ha^{-1}, respectively). CCE117 higher oil production was mainly driven by its superior seed yield rather than by differences in seed oil concentration, confirming the agronomic advantage of CCE117 at the system level.

Table 9

Land-use efficiency (LUE, %) of the different cropping systems tested at Bologna experimental farm in 2022–2024: sorghum and sunflower grown as sole crop (Sor-BAU, Sun-BAU), and double-cropped with camelina sprayed with pelargonic acid formulation (Cam-PA + Sor-PA; Cam-PA + Sun-PA) or harvested at full maturity (Cam-FM + Sor-PM, Cam-FM + Sun-FM) in 2022–24.

Crop	Cropping system	LUE 2022-23 (%)	LUE 2023-24 (%)
Sorghum	Sor-BAU	38.6	40.3
	Cam-PA + Sor-PA	87.9	92.1
	Cam-FM + Sor-FM	90.1	98.4
Sunflower	Sun-BAU	38.9	40.3
	Cam-PA + Sun-PA	87.9	88.2
	Cam-FM +Sun-FM	90.1	98.4

Table 10

System gross revenue (€ ha^{-1}) of all the cropping systems tested at the Experimental Farm of Bologna in 2022–24.

Cropping system	System gross revenue (€ ha^{-1})
Sor-BAU	1231^{b}
Cam-Sor-FM	888^{d}
Cam-Sor-PA	1017 ^{cd}
Sun-BAU	913^{d}
Cam-Sun-PA	1675^{a}
Cam-Sun-FM	1197^{bc}

Cam-PA showed a lower seed oil content in comparison with Cam-FM (26.1% vs. 30.4%, respectively, $P \leq 0.05$). One possibility is that, at the time of pelargonic acid application, camelina seeds had not yet reached the ceiling oil content, as in the case of seeds harvested at full physiological maturity. It is important to highlight that the pelargonic acid application timing was determined according to a previous study carried out in Minnesota, USA (i.e., 35% seed residual moisture, (Walia et al., 2018). Nonetheless, in the present experimental conditions, seeing as camelina undergoes a shorter growth cycle than in the Northern USA this moisture value would need climate-specific optimization to not impair oil accumulation in the seed. In any case, the resulting camelina seed oil contents are in the range (27–37% DM) of the values observed under comparable growing conditions (Pecchia et al., 2014; Zanetti et al., 2021; Zubr, 1997).

As the main goal of the study was to demonstrate the feasibility of double-cropping systems in Northern Italy, the trade-off between the achievement of the maximum seed oil content in camelina and the success of the second crop should be carefully considered. In the present study, sorghum yield in the "business as usual" cropping system was consistent with the values reported in the literature (Assefa et al., 2024; Staggenborg et al., 2008). It is notable that sorghum in Emilia Romagna region is a traditional summer crop able to achieve the highest seed yield in Europe, thus demonstrating the extreme suitability of this cereal to the local pedoclimate. For this reason, the results obtained by the Sor-BAU were well-expected. Otherwise, the yield reduction of about 90% from Sor-BAU to Sor-PA and 86% reduction from Sor-BAU to Sor-FM suggested that camelina-sorghum sequence is not suitable for the north Mediterranean basin.

