

Article

Seeds Mineral Profile and Ash Content of Thirteen Different Genotypes of Cultivated and Wild Cardoon over Three Growing Seasons

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Abstract: Cultivated and wild cardoons are versatile plants with significant economic and bioactive potential. They have gained attention in recent years for their nutritional value and potential health benefits due to their high mineral content and unique composition. The aim of this study was to investigate the variations in mineral composition and ash content of thirteen distinct genotypes (four commercial, four wild, and five self-developed by Catania University) of cultivated and wild cardoon seeds over three consecutive growing seasons. The results showed that ash content and macro and micro-elements are significantly influenced by environmental conditions, genetic factors, and the interaction between both. For example, ash content showed notable fluctuations over the three seasons, with the lowest value recorded in season 2, probably linked to the higher rainfall level with respect to seasons 1 and 3. The genotypes self-developed showed the highest mean content of all micro-mineral elements under study, with Zn and Cu peaking in Linea 7. In general, it was reported that cardoon seeds are a valuable source of macro and micro-elements, highlighting, in particular, the potential of the genotypes developed by Catania University. This research provides, for the first time, valuable insights into the long-term consistency and variability of mineral content and ash composition in cardoon seeds, contributing to a more comprehensive understanding of their nutritional value and potential applications.

Keywords: cardoon; genotype; season; macro elements; micro elements; seed; *Cynara cardunculus*



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1. Introduction

Cynara cardunculus L. is a perennial plant native to the Mediterranean region. These herbaceous species belong to the Asteraceae family and comprise three botanical varieties: the ancestor, so-called wild cardoon or wild artichoke (*C. cardunculus* L. var. *sylvestris* (Lamk) Fiori), and its two descendants: cultivated cardoon (*C. cardunculus* L. var. *altilis* DC.) and globe artichoke (*C. cardunculus* L. var. *scolymus* L. Fiori) [1].

With a rich history dating back to ancient civilizations such as the Egyptians, Greeks, and Romans, cardoon has been cherished for both its culinary and medicinal properties [2]. Throughout the Mediterranean region, it has played a prominent role in traditional recipes, as its immature inflorescences are consumed fresh, canned, or frozen [3]. As mentioned,

it has also been used in traditional medicine as it aids in the treatment of liver diseases, diabetes, and heart conditions, and acts as a choleric and anti-hemorrhoidal agent [4–6]. Thus, in recent years, some research has revealed its rich content of bioactive compounds, making it appealing for various applications [7]. This plant is a valuable source of dietary fibers, minerals, inulin, and phenolic and antioxidant compounds [8–11].

Cardoon cultivation is concentrated in southern Europe, particularly in Italy, Spain, Portugal, Greece, and France [12,13]. Well-adapted to Mediterranean climates, where it thrives under conditions of hot, dry summers and mild, humid winters [14], this species tolerates abiotic stress and contributes to soil health by improving fertility and preventing degradation [15]. Its cultivation enhances soil microbial activity and nutrient content, including organic matter, nitrogen, potassium, and phosphorus [13,16,17].

Due to its diverse applications, cardoon has garnered growing industrial interest. It is consumed as a traditional and functional food [18–21], and its flowers are used as vegetable rennet in PDO (Protected Designation of Origin) cheeses from Portugal, Spain, and Italy [18,20,22]. Cardoon by-products serve as sustainable animal feed [23–26], and the plant is a promising bioenergy crop owing to its high biomass and low input needs [27–29]. It also finds uses in the paper, pharmaceutical, and cosmetic industries [18,23], and is increasingly cultivated for ornamental purposes [30].

Regarding the specific industrial uses of cardoon seeds, they are mostly used to obtain oil for human consumption or biodiesel [31–34]. Thus, the solid residues after oil extraction are also considered suitable for animal feed due to their high protein, fiber, and energy content, as well as their high digestibility [20,23,26,35]. Additionally, cardoon oil cakes are being explored for biodegradable and edible plastics, contributing to the circular economy and developing eco-friendly technologies [20,23,36]. Furthermore, cardoon seed has also been proven to have several pharmacological and nutraceutical properties [37,38].

Previous studies on cardoon seeds have investigated various aspects, including their chemical composition and biological activity. Mandim et al. [6] evaluated these factors across four maturity stages of a commercial cultivated cardoon genotype. Additionally, Mandim et al. [39] explored the chemical composition and ‘in vitro’ biological activities of cardoon seeds from another commercial cultivated cardoon genotype. Petropoulos et al. [11,25] conducted a series of studies investigating the chemical composition, including mineral compounds, and potential applications of cardoon. In 2018, they analyzed a commercial cultivated cardoon genotype, evaluating various extraction methods [11,25]. Subsequently, in 2019, they expanded their research to examine the bioactivities, chemical composition, and nutritional value of seeds from both wild and commercial cardoon genotypes [40]. Likewise, Angelova et al. [41] also evaluated these parameters of another commercial cultivated cardoon, while Piluzza et al. [42] evaluated only the phenolic compounds content and antioxidant capacity in cardoon seed from different head orders.

Thus, as far as we are concerned, no research has explored the influence of the genotype over multiple growing seasons on the mineral composition and ash content of different cardoon seeds. To address this research gap, this study analyses thirteen distinct genotypes of cardoon seeds across three consecutive growing seasons, providing insights into their nutritional value and stability. Understanding the variations in mineral profiles across different genotypes and growing seasons is crucial for evaluating the consistency and potential uses of cardoon seeds.

2. Materials and Methods

2.1. Field Research Site, Crop Management and Plant Materials

Plants were grown during three seasons (2017–2018, 2018–2019, and 2019–2020; hereafter referred to as S₁, S₂, and S₃, respectively) in an experimental field at the Catania plain,

Sicily (south Italy, 37°30' N. 15°4' E, 10 m a.s.l). The local climate is typically Mediterranean, with mild winters and hot, dry summers. The soil characteristics and meteorological variables are reported in Table 1. Sowing was carried out in a greenhouse at the beginning of August 2017, and seedlings, at the stage of three to four leaves, were transplanted in the field in mid-September 2017. Spacing was 1.25 m between rows and 0.8 m along the row, with a planting density of 1 plant m⁻². The plant material was arranged in a randomized block design with four replicates, with an experimental unit of 10 plants. The crop was grown for three consecutive seasons, during which the epigeal biomass was cut down in each season cycle (early August). Crop regrowth was carried out naturally following the September rains. Each season, the crop received about 50 mm of supplier water, 80 kg ha⁻¹ of nitrogen, and manual weeding. The harvest of epigeal biomass, heads enclosed, was performed each season at the end of July, when the plants were completely dried up. The achenes (seeds) were collected from the harvested heads.

Table 1. Meteorological variables and soil characteristics at the experimental field.

