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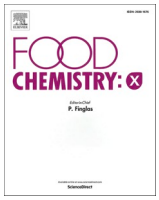

Oxidative stability and nutritional quality of stored *Linum usitatissmium* L. and *Argania spinosa* L., oil blends: Chemical compositions, properties and nutritional value

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A R T I C L E I N F O

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A B S T R A C T

Identification of the chemical compositions of fatty acids and tocopherols shows the high content of *linum usitatissimum* oil (LO) by linolenic acid 55.3735% and γ-tocopherol 570.927 mg/kg, while *argania spinosa* oil (AO) is known by the dominance of oleic acid 47.77% followed by linoleic acid 31.08% as well as tocopherols by γ-tocopherols 687.485 mg/kg and δ-tocopherols 51.035 mg/kg. This difference in compositions enables us to enrich the low-stability oil and monitor its behavior during storage at a specific time and under specific conditions. In this study, pure *linum usitatissimum* and *argania spinosa* oils extracted by cold pressing as well as their formulations at proportions of (LO: AO) respectively: (80:20; 60:40, 50:50; 40:60; 20: 80) were oxidized at 60 °C for 28 days of storage, during which time the pure oils and blends were assessed for oxidative stability by studying their different fatty acid and tocopherol profiles and physicochemical characteristics such as acidity, peroxide value and chlorophyll and carotenoid pigments, as well as nutritional indexes such as the atherogenic index (AI), the thrombogenic index (TI), and the hypocholesterolemic: hypercholesterolemic ratio (HH), ω_3:ω_6 ratio, also the oxidative susceptibility (OS), and oxidazability value (Cox), and total phenolic compounds (TPC).

1. Introduction

A cultivated food crop, linseed (*Linum usitatissimum* L.), also known as flaxseed, produces seeds that are golden yellow to reddish brown in color according to its different varieties (Freeman, 1995; Kajla, Sharma, & Sood, 2015), Having an oval shape, a pointed tip, and a smooth shiny surface,(Kaur, Singh, & Kaur, 2017) A range of bioactive compounds was also found in linseed, including ALA, protein, mucilage, minerals, and phenolic compounds such as phenolic acid compounds, lignans, flavonoids, and tannins (Bechlin, Granella, Christ, Coelho, & Viecelli, 2019; de Oliveira Giarola, Pereira, Prado, de Abreu, & de Resende, 2019; Kajla et al., 2015; Kasote, 2013; Lan, Ohm, Chen, & Rao, 2020),. In

Abbreviations: LO, *Linum usitatissimum* oil; AO, *Argania spinosa* oil; L, *Linum usitatissimum*; A, *Argania spinosa*; W_0, W_1, W_2, W_3, W_4, Week 0 to Week 4; SFA, Satured fatty acids; UFA, Unsaturated fatty acids; PUFA, Polyunsatured fatty acids; AI, Atherogenic index; TI, Thrombogenic inde; Cox, Oxidazability value; OS, Oxidative susceptibility; HH, Hypocholesterolemic: Hypercholesterolemic ratio; TFA, Trans fatty acids; ω_3/ω_6, Omega-3: Omega-6 ratio; TPC, Total polyphenols content; FFA, Free fatty acid; PV, Peroxide value; CD, Conjugated dienes.

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general,the oil contains significant amounts of polyunsaturated fatty acids (PUFAs) as well as a-linolenic acid (ALA), which is an omega-3 (55%) fatty acid and essential fatty acid (FA) (Simopoulos, 2002; Zhang et al., 2008).

ALA are prioritised by their ability to lower blood pressure, triacylglycerol levels in blood plasma, plus anticoagulant and antitumour effects (Kchaou, Jridi, Nasri, & Debeaufort, 2020) as well as reducing the likelihood of the onset of heart disease and osteoporosis, anti-mammary or tumour activities of the prostate gland, as well as anti-inflammatory and laxative activities and also the relief of menopausal symptoms, etc. (Afzal, Butt, Ashfaq, Bilal, & Suleria, 2020; DeLuca, Garcia-Villatoro, & Allred, 2018; Parikh et al., 2019; Simopoulos, 2002; Tang et al., 2021) also linseed oil having cardioprotective and antiatherogenic activity (Carneiro, Tonon, Grosso, & Hubinger, 2013; Goyal et al., 2016; Gumus, Decker, & McClements, 2017; Hano et al., 2017; Kchaou et al., 2020; Tzang et al., 2009).

