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ORIGINAL PAPER

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A COMPREHENSIVE ANALYSIS OF THE INFLUENCE OF VARIETY AND CLIMATE ON SOME PROPERTIES OF SUNFLOWER OIL

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ABSTRACT

The quantity and quality of sunflower oil are key factors for the crushing industry. This research presents a comprehensive analysis of the oil quality parameters of seven foreign sunflower hybrids grown in Morocco. Conducted over two consecutive years (2018 and 2019), the study focuses on key traits, including oil content, acidity index, peroxide index, refractive index, color index, total phenolic content, total flavonoid content, and antioxidant activity. Significant variations in most parameters, including color properties, were observed between the two years and among the seven varieties, indicating the influence of genetic and environmental factors. This highlights the importance of understanding the genetic potential of sunflower hybrids and the impact of environmental variables on oil quality. More favorable weather conditions in 2019, compared to 2018, contributed to better oil quality in all the varieties investigated. Overall, four homogeneous groups of hybrid varieties were identified based on oil content and other biochemical parameters. Some of these hybrids, like ‘Niagara’, had moderate oil content but high polyphenol content, flavonoid content and antioxidant activity, as well as a lower peroxide index, making them potential sources of natural antioxidant compounds as well as dietary supplements. Overall, this research provides sunflower breeders with valuable insights into the development of new high-performing hybrids with enhanced oil quality that could be used to produce functional foods with health benefits. These findings have implications for the use of seed oils from those hybrids in various industries and underscore the importance of further and more in-depth research on sunflower oil quality in the context of climate change.

Keyword: *Helianthus annuus* L., oil quality, polyphenol content, antioxidant activity, color properties

INTRODUCTION

Oilseed crops are the second largest food source after cereals, with a wide distribution worldwide due to the high demand for edible vegetable oils. With important functions in nutritional physiology and human health, vegetable oils are essential components of human diet (Ebrahimian et al., 2019). Among oilseed crops, sunflower (*Helianthus annuus* L.) accounts for up to 12% of global seed oil production (approximately 22 million tons), ranking fourth after palm, soybean, and canola. The total area of sunflower crop cultivation in the world was estimated at 29.2 million ha across 72 different countries (FAOSTAT, 2022).

Sunflower has the potential to be a very competitive crop due to its unusually high genetic diversity

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and oil quality. The quantity and quality of sunflower oil are key factors for the crushing industry (Petrenko et al., 2023). The oil content of sunflower seeds can vary from 35% to 50% and is predominantly comprised of desirable unsaturated fatty acids, rendering it highly suitable for human consumption (Ebrahimian et al., 2019; Hosni et al., 2022). This distinctive composition suggests a wide range of potential applications for sunflower oil (Anushree et al., 2017; De Oliveira Filho and Egea, 2021). Some studies have further highlighted its antioxidant (Zilic et al., 2010; Shahidi and Ambigaipalan, 2015), antibacterial (Darmstadt et al., 2004), and probiotic (Franco et al., 2018) properties and its bioremediation of pesticide biodegradation (Dzionek et al., 2016). These pharmacological attributes stem from its rich concentration of active secondary metabolites, particularly phenolic (including chlorogenic acid, caffeic acid, gallic acid, caffeoylquinic acid, protocatechuic acid, ferulic acid, β-coumaric acid, and sinapic acid) and flavonoid compounds (such as quercetin, kaempferol, heliannone, luteolin, and apigenin) (Javed, 2011). These metabolites not only have significant economic value in industry, such as in natural and cosmetic flavorings (Gök et al., 2022), but also contribute to various physicochemical and biological properties that boost their overall protective effects (Ambigaipalan and Shahidi, 2015). However, the composition of sunflower seeds is largely influenced by genetic and environmental factors. With regard to the effects of the environment, seed oil and its fatty acid (FA) composition are driven mainly by water availability, temperature, and duration of the growing period (Velasco et al., 2002; Bocianowski et al., 2020; Attia et al., 2021). It has been reported that the environment is the major factor contributing to final seed oil accumulation, while the genotype is the main factor influencing FA composition (Calamai et al., 2018). However, the influence of the environment on FA composition has been extensively documented, especially for High-Oleic varieties, for which the temperature during the development and maturation of sunflower achenes affects the production of oleic acid (Sobrino et al., 2003; Diovisalvi et al., 2018). According to Cojocaru et al. (2023), the unsaturated fatty acids of sunflower oil are much more impacted by genotype and environment than the saturated fatty acids. Additionally, the environmental effects on linoleic acid synthesis are much greater than the genetic effects (Akkaya et al., 2019; Ghaffari et al., 2023). It has been concluded that all sunflower genotypes (linoleic and oleic hybrids) vary and react differently to the environmental conditions under which they grow (Gül and Coban, 2020; Chernova et al., 2021). Therefore, determining the appropriate sunflower genotypes for a given region promises to provide an opportunity to obtain high seed yield and high oil quality.

In Morocco, sunflower stands as the preeminent oilseed crop, followed by rapeseed and sesame (Kouighat et al., 2022). Sunflower crop covers approximately 16,286 hectares (FAOSTAT, 2022), mainly concentrated in the areas of Gharb, Saïs, and Zaer. Total production was 24,601 tons in 2021 (FAOSTAT, 2022). However, there is a political will to promote and develop the oilseed crops sector in the frame of the new agricultural development strategy ‘Green Generation 2020–2030’. Among the main objectives, one could cite the extension of the area of sunflower crop under cultivation from 32,500 ha in 2019 to 80,000 ha in 2030, the improvement of sunflower seed yield from 1.2 t/ha in 2019 to 1.8 t/ha in 2030, and the increase in overall oil production (from all oilseed crops) from 38,000 t in 219 to 126,000 t in 2030. In parallel with these prospective developments, the study of seed oil quality can provide valuable scientific insights that can lead to improved dietary recommendations, disease prevention, better food safety, allergen detection, and improved sustainability associated with edible oils. Furthermore, this enables producers, companies (crushers), and consumers to make reasoned choices, ensuring that the oil is not only free from contaminants but also rich in health-promoting compounds like phenolics and flavonoids. In addition, understanding how oil quality parameters are influenced can help to optimize production processes, enhance oil shelf life, and ensure that oil meets both industry standards and consumer expectations. Likewise, investigating the diversity of sunflower seeds through a comprehensive analysis of their oil characteristics in contrasting environmental conditions could provide valuable information on germplasm conservation and utilization by breeders to improve these characteristics and help bolster national food security in edible oils.

In this context, a number of sunflower hybrids with different origins were introduced to Morocco to test their performance and adaptation to local conditions. The agronomic performance of these hybrids had previously been studied, revealing that some of them were well adapted to local conditions, exhibiting high seed yield (Kettani et al., 2017). However, their seed oil quality had not been investigated. Therefore, the present study aimed to characterize these hybrid varieties grown in two contrasting environments by their oil content as well as other important oil quality parameters. Among these parameters, oil color properties as affected by genotype and climate conditions were investigated (for the first time, to the best of our knowledge). In fact, the existing literature on sunflower oil has predominantly focused on the modification of color attributes during various processes like frying and refining. The relevant studies have meticulously documented how thermal and chemical treatments alter the visual and physicochemical characteristics of the oil, highlighting its stability and quality degradation over time and at different temperatures (Maskan, 2003; Gotor and Rhazi, 2016; Godswill et al., 2018; Chen et al., 2023). However, there is a notable absence of investigations into the influence of genetic and environmental variables on sunflower oil color properties. The ultimate goal of this study was to identify those hybrid seeds with higher oil quality and added value not only for nutritional use but also for diverse industrial applications.