Parameter	
Meteorological variables	
Temperature min (°C) 2017 ^a	13.2
Temperature min (°C) 2018 ^b	13.1
Temperature min (°C) 2019 ^c	13.4
Temperature max (°C) 2017 ^a	23.8
Temperature max (°C) 2018 ^b	23.4
Temperature max (°C) 2019 ^c	24.0
Rainfall (mm) 2017 ^d	448.2
Rainfall (mm) 2018 ^e	758.1
Rainfall (mm) 2019 ^d	571.3
Soil characteristics	
Clay (<0.002 mm) (%)	46
Silt (0.02–0.002 mm) (%)	36
Sand (2–0.02 mm) (%)	18
Total N (%)	0.1
Organic Matter (%)	1.1
P ₂ O ₅ available (ppm)	11
K ₂ O (exchangeable) (ppm)	704
Electrical conductivity (mS cm ⁻¹)	0.2
pH	7.2
Cation exchange capacity (meq 100 g ⁻¹)	32.4
Ca (ppm)	5435
Mg (ppm)	308
Na (ppm)	216
K (ppm)	577
Fe (ppm)	118
Zn (ppm)	3.0
Mn (ppm)	162
Cu (ppm)	4.0

^a Average from August 2017 to July 2018. ^b Average from August 2018 to July 2019. ^c Average from August 2019 to July 2020. ^d Total from August 2017 to July 2018. ^e Total from August 2018 to July 2019.

The study involved thirteen genotypes of a germplasm collection (Table 2): four commercial cultivated cardoon varieties ('Cardo Avorio', 'Cardo Gobbo', 'Gigante Inerme', and 'Verde di Peralta'); four wild cardoon varieties ('Creta', 'Kamarina', 'Marsala', and 'Valparaiso'); and five selected lines from a cultivated cardoon crossing program ('Altilis 41', 'Linea 1', 'Linea 7', 'Linea 25', and 'Linea 32'). The cultivated cardoons are commercial varieties traditionally cultivated as vegetables in Mediterranean countries for their enlarged

blenched petioles. The wild cardoons are landrace genotypes collected from a population in Creta ('Creta'), the coast of Sicily ('Marsala', 'Kamarina'), and central Chile ('Valparaiso'). The cardoon lines were developed by the University of Catania (UniCT) from progenies obtained through controlled cloning of commercial varieties of cardoon and selected on the basis of their high biomass and phytochemicals yield production [43].

Table 2. List of genotype seeds selected, and acronyms used for this experiment, according to their plant material.

Plant Material	Genotype	Acronyms
<i>C. cardunculus</i> L. var. <i>altilis</i> DC.	Commercial CC	Gigante Inerme
		Verde di Peralta
		Cardo Gobbo
		Cardo Avorio
	CC developed by Catania University (UniCt)	GI
		VdP
		CG
		CA
		Altisil 41
		Linea 1
		Linea 7
		Linea 25
		Linea 32
<i>C. cardunculus</i> L. var. <i>sylvestris</i> (Lamk) Fiori	Wild Cardoon	Marsala
		Val Paraiso
		Kamarina
		Creta
		MA
		VP
		KA
		CR

CC: cultivated cardoon.

2.2. Sampling and Determination of Seed, Ash, and Mineral Content

At each growing season, about 1000 seeds per genotype and replicate were oven-dried at 65 °C (Binder, Milan, Italy), until a constant weight. The dry material was ground and used for the ash, macro-mineral (N, K, Mg, Ca, and Na), and micro-mineral (Zn, Fe, Mn, and Cu) determination. The ash content was determined by AOAC official method 923.03 (2005), which involved dry ashing in a muffle furnace at 550 ± 2 °C until a greyish-white ash was obtained. N determination was performed using the Kjeldhal method. The other minerals were determined following the AOAC official method (1995) using a Perkin Elmer AAnalyst 200 flame atomic absorption spectrometer (Norwalk, USA). The quantification of the mineral content in the sample was performed by calibration curves. All data presented are mean values of two independent experiments and expressed as g kg^{-1} and mg kg^{-1} of dry matter (DM), respectively, for macro and micro-element minerals. All the chemical products adopted for analyses were purchased from Sigma-Aldrich (Milan, Italy) and were of analytical grade.

2.3. Statistical Analysis

Bartlett's test was adopted to test for homoscedasticity, and then the data were subjected to a two-way analysis of variance (ANOVA), based on a factorial combination of "genotype (13) $\times$ growing season (3)". Means were separated by the Duncan test when the F-test was significant. Statistical analysis was performed using SPSS software package v. 20 for Windows (IBM Corp., Armonk, NY, USA). The genotypic coefficient of variation (CV%) was calculated for each mineral element. Standardized values were then subjected to principal component analysis (PCA) to identify the traits most effective in discriminating among genotypes. The first two principal components, which accounted for the greatest proportion of variance, were selected for ordination analysis. Correlations between the original traits and each principal component were calculated, with traits showing correlation coefficients greater than 0.6 considered relevant for that component [44]. The multivariate

analysis was performed with XLSTAT® statistical software version 2025 (Lumivero, Denver, CO, USA).

3. Results

The ANOVA results (Table 3) clearly indicate that both genotypes, growing season, and their interaction significantly affected the ash and mineral elements content of cardoon seeds.

Table 3. Mean square for each source of variation (percentage of total) resulting from analysis of variance.

Source of Variation	Degree of Freedom	Ash Content	Mineral Element								
			N	Ca	K	Mg	Na	Fe	Zn	Mn	Cu
Genotype (G)	12	11.4 ***	58.7 ***	19.1 ***	23.0 ***	14.0 ***	23.1 ***	16.5 ***	50.5 ***	57.6 ***	54.1 ***
Growing season (S)	2	81.5 ***	11.1 *	72.5 ***	73.0 ***	68.0 ***	23.1 ***	66.4 ***	38.7 ***	16.9 ***	33.9 ***
(G) × (S)	24	7.1 ***	30.1 ***	8.2 ***	4.1 ***	18.0 ***	53.8 ***	17.1 ***	10.8 ***	25.4 ***	12.0 ***

*** and * indicate significant at $p \leq 0.001$ and $p \leq 0.05$.

3.1. Influence of Genotype on Ash Content and Macro-Elements Content of Cardoon Seeds

The genotype significantly influenced ash and macro-elements. The most notable contribution was observed in N at 58.7% (Table 3).

On average, the commercial cultivated cardoon genotypes accumulated less N ($27.7 \text{ g kg}^{-1} \text{ DM}$) than both the cultivated cardoon developed by UniCT and the wild cardoon, respectively ($28.8 \text{ g kg}^{-1} \text{ DM}$) (Table 4). On the contrary, the commercial cultivated cardoon recorded the highest mean ash content ($38.1 \text{ g kg}^{-1} \text{ DM}$) with respect to the other genotype groups (approximately 3.9% more on average). Moving to the individual genotypes, it is worth noting that CR showed the highest N content ($31.0 \text{ g kg}^{-1} \text{ DM}$) and lower ash content ($32.8 \text{ g kg}^{-1} \text{ DM}$) with respect to the other genotypes under study. Regarding Ca content, the wild genotypes demonstrated a unique profile with the highest mean level ($3.12 \text{ g kg}^{-1} \text{ DM}$). Controversially, the genotypes developed by UniCT recorded the lowest mean Ca content ($2.26 \text{ g kg}^{-1} \text{ DM}$). Within the wild genotypes, MA revealed the highest amount, followed by KA (3.73 and $3.55 \text{ g kg}^{-1} \text{ DM}$, respectively). MA also stood out for the lowest K content among all genotypes under study ($1.18 \text{ g kg}^{-1} \text{ DM}$). The genotypes developed by Catania University showed the highest mean K content ($1.82 \text{ g kg}^{-1} \text{ DM}$), with A41 having a notable content of $2.18 \text{ g kg}^{-1} \text{ DM}$, which was the highest among all genotypes. Furthermore, the commercial genotypes exhibited the highest Mg and Na mean content among the three groups (1.43 and $0.21 \text{ g kg}^{-1} \text{ DM}$, respectively). In contrast, the genotypes developed by UniCT and the wild genotypes presented average reductions of approximately 5.6% and 7.0% in Mg content, respectively, and about 9.5% in Na content, compared to commercial genotypes.