Argan oil comes from the Argan tree *Argania spinosa* originating from the Moroccan southwest., as a multipurpose tree, Argan plays an important socio-economic role, and maintain the ecological balance and protect biodiversity (Khallouki et al., 2017), each fruit's core contains one to three seeds, of which each is composed of up to 58% of oil (El Idrissi et al., 2023; Hanana et al., 2018), that contains large amounts of unsaturated (80%) and saturated (20%) fatty acids (Sevindik, Amanpour, Tsouli Sarhir, Kelebek, & Selli, 2019), and the non-saponifiable materials consist of a range of biologically active compounds including carotenes (37%), tocopherols (8%), triterpenic alcohols (20%), sterols (29%) and xanthophylls (5%) (Lall et al., 2019).

The use of a combination of common edible oils and unconventional oils is allowed so that costs can be reduced and the needs of the industry can be met also to keep the normal physiological functions of the human body (Choudhary, Grover, & Kaur, 2015), blended oil is an edible oil product prepared from two or more vegetable oils refined by specific proportions according to nutritional needs such as the proportion of fatty acids in blended oils is likely to be produced to meet the needs of the human body and therefore blended oils not only improve human health and achieve the goal of a balanced diet, but also reduce the incidence of certain chronic diseases (Li et al., 2014),), this is due to their increased content of bioactive lipids and natural antioxidants to provide better quality oils, including better physical and chemical properties, higher nutritional values and affordability (Ramadan & Wahdan, 2012) plus their stability to oxidation during and after processing as an added value on the market (Tavakoli et al., 2018).

The purpose of this paper is to study the chemical compositions as well as the physicochemical and nutritional characteristics plus the oxidation stability of pure oils and their blends at different proportions. Thanks to the differences in all the parameters noted for all the oils, the healthy role of enrichment of pure oil with low stability is proven against oxidation during storage at precise conditions.

2. Materials and methods

2.1. Materials

The brown linseeds come from the Khemisset region (33.894629, −6.028125) and the argan fruits from the Agadir region (30.426467, −9.597458) in Morocco. The mature linseeds are harvested towards the end of May 2022, and the oval argan fruits at the end of August 2022, then separated from the capsules and hulls, packaged, and sent to the laboratory, where they are kept in amber bottles at 4 °C, to be cold pressed into linseed oil (LO) and argan oil (AO) vegetable oils.

2.2. Chemicals

All chemical reagents, including solvents, were of analytical grade and were obtained from local suppliers.

Chemical Solvents: cyclohexane; ethanol; chloroform; acid acetic.

Chemical reagents: Folin-Cio-calteu reagent; phenolphtaleine; sodium thiosulfate; potassium hydroxide.

2.3. Blending process

Mixtures of LO and AO were formulated to give the following (LO: AO) (wt/wt) ratios: 20:80, 40:60, 50:50, 60:40 and 80:20, in addition, pure LO and AO oils were used as controls to assess progress. As part of the preparation of the blend, the oils were thoroughly homogenized in a magnetic stirrer for 30 min at 25 °C at 100 rpm until each mixture became homogeneous and uniform. Four sets of sample vials were prepared, labelled and stored in a ventilated oven at 60 °C for 4 weeks. In each week, seven vials were removed from the oven to reach thermal equilibrium with the ambient temperature of the laboratory prior to the study.