MATERIALS AND METHODS

Plant material

The plant material used in this study consisted of seven sunflower hybrid varieties, namely '*Niagara*', '*Besana*', '*Laila*', '*Bosphora*', '*IN5542*', '*Pentasol*', and '*Meridia*'. Table 1 shows the origins and main characteristics of these varieties.

Experimental site and design

This study was conducted during two consecutive crop years, 2018 and 2019, in the Experimental Station of INRA at Douyet. Douyet station is located 10 km from Fez city (34°04'N, 5°07'W) and at an elevation of 416 m above sea level. The soil of this station is a vertisol, with an average composition of 58% silt, 29% clay, and 12% sand. The area's climate is Mediterranean, characterized by cold and rainy winters and hot and dry summers. The monthly precipitation (in mm) and average temperatures (in °C) for the years 2018 and 2019 are presented in Figure 1. An analysis of local rainfall revealed that the year 2019 was rainier than the year 2018 in November, December, January, March, and April, while February and May were rainier in 2018. Variations in temperature between the two years were also noted. In general, the year 2018 was warmer than 2019, particularly in May, when a big difference of 5°C was observed.

The experiment was carried out according to a randomized complete blocks design (RCBD) with three

Table 1. Origins and main phenotypic and agronomic characteristics of the seven sunflower hybrids studied (Kettani et al., 2017)

Variety	Origin	Main phenotypic and agronomic traits			
		Plant height	Head diameter	Thousand seeds weight TSW, g	Seed yield t/ha
Niagara	Euralis (France)	tall plant	large diameter	64.95	2.56
Besana	Euralis (France)	very tall plant	very large diameter	53.57	2.57
Laila	Euralis (France)	very tall plant	very large diameter	60.18	2.84
Bosphora	Syngenta (Switzerland)	tall plant	large diameter	68.80	2.44
IN5542	Limagrin (France)	medium plant height	small diameter	39.86	1.36
Pentasol	KWS (Germany)	very short plant	medium diameter	39.53	1.71
Meridia	KWS (Germany)	short plant	small diameter	41.14	0.91

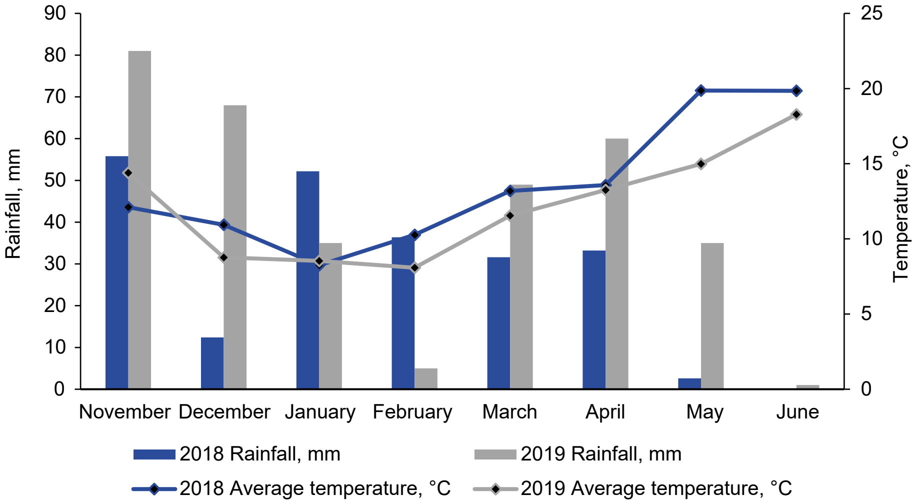

Fig. 1. Comparison of precipitation and average monthly temperatures during the experimental period in 2018 and 2019

replications, where variety and year were considered fixed factors. The field trial was set and conducted with a crop duration of about six months (from February to July). Crop management was carried out according to the conventional cultivation technique adopted in our experimental stations. Before planting, deep ploughing was carried out with fertilization at a rate of 60 units of nitrogen, 60 units of phosphorus, and 40 units of potassium. Sowing was carried out on 15 February in the first year (2018) and on 20 February in the second year (2019). After emergence, at the stage of two pairs of leaves, a thinning, along with a weeding, was carried out so as to leave an inter-plant space of 20 cm. The inter-row distance was 60 cm. The second weeding and cover fertilization (60 nitrogen units) were implemented at flower bud stage. The plants of the different varieties were harvested as they matured during the last week of June in 2018 and the second week of July in 2019.

Seed oil extraction and parameters measured

For all the parameters studied, dry, healthy, and uniform seeds were analyzed in three replicates. Sunflower seed oil was chemically extracted following ISO (1999) method 659:199 using Soxhlet solvent extraction (Model SER 148/6, VELP SCIENTIFICA, Italy). Oil was extracted by mixing 20 g of powdered seeds with pure N-hexane (150 mL) at 130°C. The extraction lasted up to 3 hours and then the solvent was evaporated under reduced pressure using a Rotavapor (Model HAHNVAPOR, HAHNSHIN, Korea).

Oil content. The oil percentage was determined using the formula: **Oil content (%) = [(M1 – M0)/ M2] × 100**, where M0 is the weight of the empty flask, M1 is the weight of the flask after evaporation, and M2 is the weight of the ground seeds.

Acidity index. This index, expressed in mg KOH/g oil, was determined by titration of a solution of oil in ethanol, according to NF EN ISO 660 of September 2009.

Peroxide index. Expressed in mill equivalent of active oxygen per kilogram of oil (meq O_2/kg), this parameter was determined according to NF ISO 3960 of March 2004.

Refractive index. An Abbe Refractometer (Model BK-R2S, BIOBASE, China) was applied in order to determine this index according to ISO 6320 of 2017.

Color index. Color in oil is a major factor in the consumer's purchase decision. Oil color was determined following the 'Commission Internationale de l'Eclairage' with three dimensions: *L*, *a*, and *b* (CIE

LAB) (RFF). All conceivable colors are located within the color sphere defined by three perpendicular axes, *L** (from white to black), *a** (green to red) and *b** (blue to yellow). In this study, color values were measured using the colorimeter NH300 (Model 3nh, Kejian, China), according to NF EN ISO/CIE 11664-4 of July 2019.

Before assessing the content of phenolic, flavonoid and antioxidant compounds, an extract was prepared according to the method described by Tsimidou et al. (1992). An oil sample of 2 g was dissolved in a mixture of 10 mL of hexane and 4 mL of 60% methanol (v/v). After agitation for 2 hours at room temperature in darkness, the supernatant was filtered through a Whatman No. 1 filter (Whatman International, Brentford, UK). Each extraction was conducted in three separate instances. The resulting three filtrates were then merged, cleansed with 10 mL of hexane, and preserved at 4°C pending subsequent analysis.