Table 4. Ash content and macro-elements content ($\text{g kg}^{-1} \text{ DM}$) for different *Cynara cardunculus* genotype seeds.

Plant Material	Genotype	Ash Content	Macro-Elements				
			N	Ca	K	Mg	Na
Commercial CC	Gigante Inerme	$35.36 \pm 2.18 \text{ cd}$	$27.13 \pm 0.67 \text{ ab}$	$2.41 \pm 0.20 \text{ c}$	$1.91 \pm 0.08 \text{ f}$	$1.45 \pm 0.02 \text{ fg}$	$0.19 \pm 0.01 \text{ c}$
	Verde di Peralta	$33.60 \pm 1.18 \text{ ab}$	$28.58 \pm 0.92 \text{ de}$	$3.00 \pm 0.33 \text{ g}$	$1.68 \pm 0.02 \text{ c}$	$1.47 \pm 0.10 \text{ fg}$	$0.23 \pm 0.03 \text{ e}$
	Cardo Gobbo	$37.78 \pm 3.30 \text{ e}$	$26.90 \pm 0.17 \text{ a}$	$3.08 \pm 0.33 \text{ g}$	$1.79 \pm 0.03 \text{ e}$	$1.43 \pm 0.05 \text{ ef}$	$0.21 \pm 0.02 \text{ d}$
	Cardo Avorio	$45.78 \pm 6.44 \text{ h}$	$28.39 \pm 0.32 \text{ c-e}$	$3.00 \pm 0.35 \text{ g}$	$1.65 \pm 0.15 \text{ c}$	$1.39 \pm 0.08 \text{ de}$	$0.20 \pm 0.02 \text{ d}$
Mean ± SE		38.13 ± 2.03	27.75 ± 0.32	2.87 ± 0.15	1.76 ± 0.04	1.43 ± 0.08	0.21 ± 0.01

Table 4. Cont.

Plant Material	Genotype	Ash Content	Macro-Elements				
			N	Ca	K	Mg	Na
CC developed by Catania University	Altilis 41	41.65 ± 0.89 g	29.51 ± 0.25 fg	1.72 ± 0.17 a	2.18 ± 0.10 g	1.34 ± 0.03 cd	0.16 ± 0.02 a
	Linea 1	34.19 ± 2.66 bc	29.65 ± 0.38 g	2.08 ± 0.05 b	1.75 ± 0.13 de	1.22 ± 0.05 a	0.18 ± 0.00 c
	Linea 7	36.60 ± 1.26 de	27.88 ± 0.97 cd	2.29 ± 0.15 c	1.65 ± 0.08 c	1.30 ± 0.08 bc	0.18 ± 0.02 b
	Linea 25	35.38 ± 2.05 cd	28.49 ± 0.39 de	2.34 ± 0.39 c	1.70 ± 0.11 cd	1.38 ± 0.13 de	0.24 ± 0.04 f
	Linea 32	35.19 ± 2.53 c	28.39 ± 0.28 c-e	2.85 ± 0.41 f	1.78 ± 0.10 e	1.50 ± 0.16 g	0.21 ± 0.02 d
Mean ± SE		36.60 ± 0.96	28.78 ± 0.25	2.26 ± 0.13	1.82 ± 0.06	1.35 ± 0.05	0.19 ± 0.01
Wild Cardoon	Marsala	33.44 ± 2.15 ab	27.64 ± 0.67 bc	3.73 ± 0.46 i	1.18 ± 0.10 a	1.36 ± 0.10 d	0.21 ± 0.02 d
	Val Paraiso	39.44 ± 0.62 f	28.90 ± 0.22 ef	2.54 ± 0.32 d	1.82 ± 0.13 e	1.28 ± 0.09 b	0.21 ± 0.04 d
	Kamarina	41.46 ± 0.75 g	27.68 ± 0.20 bc	3.55 ± 0.31 h	1.96 ± 0.05 f	1.51 ± 0.07 g	0.18 ± 0.01 c
	Creta	32.77 ± 2.73 a	30.96 ± 0.47 h	2.67 ± 0.09 e	1.46 ± 0.08 b	1.17 ± 0.06 a	0.17 ± 0.02 b
Mean ± SE		36.78 ± 1.15	28.79 ± 0.35	3.12 ± 0.19	1.61 ± 0.08	1.33 ± 0.05	0.19 ± 0.01

CC: cultivated cardoon. Data are the mean ± standard error (SE). Different letters within each column show significant differences in ash content and macro-mineral content among all genotype seeds, respectively, according to Duncan test at $p \leq 0.05$. The bold values indicate the mean content among the different plant materials, respectively. The highest means values per trait are colored in green, while the lowest averages are colored in red.

However, both groups showed high variability, since within them were present the highest and lowest genotypes in the study for both macro-minerals. In wild cardoon, CR presented the lowest Mg level and KA the highest (1.17 and 1.51 g kg⁻¹ DM, respectively). Within cultivated cardoon developed by UniCT, A41 obtained the lowest Na level and L25 the highest among all the genotypes studied (0.16 and 0.24 g kg⁻¹ DM, respectively).

3.2. Influence of Genotype on Micro-Elements Content of Cardoon Seeds

The results of the analysis of variance ANOVA regarding the genotype showed a significant influence in all micro-elements, but especially in Mn at 57.6%, Cu at 54.1%, and Zn at 50.5% (Table 3). This indicates strong genetic control over these minerals.