In terms of system productivity (i.e., camelina + sorghum, Mg DM ha^{-1}) and economic return (i.e., SCEY, kg ha^{-1}), Sor-BAU outperformed double-cropping systems (i.e., Cam-Sor-PA; Cam-Sor-FM). Among the estimated parameters, LUE (%) was the only negative factor for Sor-BAU compared with the double-cropping system, highlighting inefficient use of the available land, which was only utilized in a range of 141–147 d, corresponding to an LUE value of 40%. While camelina-sorghum sequence did not perform well in terms of productivity, it did offer some environmental benefits. The inclusion of intermediate crops has been widely recognized as an effective strategy to reduce soil erosion and mitigate climate change through enhanced carbon storage (Blanco-Canqui et al., 2015; Kaye and Quemada, 2017). The efficient use of available land is becoming even more relevant considering that in Europe arable land decreased by 13% (~10 M ha) between 1993 and 2002 and is expected to decline further in the near future (FAOSTAT, 2025). The main problem facing the camelina-sorghum sequence was sorghum growth cycle duration, which proved too long for the specific pedo-climate. Therefore, despite the adoption of very early-maturing hybrids of sorghum, as available in the Italian market, the delayed sowing after camelina harvest did not allow sorghum to complete its growth cycle until seed production. Additionally, despite a good establishment, the crop suffered high temperatures and drought at flowering stage, which may have impaired seed setting. To further complicate the growth cycle, during ripening there was high precipitation (Sor-PA: 340 mm; Sor-FM: 279 mm) and a decreasing temperature pattern (Tmin-Sor-PA-: 17.4 °C; Tmin–Sor-FM-: 13.2 °C) leading to a "stay green" habit never reaching physiological maturity. By November of both study years, sorghum had not yet reached physiological maturity, while temperatures had already dropped and compromised further growth. This condition was also confirmed by WUE values: Sor-BAU recorded lower WUE values in comparison with those for C4 species reported in the literature (Holman et al., 2023; Tolk and Howell, 2003). In addition, in the camelina-sorghum sequences, a further reduction to WUE values can be attributed to the reduction in yield combined with lower evapotranspiration, mainly due to the lower temperatures in the second half of the growth cycle (Table 8). The reduction in seed yield observed in Sor-PA and Sor-FM corroborates previous studies that highlighted the importance of selecting the optimal sowing date for each crop to maximize production (Hu et al., 2022; Ji et al., 2025). As reported by Ji et al. (2025), the cultivation of sorghum should take place adequately early to allow the crop to accumulate the resources required to achieve a satisfactory yield before low temperature occurrence. Seeing as sorghum is a C4 plant, which has yet to take hold of Europe, the availability of very early maturing hybrids is still very limited. Additionally, because the crop boasts a versatile array of end-uses (food, feed, energy), in the case of delayed maturity, as for Sor-PA and Sor-FM, it would be possible to harvest the entire biomass and use it as feedstock for biogas production. Presumably, in the near future, the breeding effort for identifying early maturing hybrids will expand the possibility to grow this crop in northern EU countries, which could promote suitability for integration into double-cropping systems (Zabuloni et al., 2025).

Nevertheless, previous studies already demonstrated the success of winter camelina preceding the establishment of sunflower (Gesch et al., 2025; Lamichhane et al., 2022; Pitchers et al., 2023). The application of pelargonic acid formulation on camelina achieved comparable seed yield as in the BAU for double-cropped sunflower, whereas camelina seed yield was either increased by the application of pelargonic acid at expenditures of negligible reduction in seed oil content. However, in the present study, the decreased production of sunflower, 64% between Sun-BAU and Sun-FM, represents a higher decrease than what reported in the literature for similar studies carried out in the Northern USA (Gesch and Archer, 2013; Gesch et al., 2022). The decline in sunflower seed production was mainly related to the delayed sowing (Gesch et al., 2022; de la Vega and Hall, 2002; Zheljazkov et al., 2011). In the first growing season, both Sun-PA and Sun-FM were sown on the same date, since adverse weather conditions (i.e., field flooding occurring in May 2023) prevented entering the field any earlier. Therefore double-cropped sunflower was planted about 12 weeks later than Sun-BAU. In the second growing season, the sowing date of Sun-PA was delayed only 7 weeks compared with Sun-BAU, which caused a minimal seed yield reduction (12%). Conversely, the sowing of Sun-FM was delayed by 11 weeks causing delayed maturity, and consequent limited seed yield. In fact, despite similar sowing date as in the first growing season, in the second year Sun-FM sowing was delayed almost one month compared with that of Sun-PA (May 30 vs. June 26). This allowed the crop to benefit from 43 mm of precipitation that occurred in June, when temperatures were not yet extremely high; this promoted good establishment and early growth of the crop. On the other hand, Sun-FM was planted at the end of June, when temperatures were already very high. Although the application of external irrigation and some precipitation (~44 mm) recorded in June, the crop did not benefit from the soil moisture conditions that had characterized the first growing season (2023–24), when 276 mm of rainfall in May caused field flooding and increased residual soil moisture at sowing. Consequently, early crop growth was stunted. In addition, the later unusually high precipitation that occurred in August and September likely caused delays in growth, impaired flowering, and influenced the seed filling stage, all of which led to low yields.