Total phenolic content. The Folin-Ciocalteu colorimetric method was used, with slight modifications, according to Singleton et al. (1999). A quantity of 50 µL of the oil extract was combined with 3 mL of distilled water, 250 µL of Folin-Ciocalteu reagent, and 750 µL of 7% sodium carbonate. The obtained solution was agitated for 8 minutes at room temperature before an additional 950 µL of distilled water were added. Following a 2-hour incubation period in the dark, the absorbance level was measured at 765 nm using an UV spectrophotometer (Model V-530, JASCO, Germany), with a blank as the reference. For the calibration curve, Gallic acid served as the standard.

Total flavonoid content. The method outlined by Favati et al. (1994) was employed to determine the flavonoid content. A 0.5 mL aliquot of the oil extract was combined with 0.5 mL of a 2% aluminum chloride methanol solution. The mixture was allowed to stand for 15 minutes at room temperature. Subsequently, the absorbance was measured at 430 nm using a UV spectrophotometer (Model V-530, JASCO, Germany), with methanol serving as the blank.

Antioxidant activity. This parameter was determined as described by Brand-Williams et al. (1995), with slight modifications, following the DPPH (2,2-diphenyl 1-picrylhydrazyl) method. A 50 µL aliquot of the oil extract was mixed with 950 µL of a DPPH solution (0.030 mg/mL) in methanol. The mixture was left to incubate in darkness for 60 minutes, after which its absorbance was measured at 515 nm, using ultrapure water as the blank. The percentage of antioxidant activity was calculated using the formula: **Antioxidant activity = (Ac − Ae/Ac) × 100**. In this formula, Ac represents the absorbance of the control, while Ae is the absorbance of the sample.

Statistical analysis

Analysis of variance (ANOVA) was performed to assess the main effects of year and variety as fixed factors, as well as their interaction, on several measured parameters. In the case of significant differences between years or among varieties, the means were compared using Duncan's test at the 5% significance level. Variability among sunflower varieties based on biochemical data was also examined using cluster analysis with a Euclidean distance matrix and principal component analysis (PCA). Finally, Pearson's correlation analysis was performed to investigate the relevance and significance of associations among the traits studied. All the statistical analyses were carried out using SPSS software version 28 (IBM, Armonk, USA).

RESULTS AND DISCUSSION

The results of the ANOVA analysis showed significant differences between years and among varieties for all the parameters studied, except for refractive index (Table 2). On the other hand, except for the peroxide index, the effect of interaction between year and variety on all the parameters studied was not significant, which indicates the stability of the ranking of varieties. These findings highlight the importance of genotype and environment in determining most of the chemical and biochemical characteristics of sunflower oil and, hence, its quality.

Comparative analysis of mean values

Oil content

The average oil content values of the varieties studied for the years 2018 and 2019, as well as the overall average, are presented in Figure 2. Overall, 'Besana' had the highest oil content with 38.25%, followed by

Table 2. Results of analysis of variance (mean squares and level of significance of differences) of seven sunflower hybrids evaluated in two contrasting years for chemical and biochemical parameters

	df	Oil content	Refractive index	Acidity index	Peroxide index	Polyphenol content	Flavonoid content	Antioxidant activity	*L*	*a*	*b*
Year (Y)	1	220.229***	0.011	22.097***	97.500***	28.810***	0.185***	116.738*	0.494*	0.036*	2.036*
Variety (V)	6	30.893**	0.001	0.444**	12.666***	9.952*	0.006**	262.529***	6.415*	0.052*	2.948*
V × Y	6	13.098	0.004	0.048	6.084***	0.646	0.005	110.282	0.985	0.019	0.522
Error	28	9.311	0.004-03	0.095	0.304	2.260	0.003	27.372	1.967	0.016	1.598

A significant effect is indicated as *** for $p \leq 0.001$, ** for $p \leq 0.01$, and * for $p \leq 0.05$.

'Niagara' with 37.38%, 'IN5542' with 35.45% and 'Laila' with 34.95%, all of them statistically comparable. On the other hand, 'Bosphora', 'Pentasol' and 'Meridia' showed the lowest oil content, with respective values of 32.44%, 32.53%, and 33.64%. Similarly, in 2018, 'Besana' and 'Niagara' presented the highest oil content of 36.17%, while 'Bosphora', 'Meridia', and 'Pentasol' had the lowest oil content, with values of 28.07%, 29.32%, and 30.78%, respectively. In 2019, 'Besana' confirmed its superiority, exhibiting the highest oil content (40.33%) followed by 'Niagara' (38.65%), while 'Pentasol' had the lowest content of 34.26%. These results are in accordance with previous studies that reported sunflower oil content ranging from 37 to 39% (Muhammad Anjum et al., 2012; Mohammed et al., 2017; Hosni et al., 2022). Under Moroccan conditions, the variety 'Besana', followed by 'Niagara', consistently exhibited the highest oil content (>37%), for the individual and combined years. This indicates that 'Besana' and 'Niagra' are promising varieties in terms of oil production. The variation observed between the two years highlights the influence of environmental factors on oil production (Mazaheri et al., 2019; Arrutia et al., 2020). The year 2019 was rainier than 2018, mainly during April and May, coinciding with flowering and grain-filling stages. Better water availability for sunflower plants in 2019, regardless of variety, may have contributed to better accumulation of fat in seeds, thus leading to a higher oil content. In a previous study, both varieties

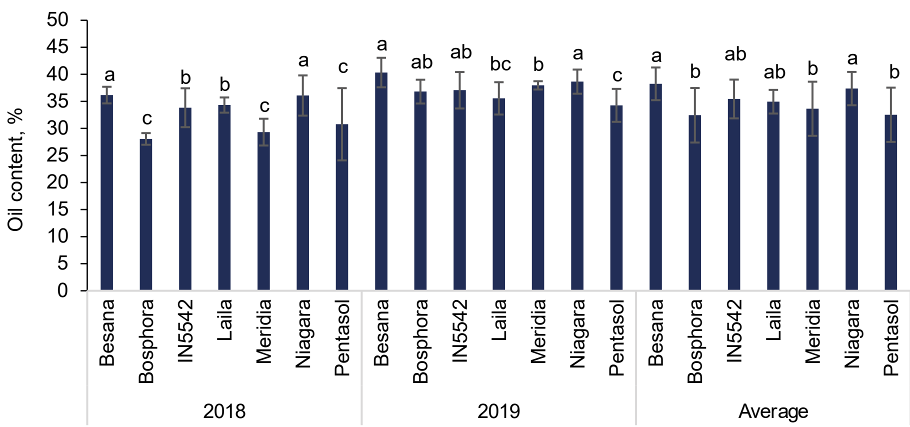

Fig. 2. Oil content of seven sunflower hybrid varieties grown in two contrasting years, 2018 and 2019. For each year and combined years (average), varieties with the same alphabetical letters are not statistically different according to Duncan's test