As a general trend, genotypes developed by UniCT showed the highest mean content of all micro-elements under study, and commercial cultivated cardoon presented intermediate contents (Table 5). On the contrary, wild genotypes exhibit the lowest mean. Fe content for the cultivated cardoon developed by UniCT was slightly higher than that obtained for the commercial cultivated cardoon (26.8 and 26.0 mg kg⁻¹ DM, respectively). However, it is worth mentioning that the genotype that obtained the highest Fe level among all, CA, was a commercial cultivated cardoon with a content of 42.6 mg kg⁻¹ DM. Regarding the wild genotypes, MA and CR stood out for the lowest content of Fe (18.1 and 16.8 mg kg⁻¹ DM, respectively) and Zn (4.38 and 4.42 mg kg⁻¹ DM, respectively). This group exhibited an average Zn content of 5.89 mg kg⁻¹ DM, displaying a reduction of 58.2% and 61.2% compared to commercial cultivated cardoon and university-developed genotypes, respectively. Moving on to the individual genotypes within the cultivated cardoon developed by UniCT, the highest Zn level was displayed for genotype L7 (20.0 mg kg⁻¹ DM), which, in turn, also had the highest content of Cu (6.52 mg kg⁻¹ DM). In contrast, L1 exhibited the lowest Cu and Mg levels (4.03 and 8.09 mg kg⁻¹ DM, respectively) with respect to the other genotypes under study. Despite this, the cultivated cardoons developed by UniCT yet again exhibited the highest Cu and Mg content (5.07 and 9.70 mg kg⁻¹ DM, respectively).

Table 5. Micro-element content (mg kg^{−1} DM) for different *Cynara cardunculus* genotype seeds.

Plant Material	Genotype	Micro-Elements			
		Fe	Zn	Mn	Cu
Commercial CC	Gigante Inerme	16.25 ± 3.16 a	9.51 ± 1.48 c	8.92 ± 0.17 c	5.10 ± 0.38 ef
	Verde di Peralta	21.09 ± 2.28 b	15.01 ± 1.67 e	10.43 ± 0.67 e	5.71 ± 0.09 g
	Cardo Gobbo	23.96 ± 1.02 d	15.18 ± 1.65 e	8.82 ± 0.46 bc	4.07 ± 0.20 a
	Cardo Avorio	42.65 ± 10.31 h	16.61 ± 2.41 f	10.25 ± 0.31 e	4.60 ± 0.36 b–d
Mean ± SE		25.99 ± 3.32	14.08 ± 1.03	9.60 ± 0.26	4.87 ± 0.18
CC developed by Catania University	Altilis 41	27.23 ± 9.36 e	16.69 ± 2.95 f	8.78 ± 0.35 bc	4.49 ± 0.11 bc
	Linea 1	23.18 ± 2.13 cd	9.01 ± 0.23 c	8.09 ± 0.54 a	4.03 ± 0.23 a
	Linea 7	21.87 ± 3.74 bc	20.00 ± 2.10 h	10.43 ± 0.22 e	6.52 ± 0.17 h
	Linea 25	35.72 ± 7.44 g	12.52 ± 2.32 d	11.53 ± 0.72 f	5.45 ± 0.31 fg
	Linea 32	26.18 ± 1.47 e	17.61 ± 1.52 g	9.65 ± 0.60 d	4.87 ± 0.21 de
Mean ± SE		26.84 ± 2.54	15.17 ± 1.12	9.70 ± 0.31	5.07 ± 0.18
Wild Cardoon	Marsala	18.08 ± 2.25 a	4.38 ± 1.15 a	8.41 ± 0.44 ab	4.83 ± 0.28 c–e
	Val Paraiso	35.20 ± 9.39 g	7.31 ± 0.93 b	8.96 ± 0.10 c	5.37 ± 0.19 fg
	Kamarina	29.71 ± 4.16 f	7.46 ± 0.72 b	10.66 ± 0.39 e	4.83 ± 0.17 c–e
	Creta	16.78 ± 5.49 a	4.42 ± 0.47 a	9.01 ± 0.31 c	4.26 ± 0.25 ab
Mean ± SE		24.94 ± 3.20	5.89 ± 0.51	9.26 ± 0.24	4.82 ± 0.13

CC: cultivated cardoon. Data are the mean ± standard error (SE). Different letters within each column show significant differences in micro-mineral content among all genotype seeds, respectively, according to Duncan test at $p \leq 0.05$. The bold values indicate the mean content among the different plant materials, respectively. The highest means values per trait are colored in green, while the lowest averages are colored in red.

3.3. Influence of Different Growing Seasons on Ash Content and Mineral Content

The ANOVA outcomes showed that the growing season had a pronounced effect on ash content (81.5%) and some mineral elements, particularly K (73.0%), Ca (72.5%), Mg (68.0%), and Fe (66.4%) (Table 3).

The influence of different growing seasons on the ash content as well as macro- and micro-elements in cardoon seeds was investigated over three consecutive growing seasons (Table 6). Ash content showed notable fluctuations over the three seasons, with the lowest value recorded in S₂ (35.7 g kg^{−1} DM), followed by S₃ (37.9 g kg^{−1} DM) and the highest in S₁ (41.7 g kg^{−1} DM). The concentration of macro-elements in cardoon seeds also varied significantly across the three growing seasons: S₁ likewise exhibits the highest Na level (0.21 g kg^{−1} DM). By contrast, S₂ showed the lowest Na content, along with S₃ (on average 0.19 g kg^{−1} DM). The N content remained relatively stable between S₁ and S₂ (on average 28.3 g kg^{−1} DM), with a slight increase observed in S₃ (28.7 g kg^{−1} DM). S₃ also recorded the highest level of both K and Mg (1.90 and 1.50 g kg^{−1} DM, respectively). Mg content decreased progressively from S₃ to S₁ (−14.7%). Additionally, the lowest Ca content was observed in S₁ (2.16 g kg^{−1} DM). This macro-mineral level peaked in S₂ (3.22 g kg^{−1} DM), as well as for the micro-minerals Fe and Zn (32.4 and 14.5 mg kg^{−1} DM, respectively). The minimum level for Fe and Zn was recorded for S₃ and S₁, respectively (17.4 and 10.3 mg kg^{−1} DM). Nevertheless, S₁ and S₂ exhibit the highest Mn content (on average 9.69 mg kg^{−1} DM) and S₃ the lowest (9.23 mg kg^{−1} DM). Conversely, the last season, along with S₂, recorded the highest Cu levels (on average 5.08 mg kg^{−1} DM), while S₁ had the lowest, with a content of 4.62 mg kg^{−1} DM.

Table 6. Ash content, macro-element content, and micro-element content of *Cynara cardunculus* seeds for different consecutive growing seasons.

		Growing Season		
		Season 1	Season 2	Season 3
Ash Content (g kg ^{−1} DM)		41.70 ± 1.47 c	35.73 ± 1.18 a	37.95 ± 0.59 b
Macro-elements (g kg ^{−1} DM)	N	28.33 ± 0.27 a	28.34 ± 0.27 a	28.74 ± 0.38 b
	Ca	2.16 ± 0.11 a	3.22 ± 0.20 c	2.75 ± 0.13 b
	K	1.79 ± 0.05 b	1.51 ± 0.06 a	1.90 ± 0.05 c
	Mg	1.28 ± 0.02 a	1.32 ± 0.05 b	1.50 ± 0.04 c
	Na	0.21 ± 0.01 b	0.19 ± 0.01 a	0.19 ± 0.01 a
Micro-elements (mg kg ^{−1} DM)	Fe	28.21 ± 3.12 b	32.36 ± 3.30 c	17.41 ± 1.16 a
	Zn	10.26 ± 1.01 a	14.47 ± 1.41 c	11.20 ± 1.18 b
	Mn	9.73 ± 0.24 b	9.65 ± 0.33 b	9.23 ± 0.26 a
	Cu	4.62 ± 0.18 a	5.10 ± 0.17 b	5.07 ± 0.17 b

Data are the mean of all genotypes ± standard error (SE). Different letters show significant differences in ash content and mineral content among growing seasons, according to Duncan test at $p \leq 0.05$. The highest means values per trait are colored in green, while the lowest averages are colored in red.