2.4. Analysis of chemical properties of pure and blended oil

2.4.1. Fatty acid composition analysis

The chemical composition of fatty acids were analyzed under conditions described in ISO 12966-4:2015 standard (P. Iso, 2015), the analysis consists of transesterifying glycerides into volatile methyl esters. In order to analyse them by gas chromatography. In a 100 mL flask, a mass of 1 g of the sample is added to a volume of 0.5 mL of methanolic KOH of normality 2, and 10 mL of methanol. Then 1 mL of heptane is added to the reaction mixture, after cooling. The heptane phase containing the methyl esters is transferred to a test tube, and a solution of sodium carbonate, Na_2CO_3 is added. The latter neutralises all the free acids by giving sodium salts with a release of carbon dioxide. The methyl esters, which are in the organic phase, are removed using a pipette. These are analyzed by gas chromatography GC. The HP Hewlett Packard 6890 series GC system is equipped with a splitter injector (T: 240 °C) and an FID (T: 260 °C). The carrier gas is nitrogen (PE: 12.4 bar). The analysis is performed in temperature programming (140 °C to 200 °C with a speed of 10 °C/ min and an isotherm at 200 °C for 60 min) on a capillary column (polyethylene glycol) (30 m length × 0.32 mm, ID: 0.25 μm film thickness). The data are processed with Varian Star Workstation v. 6.30 and expressed as a relative percentage of each fatty acid (Belcadi-Haloui, Zekhnini, El-Alem, & Hatimi, 2018).

$$\sum \text{SFA} = [\text{Palmitic acid}] + [\text{Stearic acid}]$$

$$\sum \text{MUFA} = [\text{Oleic acid}] + [\text{minors monounsaturated fatty acids}]$$

$$\sum \text{PUFA} = [\text{Linoleic acid}] + [\alpha - \text{linolenic acid}]$$

2.4.2. Tocopherols determination

The tocopherol composition was determined according to the "ISO 9936" method (I. S. O. Iso, 2006), by means of high performance liquid chromatography (HPLC) using a solution of 250 mg of oil in 25 ml of n-heptane, via Shimadzu CR8A instruments connected to a C18-Varian column, and then Detection is carried out using a fluorescence detector (excitation wavelength 290 nm − emission wavelength 330 nm) on a silica column (25 cm × 4 mm). The mixture of isooctane/isopropanol (99:1) (*V*/V) occupies the eluent and α-tocopherol acts as the external standard.

2.4.3. Total phenolic compounds (TPC)

An aliquot (0.2 mL) of the methanolic phase was diluted with water to a total volume of 5 mL, followed by the addition of 0.5 mL Folin-Cio-calteu reagent. After 3 min, 1 mL sodium carbonate solution (20% *w/v*) was added to the reaction mixture which was finally mixed and diluted with water to 10 mL. The absorbance of the solution was measured after 2 h against a blank sample on a Shimadzu Spectrophotometer at the wavelength of 765 nm. Concentration values were reported by using a

standard curve obtained with gallic acid. This method was performed accordingly to (Hrncirik & Fritsche, 2004) with minor modifications.

2.4.4. Physicochemical properties

The oxidative stability of cold-pressed pure and blended oils throughout their shelf life (at 60 °C) was determined according to the American Oil Chemists' Society (Aocs, 1998), by the free fatty acids (FFA), peroxide value (PV) (Iso, 2012), and specific extinction coefficients (K232 and K270) (I. S. O. Iso, 2011), also determination of chlorophylls and carotenoids (Gharby et al., 2018) after 28 days of storage.

The FFA was expressed in (% of oleic acid).

The peroxide index was expressed as (meq O_2/kg oil).

The specific extinction coefficients (K232 and K270) were expressed as the extinction Specificity of a 1% (*w/v*) solution of oil in cyclohexane.

The carotenoids are expressed at 470 nm as mg of lutein per kg of oil, and at 670 nm the chlorophylls are analyzed as mg of pheophytin per kg of oil.

$$[\text{Chlorophylls}]\ (\text{mg/kg}) = A_{670} \times 10^6 / 613 \times 100 \times d \quad (1)$$

$$[\text{Carotenoids}]\ (\text{mg/kg}) = A_{470} \times 10^6 / 2000 \times 100 \times d \quad (2)$$

'A' = the absorbance

'd' = the thickness of the spectrophotometer cell (1 cm).

The specific extinction coefficients used were $E_0 = 613$ for pheophytin, a major component of the chlorophyll fraction, and $E_0 = 2000$ for lutein, a major component of the carotenoid fraction.