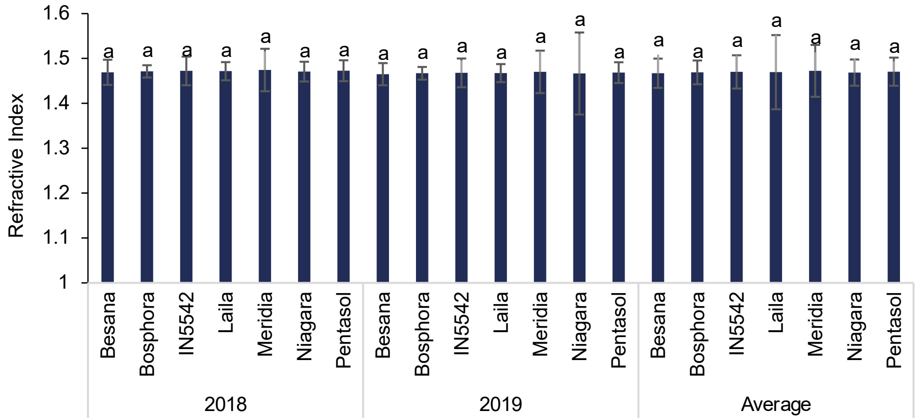

Fig. 3. Refractive index of seven sunflower hybrid varieties grown in two contrasting years, 2018 and 2019. For each year and combined years (average), varieties with the same alphabetical letters are not statistically different according to Duncan's

had exhibited a high seed yield exceeding 2.5 t/ha (unpublished data). Overall, these findings suggest the importance of selecting 'Besana' and 'Niagara' as potential cultivars for sunflower production in Morocco. This also provides valuable information for breeders, crushers, and farmers about the exploitation and fair use of these hybrids in a Moroccan context.

Refractive index

All the varieties studied were statistically comparable for this trait. Nevertheless, in terms of overall average, the 'Besana' variety had the lowest refractive index (1.467), closely followed by 'Laila' (1.469) (Fig. 3), while 'Meridia' exhibited the highest value with 1.472. In 2018, 'Besana' had the lowest refractive index (1.469), while 'Meridia' had the highest value (1.474). In 2019, 'Besana' recorded, once again, the lowest refractive index (1.465), while 'Meridia' confirmed its highest value (1.470).

The refractive index is an essential parameter for assessing oil quality (Rebolleda et al., 2012; Godswill et al., 2018). Lower refractive index values are generally associated with better sunflower oil quality. Thus, varieties like 'Besana' and 'Laila' would be expected to have better oil quality than the other varieties.

Acidity index

The average acidity index across all varieties and years was approximately 2.37 mg KOH/g (Fig. 4). The average acidity index ranged from 1.80 mg KOH/g in 'Pentasol' to 2.60 mg KOH/g in 'Niagara'. Similarly, in 2018 and 2019, the highest acidity index was observed in 'Niagara', with mean values of 3.46 mg KOH/g and 1.74 mg KOH/g, respectively, while the lowest acidity index was recorded in 'Pentasol' (2.40 mg KOH/g in 2018 and 1.21 mg KOH/g in 2019), and 'IN5542' (2.59 mg KOH/g in 2018 and 1.30 mg KOH/g in 2019). These results indicate that this index is impacted by the genotype and the growing environment. Previous work has also highlighted the significant influence of climatic conditions, in addition to agricultural practices and processing techniques, on the acidity of vegetable oils (Flagella et al., 2002; Guirrou et al., 2023). Acidity index is a measure of the concentration of free fatty acids in oil. A higher acidity index indicates a greater presence of free fatty acids, which can be attributed to oil degradation processes during storage (Harris et al., 1978; Coradi et al., 2017; Mengistie et al., 2018). Thus, according to our results the varieties 'Pentasol' and 'IN5542' are the best for oil acidity, while 'Niagara' is the worst.

However, according to the CODEX ALIMENTARIUS (standard for named vegetable oils-CXS 210-1999-Revised and amended in 2019), after normalizing the quality characteristics of vegetable oils, all the studied varieties are within sunflower acidity index oil limits (≤4.0 mg KOH/g oil) (Zhang et al., 2015). These results can guide the choice of varieties to favor the production of high-quality sunflower oil with low acidity.

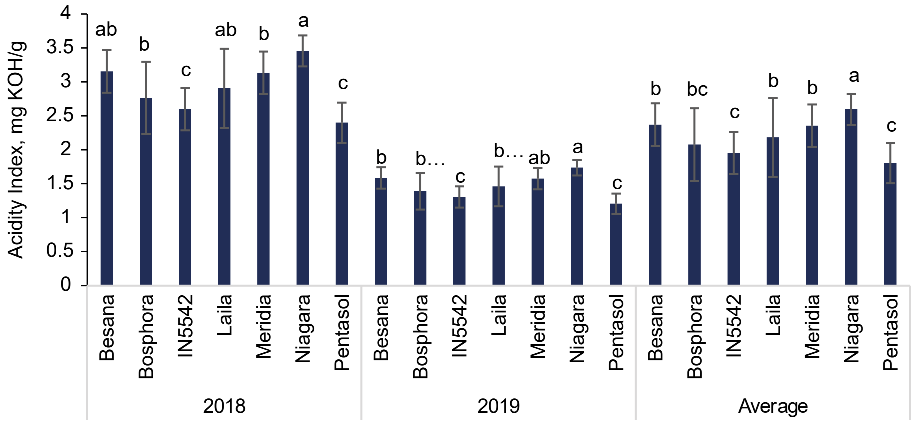

Fig. 4. Acidity index of seven sunflower hybrid varieties grown in two contrasting years, 2018 and 2019. For each year and combined years (average), varieties with the same alphabetical letters are not statistically different according to Duncan's test

Peroxide index

Overall, the varieties 'Bosphora', 'Besana', 'Pentasol', 'IN5542', and 'Niagara' had the lowest peroxide index with a mean value between 2.24 and 2.91 meq O_2/kg (Fig. 5). In contrast, 'Laila' and 'Meridia' had the highest peroxide index with a mean value of 5.46 meq O_2/kg. In 2018, 'Besana' had the lowest peroxide index with a value of 2.12 meq O_2/kg, while 'Laila' and 'Meridia' had the highest values (7.84 and 7.87 meq O_2/kg, respectively). In 2019, 'IN5542' and 'Pentasol' exhibited the lowest peroxide index (about 0.5 meq O_2/kg), whilst 'Laila' and 'Meridia' had the highest average value (about 3.10 meq O_2/kg). The higher the peroxide index, the greater oil oxidation, which can be attributed to factors such as raw material quality, storage conditions, or processing practices (Kaleem et al., 2015; Flores et al., 2021). Compared to 2018, the cropping year 2019 presented better conditions for sunflower varieties to produce more oil with the best quality, in particular higher rainfall and lower average temperatures. In fact, it has been reported that higher temperatures can influence the stability of seed oil, increasing