3.4. Influence of the ‘Genotype × Growing Season’ Interaction on Ash and Macro-Elements Content of Cardoon Seeds

The results of the analysis of variances (ANOVA) indicate that the interaction between genotype and growing season contributed significantly, albeit to a lesser extent than the other factors (Table 3). The interaction effects were particularly prominent for macro-elements Na (53.8%), N (30.1%), and Mg (18.0%).

The influence on the ash content and macro-elements content (N, Ca, K, Mg, and Na) resulting from the interaction of cardoon seed genotypes across three consecutive growing seasons (S₁, S₂, and S₃) is represented in Figure 1. The ash content of cardoon seeds exhibits significant variability both among different genotypes and across different growing seasons. A remarkably general season trend can be observed: S₂ was characterized by a reduction of 23.9% and 16.4% with respect to S₁ and S₃. In addition, all genotypes in S₂ showed the lowest ash content, except for A41 and KA. This tendency was particularly noticeable for commercial cultivated cardoon, which showed the lowest average ash content in S₂ compared to the other groups and growing seasons (29.5 g kg^{−1} DM). The lowest values were detected in CR, followed by L1 (24.2 and 25.8 g kg^{−1} DM, respectively). In contrast, genotype CA consistently shows the highest ash level across all growing seasons, with a marked peak in S₁ (65.6 g kg^{−1} DM).

A similar seasonal trend was found in K content, with S₂ also showing the lowest level, with a reduction of 15.6% and 20.5% compared to S₁ and S₃, respectively. However, in this case, the lowest mean values were found in wild genotypes (1.38 g kg^{−1} DM), especially in MA and CR (0.88 and 1.22 g kg^{−1} DM, respectively). The highest K level was recorded in S₃ for the cultivated cardoon developed by UniCT, with an average content of 2.01 g kg^{−1} DM. Within this group, A41 consistently showed the highest K content, peaking in that season at 2.34 g kg^{−1} DM. In the same way, the highest N and Mg content was also recorded in S₃ for university-developed genotypes, with an average level of 29.4 and 1.60 g kg^{−1} DM, respectively. Genotypes like VdP and CR highlight the highest N content (31.2 and 31.3 g kg^{−1} DM, respectively). In turn, genotypes such as L32 and L25 stood out with the highest Mg content (1.98 and 1.80 g kg^{−1} DM, respectively). On the contrary, the lowest amount among groups was likewise found within university-developed genotypes in S₂ for Mg and Na elements (on average 1.14 and 0.14 g kg^{−1} DM, respectively). That season also showed the lowest Ca level, in particular in the cultivated cardoon developed

by UniCT (on average $1.71 \text{ g kg}^{-1} \text{ DM}$). Conversely, all commercial genotypes accumulated the highest content of Ca in season 2 (on average $3.82 \text{ g kg}^{-1} \text{ DM}$, respectively). A similar trend was found in wild cardoon for Ca content (on average $3.81 \text{ g kg}^{-1} \text{ DM}$) with MA and KA genotypes peaking in that season (5.15 and $4.50 \text{ g kg}^{-1} \text{ DM}$, respectively). Quite the reverse was observed for Na levels, which had their highest mean content in S_1 , like VP, and the lowest in S_2 , with the exception of some commercial genotypes, such as VdP.



Figure 1. Ash and macro-mineral content of *Cynara cardunculus* seeds in relation to ‘genotype $\times$ growing season’ interaction. Different letters show significant differences, according to Duncan test at $p \leq 0.05$. Data are the mean $\pm$ standard error. CC: cultivated cardoon. For acronyms, see Table 2.

3.5. Influence of the ‘Genotype $\times$ Growing Season’ Interaction on Micro-Elements Content of Cardoon Seeds

Following the same tendency as in the macro-element profile, the ANOVA analysis of the interaction between genotype and growing season revealed significant differences. However, as before, these differences were less pronounced than those between the individual factors. Nonetheless, there were still significant differences. The maximum percentage of interaction was found for Mn (25.4%), followed by Fe (17.1%), Cu (12.0%), and, lastly, Zn (10.8%).

The results of the interaction between cardoon genotype and growing season on micro-mineral content (Fe, Zn, Mn, and Cu) over three consecutive growing seasons (S1, S2, and S3) are presented in Figure 2.

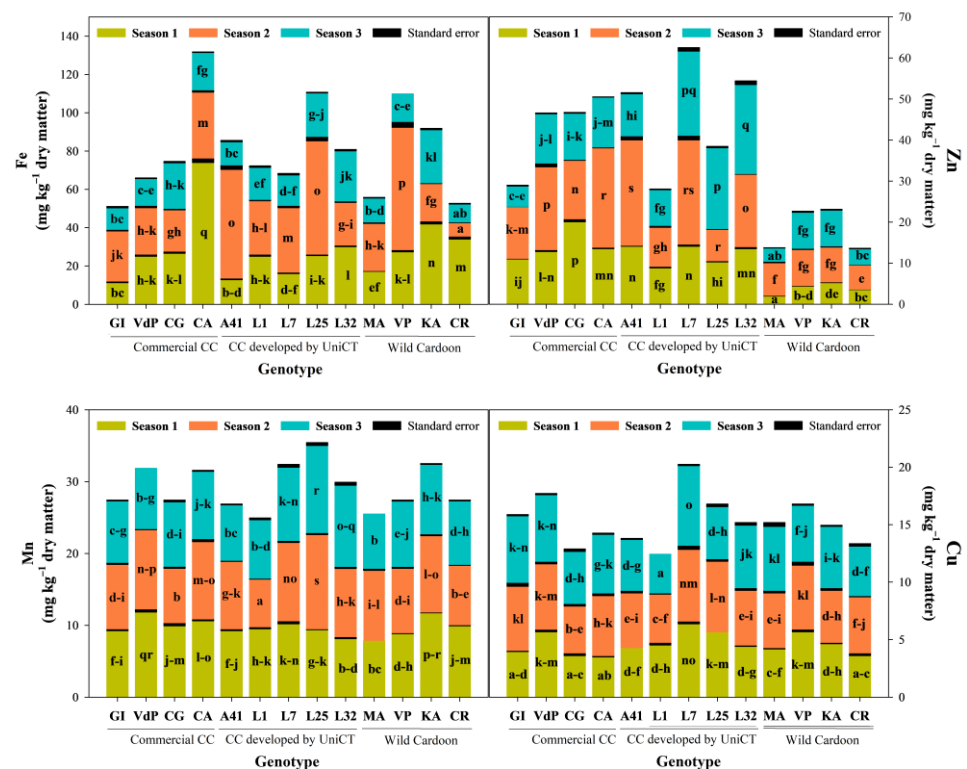


Figure 2. Micro-mineral content of *Cynara cardunculus* seeds in relation to ‘genotype × growing season’ interaction. Different letters show significant differences, according to Duncan test at $p \leq 0.05$. Data are the mean $\pm$ standard error. CC: cultivated cardoon. For acronyms, see Table 2.