2.4.5. Nutritional indexes

Nutritional properties were evaluated using different indexes: the atherogenic index (AI), the thrombogenic index (TI), oxidazability value (COX), also the oxidative susceptibility (OS), and the hypocholesterolemic: hypercholesterolemic ratio (HH).

Calculation of these factors was carried out based on the levels of fatty acids using the equations:

The formulas for calculating (AI) and (TI) appear to be (Hashempour-Baltork, Torbati, Azadmard-Damirchi, & Savage, 2018):

$$AI = \left[((4 \times C14:0) + C16:0 + C18:0) \Big/ \left(\sum MUFA + \sum \omega_6 \times PUFA + \sum \omega 3 \times PUFA\right)\right] \quad (3)$$

$$TI = [(C14:0 + C16:0 + C18:0)]/[(0.5 \times MUFA) + (0.5 \times \omega_6 \times PUFA) + (3 \times \omega_3 \times PUFA) + (\omega_3/\omega_6 \times PUFA)] \quad (4)$$

and the Cox's equation is (Fatemi & Hammond, 1980):

$$COX = [C18:1 + (10.3 \times C18:2) + (21.6 \times C18:3)] \times 100 \quad (5)$$

Oxidative susceptibility (OS) was calculated using the formula according to (Cecchi, Passamonti, Alfei, & Cecchi, 2011):

$$OS = [MUFA + (45 \times C18:2) + (100 \times C18:3)] \quad (6)$$

Hypocholesterolemic /hypercholesterolemic ratio (HH) (Mierliță, 2018):

$$HH = [(cis - C18:1 + \Sigma PUFA)/(C12:0 + C14:0 + C16:0)] \quad (7)$$

2.5. Statisctical analysis

Each variable was studied in triplicate, and results were expressed as the mean of the three independent one-sample measurements ($n = 3$) ± SD (n = 3). Statistical analyses were performed using GraphPad Prism software version 10.1.2(324). An analysis of variance (ANOVA) was performed using a two-way followed by Tukey's significant difference test ($p < 0.05$). An analysis of correlation was performed by Pearson's test.

3. Results and discussion

No single oil satisfies all nutritional needs or has an ideal fatty acid profile, hence the idea of careful blending of vegetable oils, is a cost-effective practice for modifying their fatty acid composition and physicochemical properties (Choudhary et al., 2015) (Anwar et al…, 2007; Reena & Lokesh, 2007), creating higher levels of natural antioxidants and bioactive lipids and, consequently, improving the oils' stability and nutritional values (Aladedunye, Przybylski, & c., 2013).

3.1. Fatty acids

3.1.1. Changes in fatty acid contents during oxidation

The fatty acids of LO and AO oils and their blends are shown in Table 1, Linseed oil is characterized by a high percentage of linolenic acid (C18:3; 55.3735 ± 0.006), and linoleic acid (C18:2; 15.005 ± 0.007), followed by oleic acid (C18:1; 19.565 ± 0.021), while argan oil is identified by the majority compound oleic acid (C18:1; 47.777 ± 0.0042) followed by linoleic acid (C18:2; 31.08 ± 0.028) and the low linolenic acid content (C18:3: 0.125 ± 0.007). The monounsaturated fatty acid content in AO is higher than in LO, which increases its oxidative stability. Vegetable oils with a high proportion of unsaturated fatty acids are generally not as stable as vegetable oils with a high proportion of saturated fatty acids (Micić et al., 2015). (See Figs. 1–17.)

These results are consistent with the fatty acid composition of AO reported by (El Idrissi et al., 2023; Fellat-Zarrouck, 1987), on the other hand the identification of LO fatty acids is in the interval of recent results (Alshehri, Tolba, Salama, Saleh, & Kamel, 2024; Golmakani, Soltani, Hosseini, & Keramat, 2020; Mostafa, Moharram, Attia, & El–Sharnouby, S. A., 2013; Sharma & Lokesh, 2013).

Accelerated oxidation of pure oils and blends at 60 °C and increased storage time revealed a similar trend, at a non-significant difference at ($p > 0.05$), in the fatty acid contents of the seven oils at the start and at day 28 of the accelerated storage experiment.