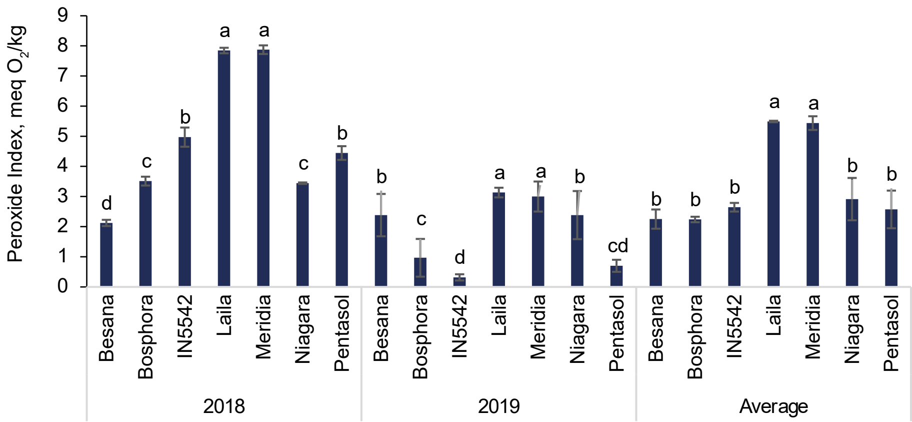

Fig. 5. Peroxide index of seven sunflower hybrid varieties grown in two contrasting years, 2018 and 2019. For each year and combined years (average), varieties with the same alphabetical letters are not statistically different according to Duncan's test

the risk of oxidation and the formation of peroxides (Godswill et al., 2018). Generally, lower peroxide values are preferable, indicating better oil quality following the CODEX ALIMENTARIUS (standard for named vegetable oils-CXS 210-1999-Revised and amended in 2019). The peroxide index for virgin oils should be less than 15 meq O_2/kg oil (Goszkiewicz et al., 2020), which was met in all the varieties investigated, especially 'Besana' and 'Bosphora', suggesting that they would produce sunflower oil with lower oxidation and better stability.

Polyphenolic compounds

Total polyphenol content varied across years and varieties (Fig. 6). Overall, 'Pentasol' presented the highest level of polyphenol (7.02 mg GAE/100 g), statistically comparable with 'Laila' (6.91 mg GAE/100 g), 'Niagara' (6.40 mg GAE/100 g) and 'Bosphora' (5.88 mg GAE/100 g). On the other hand, 'Besana' and 'Meridia' displayed the lowest level of polyphenol with a mean value of 4.04 mg GAE/100 g. In 2018, 'Pentasol' had the highest polyphenol content (6.29 mg GAE/100 g), while 'Besana', 'Meridia' and 'IN5542' had the lowest content (3.16, 3.49 and 4.67 mg GAE/100 g, respectively). In 2019, 'Laila' exhibited the highest polyphenol content (8.21 mg GAE/100 g), which was not statistically different from that of 'Pentasol', which had 7.75 mg GAE/100 g. In contrast, 'Besana' recorded the lowest mean value of 3.76 mg GAE/100g. A previous study demonstrated that this parameter is significantly impacted by genotype, with a range of 1.35–10.35 mg GAE/100 g (Yang et al., 2018). In addition to genetic effect, sunflower oil and its minor constituents, including phenolic compounds, are influenced by environmental factors, as well as their interaction (Velasco and Ruiz-Méndez, 2015). In fact, seeds developed under water stress and/or elevated temperatures, mainly during the reproductive stage, have reduced seed oil content and quality (Balbino, 2017). This is why overall polyphenol content, regardless of variety, was lower in 2018 than 2019. Our findings also indicate that sunflower oil has much higher levels of total phenols than rapeseed oil (4.16 mg GAE/100 g) (Guirrou et al., 2023), soybean oil (0.89 mg GAE/100g) (Liu et al., 2020), or sesame oil (0.26 mg GAE/100g) (Xuan et al., 2018).

Polyphenols are compounds that are beneficial to human health due to their antioxidant properties, which can help to neutralize free radicals and reduce oxidative damage in the body (Rabiej-Kozioł et al., 2020). Varieties such as 'Pentasol', 'Laila' and 'Niagara', which have high polyphenol content, can be considered potential sources of healthy sunflower oil. These findings could be of great importance and interest to the sunflower oil industry. Sunflower varieties rich in polyphenols can be used in the production of

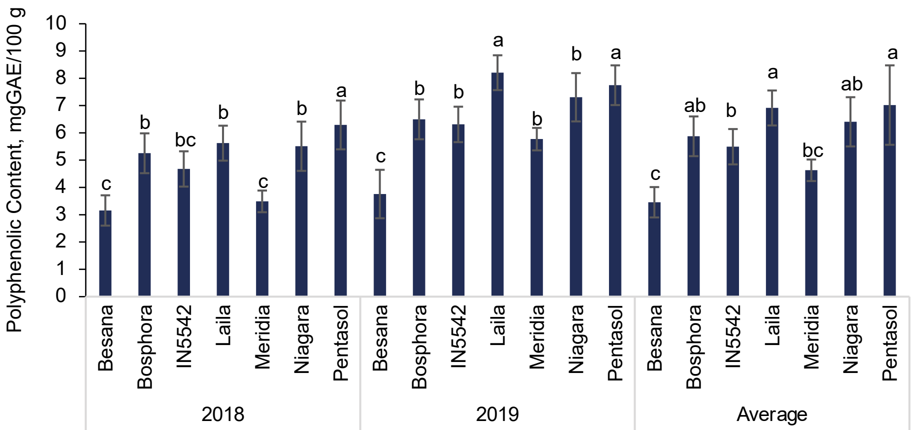

Fig. 6. Polyphenol content of seven sunflower hybrid varieties grown in two contrasting years, 2018 and 2019. For each year and combined years (average), varieties with the same alphabetical letters are not statistically different according to Duncan's test

functional sunflower oils with increased antioxidant properties, which may be of benefit to health-conscious consumers.

Flavonoid content

Overall, total flavonoid content ranged from 0.05 mg/g in 'Besana' to 0.14 mg/g in 'Niagara', with a noticeable superiority in 2019 over 2018, regardless of variety (Fig. 7). However, 'Niagara', 'Pentasol', and 'Laila' were statistically comparable. In 2018, 'Pentasol' had the highest flavonoid content of 0.07 mg/g, while the lowest value of 0.01 mg/g was recorded for 'Besana'. In 2019, 'Niagara' and 'Laila' exhibited the highest mean value of 0.23 mg/g, while 'Besana' had the lowest value of 0.09 mg/g. These results are in agreement with previous work reporting that flavonoid content in sunflower oil ranged from 0.01 to 0.25 mg/g (Bopitiya and Madhujith, 2015; Avni et al., 2016; Xuan et al., 2018). The variations observed between years indicate that flavonoid content is highly influenced by environmental conditions. Higher precipitation in 2019 improved the flavonoid content in sunflower oil by five times, suggesting the importance of the effect of climate on oil quality. Flavonoids are beneficial compounds due to their antioxidant potential and health effects, including their role in the prevention of chronic diseases (Avni et al., 2016). Thus, these findings are relevant to the food industry and nutrition. Sunflower varieties with higher flavonoid content, such as 'Niagara', 'Laila', and 'Pentasol', could be valued for the production of functional foods or ingredients rich in flavonoids. However, further studies are needed to deepen our understanding of the flavonoid profiles of different sunflower varieties and their impact on the quality of food products.