As a general season trend, it could be observed that most genotypes showed a peak in Fe content in either S₁ or S₂, with a decrease in S₃. This was the case with the commercial genotype CA and the wild genotype VP, which exhibited the highest Fe contents among all genotypes under study in S₁ and S₂, respectively (74.0 and 63.8 mg kg^{−1} DM). Thus, cultivated cardoon developed by UniCT exhibited the highest Fe mean content in S₂ (30.9 mg kg^{−1} DM). On the contrary, S₃ recorded the lowest values regardless of the group analyzed. Nevertheless, the lowest genotype values were observed by CR in season 2, followed by S₃ (6.98 and 9.32 mg kg^{−1} DM, respectively). Following the previous season’s tendency, most genotypes showed an increase in Zn content in S₂, followed by a decrease in S₃ (on average, −22.6%), except for L25 and L32, which peaked in S₃ (+157% and +23%). Commercial cultivated cardoon and university-developed genotypes, as observed for Fe, showed the highest Zn content (on average 17.5 mg kg^{−1} DM) and within this last group, genotypes like A41 and L7 in season 2 exhibit the highest Zn content among all the genotypes under study (25.7 and 25.4 mg kg^{−1} DM, respectively). However, the most important thing to note is that, regardless of the growing season, wild cardoon genotypes exhibited the lowest Zn content among the three groups, displaying a mean reduction of 59.7% with respect to commercial cultivated cardoon and genotypes developed by UniCT. This trend also maintained for Mn. In the same way, wild genotypes generally exhibited lower Mn content compared to the other two groups (on average, −4.0%), with notable variability season-to-season. In addition, in S₃, the lowest mean levels of Mn for wild genotypes and commercial cultivated cardoon were recorded (8.79 and 8.82 mg kg^{−1} DM, respectively). Conversely, commercial cultivated cardoon showed the highest mean content of this micro-

element on S_1 ($10.4 \text{ mg kg}^{-1} \text{ DM}$). Regarding the individual genotypes, L25 exhibits the highest Mn content among all genotypes under study, especially for S_2 and S_3 (on average $12.6 \text{ mg kg}^{-1} \text{ DM}$). The lowest values were recorded by L1 with $6.62 \text{ mg kg}^{-1} \text{ DM}$, and CG and MA, both at $7.58 \text{ mg kg}^{-1} \text{ DM}$. Genotypes like VP maintained the most consistent level of Mn among the three growing seasons. Likewise, VdP also showed this stable trend in the Cu content. Though most commercial genotypes showed an increasing trend in Cu content over the three growing seasons, from the minimum amount of Cu in S_1 ($4.18 \text{ mg kg}^{-1} \text{ DM}$) to the maximum achieved in S_3 ($5.30 \text{ mg kg}^{-1} \text{ DM}$). Despite this, L7 (a university-developed genotype) showed the highest and most consistent content of Cu, peaking slightly higher in S_3 with $6.94 \text{ mg kg}^{-1} \text{ DM}$ compared to the others.

3.6. Principal Component Analysis and Coefficient of Variability on Mineral Elements Content of Cardoon Seeds

Table 7 presents the principal component coefficients for two principal components (PC1 and PC 2) derived from mineral elements (e.g., ash, Ca, K, etc.), averaged across years. Together, PC1 and PC2 (with eigenvalues > 1) accounted for 54.98% of the total variability. PC1, which explained 31.19% of the variance, showed strong positive correlations with Mg and Mn, and to a lesser extent with Fe, Zn, and Na. In contrast, N was negatively associated with PC1, indicating that higher N values corresponded to lower PC1 scores. Thus, PC1 likely differentiated genotypes rich in Mg, Mn, Fe, Zn, and Na from those characterized by higher N content. PC2, which accounted for 23.79% of the variance, was positively associated with K and ash, and negatively associated with Ca and Na. Accordingly, PC2 appeared to differentiate genotypes with high levels of K and ash from those with elevated Ca and Na concentrations.

Table 7. Correlation coefficients for each mineral element of *Cynara cardunculus* seeds, averaged across three growing seasons, with respect to the first two principal components, eigenvalues, and relative and cumulative proportions of total variance.

Trait	Common Principal Component Coefficients	
	PC1	PC2
Ash	0.488	0.609
Ca	0.241	−0.742
K	0.277	0.773
Mg	0.774	−0.220
Na	0.516	−0.566
N	−0.624	0.354
Fe	0.583	0.400
Zn	0.585	0.418
Mn	0.763	−0.062
Cu	0.477	−0.168
Eigenvalue	3.119	2.379
Variability (%)	31.19	23.79
Cumulative (%)	31.19	54.98

The bold values indicate the most relevant trait for each principal component.

The PCA biplot (Figure 3) clearly distinguished the *C. cardunculus* genotypes based on their seed mineral elements. For instance, CA and L7 were associated with high concentrations of ash, K, Fe, and Zn, whereas L25, SK, and CG aligned with Mg, Mn, and Cu, and to a moderate extent with Na. SC and M appeared as outliers: located on the far negative side of F1, they are likely characterized by low levels of Mg, Mn, Zn, and Fe, and comparatively higher concentrations of N or Ca. GI and VP were positioned near the

centroid, indicating that they were not strongly influenced by any particular trait under study (Figure 3).