According to previous studies, cultivating two crops in sequence within a single season generally reduces soil moisture content (Gesch et al., 2022; Gesch et al., 2025). Camelina is known for its limited water requirements, however, its inclusion in the double-cropping system may reduce soil water availability for subsequent crops. In 2022–23, unusually high-water availability, due to intense precipitation events in May 2023, reduced sunflower seed yield (Sun-BAU: 1. 57 Mg DM ha^{-1}) and, consequently, the WUE (WUE: 1.97 kg ha^{-1} mm^{-1}). Meanwhile, Sun-PA and Sun-FM achieved a higher WUE of 4.59 kg ha^{-1} mm^{-1} due to the proportionally greater reduction in evapotranspiration combined with increased yield (1.89 Mg DM ha^{-1}). Despite the reduction in evapotranspiration, the yield performance of Sun-PA and Sun-FM suggest the ability of sunflower to efficiently use water and its notable tolerance to water stress (Hussain et al., 2018). Consequently, comparable weather conditions in the 2023–24 growing season, when Sun-FM recorded a lower WUE, indicate that the yield decrease was likely due to delayed sowing rather than soil water shortage (Gesch et al., 2025). It is probable that the application of external irrigation in double-cropped sorghum and sunflower (Sor-PA, Sor-FM, Sun-PA, Sun-FM) was unable to fully compensate the water needs of the two crops at early stage. Irrigation also favored weed pressure, which had much greater impact in the double-cropped summer crop systems than in the sole-crop system. This was particularly true in the first growing season, while in the second growing season, the adoption of an herbicide-tolerant sunflower hybrid permitted a much easier weed control and overall management of the crop.

Camelina-sunflower sequences ensured land utilization for a longer period of the calendar year compared to Sun-BAU (LUE: ~40% vs. ~90%). Moreover, Cam-Sun-PA system achieved the highest system gross revenue among cropping systems (€1675 ha^{-1}, Table 10). Nevertheless, it is worth remarking that growing two crops within the same season resulted in higher production costs. In particular, additional expenses were associated with camelina sowing, fertilization, and harvesting. Furthermore, although pelargonic acid proved to be an effective strategy for anticipating camelina harvest and potentially increasing the yield of the following sunflower crop, its market price is still not set, as the product is pretty new in the market. From a preliminary calculation of these system revenues, it should be stated that pelargonic acid formulation price should not exceed 12 € L^{-1} (considering an application rate of 14.5 L ha^{-1}), in order to make its application profitable for farmer adoption in this type of double cropping systems. Achieving higher camelina seed yields than those obtained in the present study remains the most effective strategy to compensate for the additional cultivation costs and to increase the profitability of the double-cropping system, especially considering that greater camelina productivity has already been reported in Northern Italy (Berzuini et al., 2024; Ghidoli et al., 2023; Zanetti et al., 2017).

The findings of the present study are of particular interest as it demonstrates for the first time that double-cropping systems could represent an opportunity for famers in Northern Italy. Double-cropping can diversify production and reduce complete failure risk, while also earning farmers higher revenues than typical sole-crop systems, even in the case of a very productive crop, such as sorghum. Considering the market prices of the different crops, the most profitable option was Cam+Sun-PA (1675 € ha^{-1}).

5. Conclusion

Crop diversification is mandatory for the near and long-term sustainability of European agriculture, however, sustainable strategies should meet environmental goals while also satisfying the needs of farmers. Double-cropping systems appear as a feasible strategy for diversifying Northern Italy systems, particularly when camelina is included as a winter intermediate crop preceding sunflower. This crop combination achieved the optimal balance of sustainable land use and resources in harmony with additional revenue for farmers. So far, sunflower breeding programs have populated the market with a wide range of hybrids demonstrating variable precocity and resistance to herbicides, making their acceptance to farmers easier by simplifying overall system management. For sorghum, the available genetic materials are not yet suitable for the tested double-cropping systems in a grain production context. However, the same system can be feasible in the context of silage or biogas production. Camelina has confirmed its strong potential to enter European cropping systems, and not just on marginal lands. Its flexible growth cycle, low input and water requirements, and ongoing development of varieties with even shorter growth cycle will enable further development of double-cropping systems including camelina. The use of pelargonic acid to terminate the camelina had multiple advantages: *i)* improving its seed yield, and *ii)* anticipating the establishment of the following crop with increased yield results. Pelargonic acid represents an eco-friendly herbicide, as well an example of circularity, as the formulation used in the present study is produced directly from vegetable oil and could make EU agriculture less reliant on external inputs. The future large-scale deployment of double-cropping systems in Europe will encompass shared success stories of open field trials similar to those in the present study, carried out in the framework of international projects.

CRediT authorship contribution statement

Maria Giovanna Sessa: Writing – original draft, Formal analysis, Data curation. **ZANETTI FEDERICA:** Writing – original draft, Conceptualization. **Barbara Alberghini:** Data curation. **Dalila Villano:** Writing – review & editing. **Gian Maria Baldi:** Writing – review & editing. **Anna Ciancolini:** Writing – review & editing, Methodology. **Michele Falce:** Writing – review & editing. **Erika Facciolla:** Data curation. **Andrea Monti:** Writing – review & editing, Supervision, Funding acquisition.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andrea Monti reports financial support was provided by European Commission. Andrea Monti reports a relationship with European Commission 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.

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Data availability

Data are available at DOI: 10.5281/zenodo.17536096

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