Antioxidant activity

Figure 8 presents the percentage of antioxidant activity in different sunflower varieties. Regardless of year, the highest percentage of antioxidant activity (59.53%) was found in 'Pentasol', but this was statically comparable with the levels in 'IN5542' (59.51%), 'Niagara' (59.43%), 'Bosphora' (54.42%), and 'Laila' (51.52%). In contrast, the varieties 'Besana' and 'Meridia' had the lowest percentages of 42.26% and 46.69%, respectively. All these studied sunflower hybrids exhibited much higher level of antioxidant activity than previously reported (Abdalla et al., 2021; Gagour et al., 2022). In 2018, 'Niagara' registered the highest percentage of antioxidant activity (63.61%), followed by 'IN5542' (58.91%) and 'Pentasol' (56.83%), while 'Besana' had the lowest percentage (36.99%), which was statistically comparable with the percentage for 'Meridia' (41.97%). In 2019, 'Pentasol', 'IN5542' and 'Bosphora' exhibited the highest percentages of antioxidant activity, reaching 62.23%, 60.11% and 59.98% respectively, whilst 'Besana' had the lowest antioxidant activity, with a mean value of

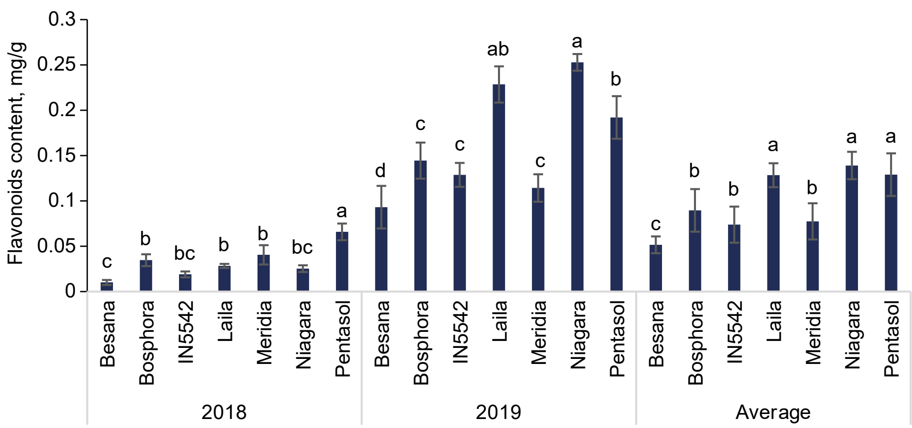

Fig. 7. Flavonoid content of seven sunflower hybrid varieties grown in two contrasting years, 2018 and 2019. For each year and combined years (average), varieties with the same alphabetical letters are not statistically different according to Duncan's test

47.53%, which was statistically comparable with the values for 'Laila' (50.69%), 'Niagara' (50.90%) and 'Meridia' (51.41%). The variations observed between years and varieties indicate that differences in the antioxidant capacity of the sunflower varieties studied are influenced by genetic and environmental factors. Sunflower varieties with higher levels of antioxidant activity, such as 'IN5542', 'Niagara', and 'Pentasol', may be suitable for the production of functional foods or antioxidant-rich ingredients. These findings are relevant to the food industry and nutrition, as antioxidants play an important role in promoting optimal health.

The antioxidant properties of sunflower seeds and the factors influencing their antioxidant capacity have been extensively documented (Zilic et al., 2010; Nadeem et al., 2011; Muhammad Anjum et al., 2012; Karamać et al., 2012; Niemann et al., 2018; Gagour et al., 2022). Other studies indicate that antioxidant activity in vegetable oils in general decreases when the levels of nutritional compounds, including polyphenols and tocopherols, are reduced (Velasco and Ruiz-Méndez, 2015; Yang et al., 2018). The positive and significant correlation between antioxidant activity and polyphenols in sunflower oil was also confirmed in the present study (Table 4).

It has previously been reported that sesame oil possesses more potent antioxidant properties, followed by sunflower and rapeseed oils (Sumara et al., 2023). Sesame oil has an antioxidant activity range of 46–68% (Bopitiya and Madhujith, 2015), while rapeseed oil exhibits a range of 22.7–42.9% (Guirrou et al., 2023). According to our results, sunflower oil extracted from the studied varieties exhibits a good level of antioxidant activity, varying from 47% to 63%, which is close to that of sesame oil.

Oil color properties

Table 3 presents average values of the different parameters of oil color in the seven sunflower varieties investigated. Aesthetic quality is a parameter that matters commercially; it is crucial to monitor both the color and the appearance of the oil to manage the quality of the finished product and its final characteristics. The presence of carotenoid or chlorophyll pigments gives oils their color; the latter give virgin oils a greenish tint. Also, due to field damage, poor storage, or careless treatment during crushing or extraction, some crude oils may exhibit unexpectedly high pigmentation (Ramos-Escudero et al., 2019).

The L^* value represents the lightness of the color, with higher values indicating lighter colors. Overall, when considering all varieties and both years, the average L^* value is 31.68. This suggests that, on average, the sunflower varieties have a moderately light color. In summary, 'Meridia' has the highest L^* value (33.62), suggesting it has the lightest color among the varieties, followed by Laila (32.19), 'Besana'

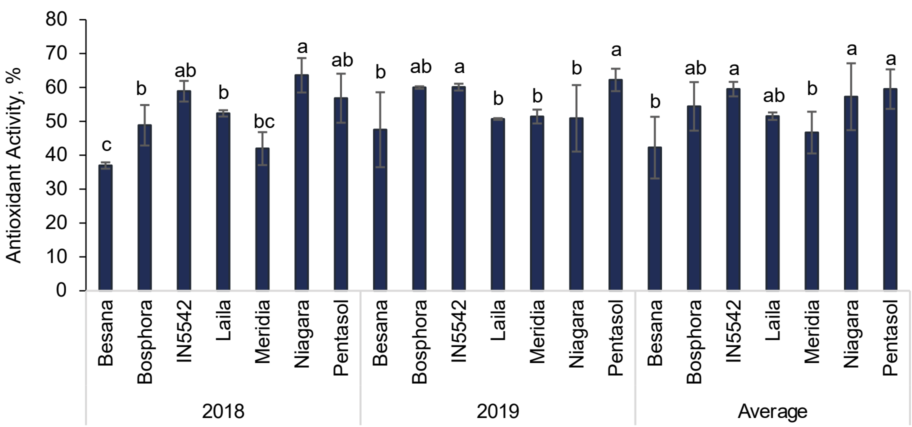

Fig. 8. Antioxidant activity of seven sunflower hybrid varieties grown in two contrasting years, 2018 and 2019. For each year and combined years (average), varieties with the same alphabetical letters are not statistically different according to Duncan's test

Table 3. Variation in oil color parameters in different sunflower varieties grown over two consecutive years (values are expressed as mean ±SD).