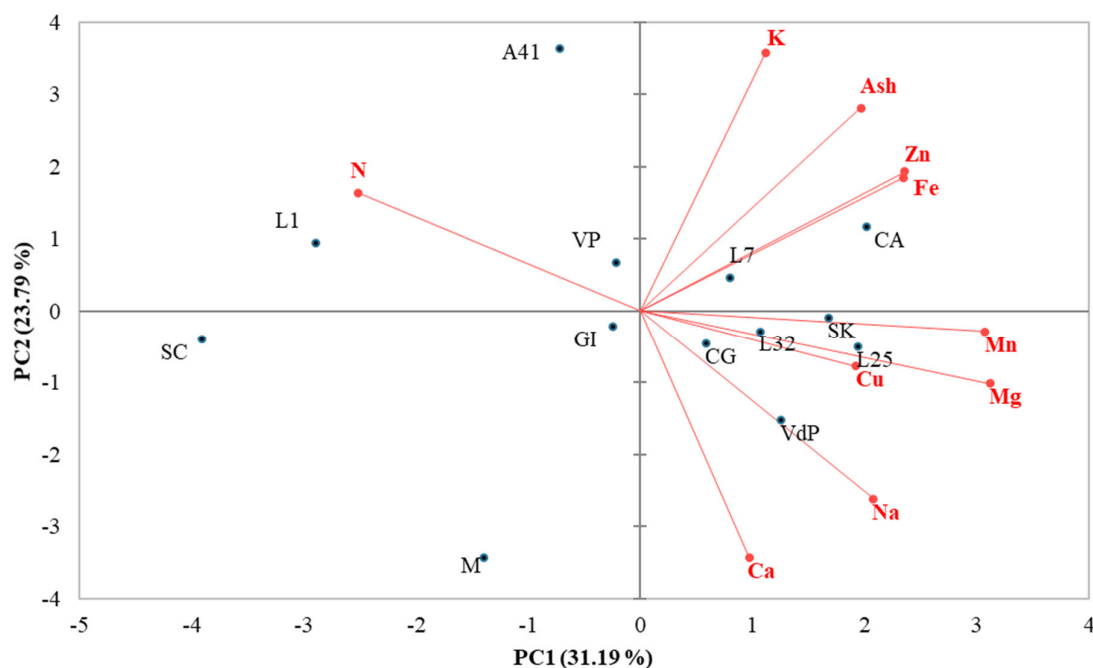


Figure 3. Principal component biplot showing variation of *C. cardunculus* genotypes by seed mineral elements on average, over three growing seasons.

In terms of genotypic CV, ash content exhibited considerable variation, with CVs ranging from 3.8% in VP to 34.5% in CA (Table 8). The latter also reported the highest CVs for K and Cu. On the contrary, the lowest values of these mineral elements were recorded in VdP. L1 was characterized by the lowest CVs for Ca, Na, and Zn and the highest CV for Mn (Table 8). CVs for N content were relatively low, ranging from 1.5% (CG) to 8.5% (L7), while Fe presented the highest CV among all mineral elements (up to 84.2% in A41), pointing to pronounced differences in Fe uptake and storage capacity by genotype and possibly environmental interactions.

Table 8. Coefficient of variation (%) of ash and mineral elements content in seeds of *Cynara cardunculus* genotypes on average, over three growing seasons.

Plant Material	Genotype	Ash Content	Mineral Element								
			N	Ca	K	Mg	Na	Fe	Zn	Mn	Cu
Commercial CC	Gigante Inerme	15.1	6.1	20.6	10.5	3.8	13.6	47.6	38.2	4.6	18.2
	Verde di Peralta	8.6	7.8	27.2	2.8	16.4	29.6	26.5	27.3	15.6	4.0
	Cardo Gobbo	21.4	1.5	26.6	3.7	9.4	19.0	10.4	26.6	12.6	11.8
	Cardo Avorio	34.5	2.8	28.2	21.6	15.0	22.5	59.2	35.5	7.3	19.1
CC developed by Catania University	Altilis 41	5.2	2.1	24.1	11.2	6.2	24.6	84.2	43.2	9.7	6.0
	Linea 1	19.1	3.2	5.9	18.7	9.4	4.3	22.5	6.2	16.3	13.7
	Linea 7	8.5	8.5	15.9	11.9	14.8	22.0	41.9	25.8	5.2	6.6
	Linea 25	14.2	3.3	40.4	16.4	23.5	35.7	51.0	45.3	15.3	14.1
	Linea 32	17.6	2.5	35.6	13.5	26.2	26.8	13.8	21.2	15.2	10.7
Wild Cardoon	Marsala	15.8	5.9	30.1	21.3	18.3	29.2	30.5	64.3	12.9	14.0
	Val Paraiso	3.8	1.9	30.6	17.3	17.0	41.7	65.3	31.1	2.7	8.8
	Kamarina	4.4	1.8	21.4	6.2	10.9	17.1	34.3	23.5	9.0	8.8
	Creta	20.4	3.8	8.4	13.0	12.6	21.2	80.1	26.2	8.5	14.2

CC: cultivated cardoon.

4. Discussion

Cardoon seeds are very important from a nutritional point of view, as they are a proven source of various minerals [37,40,45]. In this sense, mineral elements play critical roles in both human health and animal and livestock health. In human well-being, minerals perform diverse and vital functions in numerous biochemical processes, including the regulation of blood pressure and the reduction in cardiovascular disease risk, structural tasks in bones and teeth, and regulatory roles in metabolism and immune defense, among others [46]. Ensuring an adequate intake of these essential nutrients through diet or supplementation is crucial for maintaining overall health and preventing deficiency-related diseases [37].

Concerning livestock, in recent decades, there has been a significant increase in its production, driven by a rising demand for animal-source foods, particularly in developing countries [47]. Globally, livestock production has shifted from extensive, small-scale, subsistence systems to more intensive, large-scale, commercially oriented, specialized units [48]. To sustain high production standards, animal nutrition has become highly specialized, relying almost exclusively on concentrate feed sourced from the international market. Consequently, correct mineral supplementation in concentrated feed—which is not only the primary or only feed used in intensive systems but also a complementary feed for many traditional farms—is crucial. It is well known that mineral micronutrients are required for the normal functioning of all biochemical processes in the animal organism. They are part of numerous enzymes and coordinate a great number of biological processes, and consequently, they are essential to maintain animal health and productivity.

According to the existing literature, the concentration and availability of chemical compounds in plant tissues, including seeds, may be determined by a complex interaction between genetic, developmental, and environmental factors [6,39,40,49–54]. Seasonal variations in temperature, precipitation, radiation, and soil characteristics can significantly affect the uptake, transport, and accumulation of these compounds within plant tissues [49,55–57]. Environmental stressors and harvesting time may either enhance or limit the absorption and distribution of certain elements depending on the plant's physiological status and growth stage [58–61]. Concurrently, genotypic differences determine the efficiency of nutrient acquisition and internal allocation, as different plant types exhibit varying capacities for regulation and adaptation [40,50–53,58,62]. Moreover, the developmental stage also plays a role, as metabolic demands and physiological priorities shift throughout growth and maturation, changing throughout the plant's life cycle [6,39].

The importance of considering both genetic and environmental dimensions and their synergy when aiming to characterize the chemical composition and nutritional quality of plant-derived products is further supported by our results, which show that genotype and growing season significantly influence the mineral content and ash composition of cardoon seeds, both separately and with interaction effects. In particular, regarding the genotypic effect, wild cardoons presented lower ash content than commercial and UniCT-developed cultivated cardoons. Opposite results were observed in the study by Petropoulos et al. [40], where wild cardoon genotypes showed a higher ash content (between 26.7 and 27.7 g kg^{−1} DM) compared to commercial genotypes (20 g kg^{−1} DM). However, in the present study, the average ash content across all genotypes analyzed was approximately 49% higher than that reported by Petropoulos et al. [40].