Year	Variety	*L**	*a**	*b**
2018	Besana	31.69 ±5.83 ab	–0.13 ±0.10 c	6.74 ±1.17 a
	Bosphora	29.77 ±1.83 c	0.29 ±0.26 b	5.43 ±1.68 b
	IN5542	31.31 ±2.44 ab	–0.17 ±0.24 c	5.02 ±0.90 c
	Laila	31.99 ±1.25 ab	–0.26 ±0.10 b	6.56 ±1.51 ab
	Meridia	33.62 ±1.76 a	–0.18 ±0.12 c	6.79 ±1.16 a
	Niagara	32.09 ±0.86 a	–0.41 ±0.16 a	6.60 ±1.58 a
	Pentasol	30.59 ±1.93 bc	0.09 ±0.01 d	5.47 ±0.83 b
2019	Besana	31.79 ±0.39 ab	0.10 ±0.11 d	6.09 ±1.41 b
	Bosphora	31.45 ±1.74 ab	–0.19 ±0.05 c	5.42 ±0.75 bc
	IN5542	31.71 ±1.33 ab	–0.33 ±0.11 a	4.56 ±0.43 c
	Laila	32.39 ±1.04 a	0.06 ±0.01 e	6.24 ±1.78 ab
	Meridia	33.62 ±1.46 a	–0.07 ±0.01 e	6.79 ±1.16 a
	Niagara	31.03 ±0.86 ab	–0.29 ±0.03 b	4.95 ±1.62 c
	Pentasol	30.59 ±0.26 b	0.09 ±0.01 e	5.47 ±0.83 bc
Average	Besana	31.74 ±0.39 ab	–0.02 ±0.10d	6.41 ±1.17 a
	Bosphora	30.61 ±1.60 b	0.05 ±0.18d	5.43 ±1.68 b
	IN5542	31.51 ±1.98 ab	–0.25 ±0.19b	4.79 ±0.90 c
	Laila	32.19 ±1.05 ab	–0.10 ±0.13c	6.40 ±1.51 a
	Meridia	33.62 ±1.46 a	–0.13 ±0.10c	6.79 ±1.16 a
	Niagara	31.56 ±0.77 b	–0.35 ±0.12a	5.78 ±1.58 b
	Pentasol	30.59 ±1.36 b	0.09 ±0.01d	5.47 ±0.83 b

Significant differences between groups are indicated by different alphabetical letters, following Duncan's test ($p < 0.05$).

(31.74) and 'IN5542' (31.51). In contrast, 'Pentasol' and 'Bosphora' have a relatively dark oil color (about 30.60).

The *a** value represents the position between red/magenta (+) and green (–) in oil color. Overall, the average a* value, across both years and for all varieties, is approximately –0.101. This suggests a slight tendency towards green hues. 'Bosphora' and 'Pentasol' have the highest positive *a** value (0.09 and 0.05), indicating a tendency towards red/magenta hues in their oils. However, 'Niagara' and 'IN5542' have negative *a** value (–0.35 and –0.25), suggesting a tendency towards green hues.

The *b** value represents the position between blue/yellow (+) and white/gray (–) in oil color. Considering all varieties and years, the overall average *b** value is approximately +5.866, which suggests a marked tendency towards yellow hues. 'Meridia', 'Laila', and 'Besana' have the highest average *b** value (>6.40), indicating a tendency towards yellow hues. In contrast, 'IN5542' presented a slightly lower average value (+4.79), indicating that its oil had bluer hues.

Our findings reveals that each variety exhibits specific shades of brightness, red-green and yellow-blue components, chromaticity, and hue, which is attributed to variations in pigment composition that may be under genetic control in the different sunflower varieties studied.

Correlation analysis

With regard to correlations among the parameters listed in Table 4, only coefficients greater than |0.5| were considered and interpreted. Oil content has a significant and negative correlation with refractive index (–0.505), suggesting that sunflower oil samples with high oil content tend to show better quality in terms of refraction. In turn, refractive index has a significant and positive correlation with acidity index (0.600) and peroxide index (0.645), which may be explained by the fact that these three parameters are often associated with the degradation of sunflower oil. An increase in acidity index and peroxide index may indicate increased oxidation or degradation of the oil, which may influence its chemical composition and therefore its refractive index. Acidity index shows a significant and positive correlation with peroxide index (0.616) and a negative correlation with polyphenol content (–0.503). When sunflower oil undergoes oxidation, the fatty acids present in the oil can degrade, which increases the free acid content and therefore the acidity index. In parallel, the oxidation of fatty acids can also lead to the formation of peroxides, which explains the positive correlation observed. Thus, an increase in the oxidation of sunflower oil leads to an increase in both the acidity and the peroxide index, which is a measure of the peroxide content and shows the degree of oxidation of an oil in the early stages of oxidative rancidity (Goszkiewicz et al., 2020). The negative correlation between acidity index and polyphenol content can be explained by the role of polyphenols in protection against oil oxidation. Polyphenols are antioxidant compounds found in many foods, including sunflower oil. Their presence can reduce the oxidation of fatty acids and therefore delay the formation of free acids, which explains the negative correlation with the acidity index. Polyphenols can react with free radicals generated during oxidation, neutralizing them and thus protecting the oil against oxidation.

On the other hand, polyphenol content shows a significant and positive association with flavonoid content (0.524). Polyphenols and flavonoids are known for their antioxidant properties and their ability to

Table 4. Pearson's correlation coefficients among the different parameters studied

	Oil content	Refractive index	Acidity index	Peroxide index	Polyphenol content	Flavonoid content	Antioxidant activity	*L**	*a**	*b**
Oil content	1									
Refractive index	–0.505***	1								
Acidity index	–0.381*	0.600***	1							
Peroxide index	–0.414**	0.645***	0.616***	1						
Polyphenol content	0.079	–0.352*	–0.503***	–0.328*	1					
Flavonoid content	0.282	–0.406**	–0.658***	–0.396*	0.524***	1				
Antioxidant activity	0.062	–0.045	–0.253	–0.233	0.382*	0.235	1			
*L**	0.089	0.054	0.082	0.233	–0.189	–0.095	–0.258	1		
*a**	–0.271	–0.108	–0.212	–0.081	0.072	0.037	–0.240	–0.127	1	
*b**	–0.049	0.042	0.289	0.231	–0.187	–0.350*	–0.328*	0.491***	–0.021	1

p-values *, ** and *** were significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

protect cells against oxidative damage. Thus, it makes sense to see a positive correlation between polyphenol and flavonoid content, as they can be present together in the same plant sources and contribute to the antioxidant properties of sunflower oil. Typically, when discussing phenolics in plant foods, flavonoids are the predominant class described, because they account for approximately two-thirds of the dietary phenols (Shahidi and Ambigaipalan, 2015). An overall decrease in total polyphenol and flavonoid content also indicates a decrease in the nutritional value of oils after smoking and storage (Avni et al., 2016). Flavonoid content is negatively associated with acidity index (–0.658). In fact, flavonoids can act as buffering agents, helping to maintain pH balance and reduce oil acidity. Thus, an increase in the content of flavonoids can lead to a decrease in the acidity index of sunflower oil.

Regarding color properties, weak but significant correlations were observed between some traits. The *L** parameter shows a significant positive correlation with *b** (0.491). This correlation may be related to the presence of pigments in sunflower oil, such as carotenoids, which can contribute to a more intense and more yellow (high *b** value) coloration. Additionally, the negative correlation between the *b** parameter and the flavonoid content (–0.350) as well as the antioxidant activity (–0.328) can be explained by the chemical properties of these compounds. Flavonoids and antioxidant compounds can have a blue or purple tint, which can cause a decrease in the *b** value (Sant'Anna et al., 2013). Variations in the concentration of these compounds can influence the perception of oil brightness and hue, which is reflected in the observed correlations.

Principal Component Analysis

The total variance explained by the first two components is 64.62% (Fig. 9). The first principal component (PC1), which explains 41.21% of the variance, is associated with parameters related to the acidity index, antioxidant activity, and color properties. On the other hand, the second principal component (PC2), which explains 23.41% of the total variance, is correlated with the refractive index and polyphenol content.

The projection of the varieties studied onto the PCA F1/F2 plot makes it possible to classify them into four distinct groups. Group 1 contains just one variety, namely 'Besana', characterized by relatively higher oil content (38.25%) and acidity index (2.37 mg KOH/g), but lower peroxide index (2.25 meq O_2/

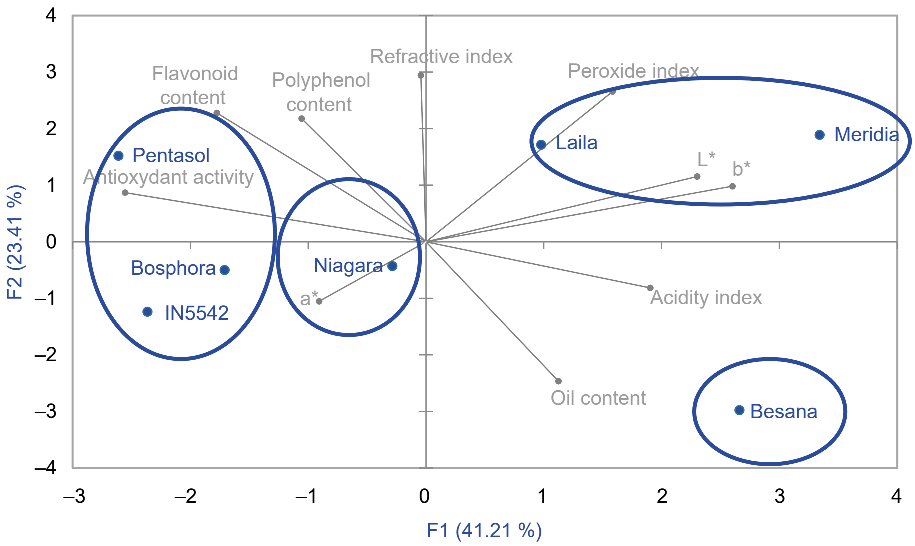

Fig. 9. Two-dimensional PCA plot of seven sunflower varieties based on biochemical traits: visualization of biochemical parameters and varietal distribution along the first two principal axes (F1 and F2)

kg), polyphenol content (3.45 mg GAE/g), flavonoid content (0.05 mg/g), and antioxidant activity (42.26%) compared to the other groups. This variety has a clear and vivid color, with a hue closer to red and a weak green component, suggesting its potential use in several fields, such as the culinary industry, cosmetics, skin care products, the production of functional foods, and the paints and dyes industry.

'Pentasol', 'Bosphora', and 'IN5542' constitute the second group, which is distinguished by low average values in oil content (32–35.45%), peroxide index (2.23–2.64 meq O_2/kg), and acidity index (1.8–2.07 mg KOH/g). The antioxidant activity (54.42–59.51%), polyphenols (5.49–5.87 mg GAE/g), and flavonoids (0.07–0.09 mg/g) are higher in these varieties, suggesting higher oil stability, compared to the other groups. In this group, an average value of –0.13 of *a** indicates lighter colors with a more pronounced green tint. Thus, the oils of these three varieties can be used in a variety of applications including cooking, the manufacture of bakery and pastry products, seasonings, and dressings, as well as in the cosmetics industry for hair and skin care products.

Group 3, with the two varieties 'Meridia' and 'Laila', has moderate average oil content (33.64%), antioxidant activity (46.69–51.52%), polyphenols (4.63–6.91 mgGAE/100g), and flavonoids (0.07–0.12 mg/g) compared to the first two groups. The average values of the acidity index (2.16–2.35 mg KOH/g) and the peroxide index (4.45 meq O_2/kg), are higher than those of the other groups, suggesting a lower stability of the oil. High *L** and *b** values indicate a lighter color, with a pronounced yellow tint and a slight shade of red. Although the oils of 'Meridia' and 'Laila' exhibit slightly lower values in terms of oil content and antioxidant activity, compared to the first groups, they can still be used in various applications, especially in the cosmetics and culinary industries, food supplements, and products based on flavored oils. Their attractive color characteristics add extra aesthetic value to these oils.

The 'Niagara' variety clustered in class 4 exhibits quite high oil content (37.37%) and moderate values for acidity index (2.6 mg KOH/g), antioxidant activity (57.26%), polyphenol content (6.4 mg GAE/100g), flavonoid content (0.14 mg/g), and peroxide index (2.91 meq O_2/kg), suggesting that it has high potential to produce natural antioxidant compounds. Moreover, its moderate *a** value suggests a less green color. The oil of this variety has great potential for use in various industries, including food, cosmetics, and pharmaceuticals, due to its antioxidant properties, high oil content, and attractive colors.

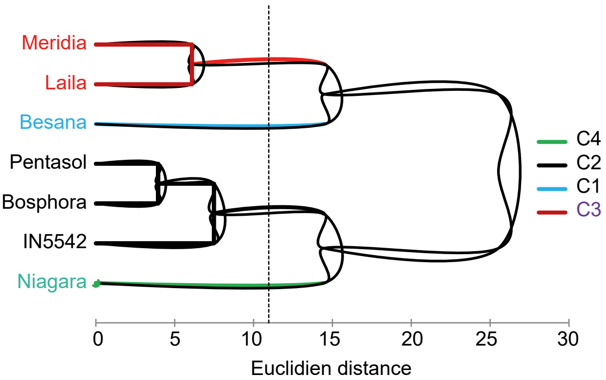

Fig. 10. Clustering of sunflower varieties based on biochemical traits using Euclidean Distance

The dendrogram generated from the matrix of Euclidean distances among the seven studied sunflower varieties (Fig. 10) corroborates these four distinct groups. This dendrogram is a useful tool that can help elucidate the genetic and biochemical relationships among the different sunflower varieties, which may be important not only for providing guidance on their nutritional and industrial use, but also for breeding purposes.

CONCLUSION

The development and promotion of sunflower crop in Morocco can be enhanced through the healthy biochemical components provided by the oil extracted from its seeds. The results of this study reveal significant differences between the two years and among varieties for oil content and all quality parameters studied except for refractive index. On the other hand, the effect of the interaction between year and variety was not significant for any parameters apart from peroxide index, indicating the stability of variety rankings for these parameters.

Overall, four homogeneous groups of hybrid varieties were identified based on oil content and other biochemical parameters. These findings have implications for the use of seed oils of these hybrids in various industries and underscore the importance of further and more in-depth research on sunflower oil quality in the context of climate change.

In addition, the homogeneous groups obtained could be considered as parental pools to be used in a sunflower breeding program aiming to develop new genetic material with better performance. In view of the findings of this study, as part of innovative research to respond to the challenge of developing sustainable agriculture, research on sunflower quality remains an effective strategy to guarantee healthy and high-quality oil for consumers.

DECLARATIONS

Data statement

All data supporting this study has been included in this manuscript.

Ethical Approval

Not applicable.

Competing Interests

The authors declare that they have no conflicts of interest.

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