Among the nine mineral elements studied, the macro-element N was present in the greatest mean quantity, followed by Ca, K, Mg, and Na. As for the micro-minerals, Fe exhibits the highest average content, with Zn, Mn, and Cu showing progressively lower levels. The same trend in the order of quantity of mineral content was also observed in other studies [25,40]. The N content was also evaluated in the study of Petropoulos et al. [40]

in wild and commercial cardoon with an average content of 41.4 and 46.6 g kg⁻¹ DM, respectively. In our study, although the content of this macro-element in general in all genotypes was approximately 34% lower, the reverse trend was found. The highest average content was found in wild genotypes, followed by those developed by UniCT, and, in last place, the commercial varieties. However, our findings on N content align with those reported by Cajarville et al. [45], who investigated the use of cardoon seeds as animal feed for ruminants. The same inverse trend occurred in the content of Ca. Petropoulos et al. [40] reported a mean content in wild cardoon that varied between 10.47 and 13.53 g kg⁻¹ DM. Our results also correlated with these differences depending on the genotype. In commercial cardoon, the average Ca content was 7.35 g kg⁻¹ DM; however, for the same genotype (CA) and plant but in the previous season, a content of 11.97 g kg⁻¹ DM was reported [25]. However, in our case, the average Ca content was higher in wild genotypes than in the commercial and UniCt-developed cultivated cardoon. In addition, the quantity reported for genotype CA in our research and, in general, in all genotypes, was approximately 70% lower, around 3 g kg⁻¹ DM. This quantity is more aligned with the results obtained by Angelova et al. [41], who reported a Ca content in seeds of commercial cardoon of 2.83 g kg⁻¹ DM. Lower contents in K macro-mineral were also found in our research compared with Angelova et al. [41] and Petropoulos et al. [25,40], as it ranges between 5.93 and 6.68 g kg⁻¹ DM. Thus, differences were also found depending on the growing season. These variations may be due to growing conditions, as reflected in our results (Table 3). The same happens with the Mg content, as the quantity reported in this study is approximately 65% lower. However, similar Na values to those obtained in this research have been reported in other studies, ranging from 0.18 to 0.24 g kg⁻¹ DM [25,40]. The uniform Na content suggests minimal variability in this element, and this consistency indicates that the seeds maintain a balance in this essential electrolyte.

The greatest differences in terms of micro-mineral content can be observed for Fe, as the results obtained in this assay differ greatly from others. Petropoulos et al. [25,40] reported Fe content that ranged between 116 and 160 mg kg⁻¹ DM, which represents an increase of more than 400% with respect to our results. On the other hand, Angelova et al. [41] described Fe content of 51.1 mg kg⁻¹ DM in cardoon seeds, which—despite being double our values—is more aligned with the results obtained in this study. The same happened for Mn, since the content obtained by Petropoulos et al. [25,40] varies between 46 and 60 mg kg⁻¹ DM, being approximately 480% higher than the quantity found in our study, while Angelova et al. [41] reported content of 18 mg kg⁻¹ DM, duplicating our results. The same study also reported an amount of Cu of 11.4 mg kg⁻¹ DM, also double the values obtained in this research.

To our knowledge, no literature specifically addresses the influence of the growing season on the ash and mineral elements of cardoon seeds. However, there are studies in different plant parts on related species, such as globe artichoke, which provide insights into similar phenomena. For example, Elia and Conversa [57] reported that the mineral element content in globe artichoke capitula was significantly affected by soil type and crop management practices. Others also highlighted that various factors, including seasonal variations, influenced the mineral composition in globe artichoke [1,49]. These findings suggest that, although specific research on cardoon seeds is lacking, it is reasonable to infer that similar seasonal effects might influence cardoon as well. Just as with globe artichoke, seasonal changes could alter the availability of nutrients in the soil, which in turn affects the mineral content in cardoon seeds. The fluctuations in climatic conditions throughout the growing season could lead to variations in nutrient uptake and accumulation, reflecting broader trends observed in related species. Ash content fluctuated considerably between seasons, with the lowest amount recorded in S₂ and the highest in S₁. This pattern could

have been associated with variations in rainfall levels throughout the growing seasons. The S_2 recorded a rainfall level of about 69% higher than S_1 and S_3 . This could have leached and diluted the soil mineral concentration and, consequently, the mineral uptake by the plant. The S_2 reduced the K level in seeds. The role of K in plant drought resistance has been well reported [63]. Probably, the major rainfall observed in S_2 could explain the lowest K content found in seeds. On the contrary, the S_2 favored the Ca accumulation in seeds. This is aligned with the findings of Sorooshzadeh et al. [61], which highlighted reduced Ca concentration in soybean plant tissues under water stress conditions. On the other hand, it is known that K^+ and Ca^{2+} compete with each other [64]. A similar trend was observed for both Fe and Zn. Also, Choukri et al. [65] documented a significant reduction in Fe and Zn content in lentil genotypes under drought stress.

The CV in ash and mineral element composition across various genotypes of *C. cardunculus* cardoons reveals substantial heterogeneity, indicative of wide genetic diversity and metabolic plasticity. These findings align with previous studies that have documented considerable biochemical variation among cultivated and wild cardoon accessions [34,66]. Notably, Ca, K, Na, and Fe displayed higher variability than the other mineral elements under study, suggesting that these mineral elements are more sensitive to genotype and possibly environmental interactions. In particular, Fe presented the highest CV among all the elements. This may indicate broader ecological adaptation strategies, as Fe availability is highly dependent on soil type and genotype-specific uptake pathways [67]. Ca and Na presented similar CVs. The high Na variability suggests differences in salt tolerance among genotypes under study, indicating that those with elevated Na variability (e.g., VP and L25) may be more adaptable to saline or marginal environments [68]. The CVs for both N and Cu were relatively low, suggesting a relatively stable N and Cu assimilation pathway across genotypes. Probably, Cu is tightly regulated due to its dual role as a micronutrient and a potential toxin, which may explain the lower variability compared to other trace elements [69].

The PCA analysis carried out for the purposes of this study confirmed significant differences in the mineral elements of *C. cardunculus* seeds depending on the genotype. At the same time, it indicated some common features of selected genotypes, owing to which it is possible to divide the analyzed seeds into those with more ash, more Ca or N content, and those with a higher content of Mn and Cu.

5. Conclusions

This research not only contributes to the understanding of cardoon seed composition but also unveils the assessment of element mineral content variation among different seed genotypes and growing seasons, reflecting the complex interplay between genetics and environmental conditions, affecting nutrient and mineral accumulation.

The results of the present study demonstrated that, in general, cardoon seeds are a good source of macro and micro-elements, such as N, K, Mg, and Fe, while they also contain a low amount of Na and Cu. Commercial genotypes generally show a higher amount of ash and macro-minerals such as Mg and Na, in particular Verde di Peralta, whereas university self-developed genotypes excel in N, K, Zn, Fe, Mn, and Cu content. For example, Linea 7 was characterized by the highest level of both Zn and Cu. Wild genotypes, while variable, stand out for Ca quantity, such as Kamarina. Overall, among the 13 genotypes studied in this research, the cultivated cardoon developed by Catania University possessed the highest and most stable content of the minerals under study. This will provide a valuable genetic reservoir for future breeding programs aimed at enhancing macro and micro-mineral content in cultivated genotypes, useful for functional food and/or feed products.

Future research should focus on understanding the specific environmental conditions that promote macro and micro-mineral accumulation and the genetic mechanisms underlying these traits. Such knowledge will be crucial for breeders and farmers in selecting suitable genotypes for specific purposes or target markets.

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