The ratios (80: 20) and (60: 40) show profiles close to or slightly different from that of control LO, such as a decrease in C18:3 ranging from 55% (LO), to (42% and 31%), and an improvement in C18:2 ranging from 15% (LO) to (18% and 21%), and an increase in C18:1 ranging from 19% (LO) to (24% and 30%), respectively for (80: 20 and 60: 40). And for the 50% proportion of each of the blended oils, shows a balance of fatty acid contents such as oleic acid (C18:1; 32.84 ± 0.028), linoleic acid (C18:2; 22.735 ± 0.007) and linolenic acid (C18:3; 27.065 ± 0.007), plus palmitic acid (C16:0; 9.005 ± 0.0014), within the range of LO and AO contents.

On the other hand, oils blended with (40: 60) and (20: 80) are identified by fatty acid percentages close to those of AO, a strong decrease is shown by C18:3, which falls from 55% for LO to (19% and 9%), and a good improvement in C18:1, which rises from 19% for LO to (35% and 41%) respectively (40: 60 and 20: 80), so AO added to LO seems useful for reducing C18:3 and enriching in C18:1.

As the proportion of AO increased in oils blended at (20: 80 and 40: 60), the proportion of MUFAs, especially oleic acid, also increased, and the PUFA/AGS ratio progressively decreased. And conversely, as the

Table 1
Major Fatty acids composition of pure LO, AO, and blended oils.

Weeks	FA	LO	(80: 20)	(60: 40)	(50: 50)	(40: 60)	(20: 80)	AO
W_0	**C16:0**	4.74 ± 0.028^{a}	5.8165 ± 0.007^{c}	8.315 ± 0.007^{d}	9.005 ± 0.0014^{e}	9.055 ± 0.007^{f}	11.0065 ± 0.000^{g}	13.146 ± 0.002^{b}
	C18:0	4.621 ± 0.049^{a}	5.015 ± 0.007^{c}	5.33 ± 0.014^{d}	5.0045 ± 0.000^{e}	4.825 ± 0.063^{f}	5.645 ± 0.021^{g}	6.25 ± 0.07^{b}
	C18:1	19.565 ± 0.021^{a}	24.265 ± 0.021^{c}	30.2 ± 0.028^{d}	32.84 ± 0.028^{e}	35.205 ± 0.007^{f}	41.56 ± 0.014^{g}	47.777 ± 0.0042^{b}
	C18:2	15.005 ± 0.007^{a}	18.0035 ± 0.0007^{c}	21.29 ± 0.014^{d}	22.735 ± 0.007^{e}	23.575 ± 0.007^{f}	27.055 ± 0.035^{g}	31.08 ± 0.028^{b}
	C18:3	55.3735 ± 0.006^{a}	42.0005 ± 0.0007^{c}	31.67 ± 0.014^{d}	27.065 ± 0.007^{e}	19.065 ± 0.007^{f}	9.105 ± 0.007^{g}	0.125 ± 0.007^{b}
	C20:0	0.161 ± 0.001^{a}	0.197 ± 0.0014^{a}	0.18 ± 0.028^{a}	0.26 ± 0.028^{c}	0.285 ± 0.003^{d}	0.26 ± 0.014^{e}	0.3865 ± 0.002^{b}
W_1	**C16:0**	4.825 ± 0.007^{a}	6.412 ± 0.001^{c}	8.346 ± 0.002^{d}	9.02 ± 0.001^{e}	9.155 ± 0.007^{f}	11.317 ± 0.00^{g}	13.163 ± 0.001^{b}
	C18:0	4.704 ± 0.001^{a}	5.234 ± 0.001^{c}	5.445 ± 0.007^{d}	5.065 ± 0.021^{e}	5.425 ± 0.021^{f}	5.91 ± 0.00^{g}	6.330 ± 0.001^{b}
	C18:1	19.669 ± 0.001^{a}	24.408 ± 0.002^{c}	30.985 ± 0.007^{d}	33.655 ± 0.007^{e}	36.21 ± 0.014^{f}	41.695 ± 0.0071^{g}	47.948 ± 0.003^{b}
	C18:2	15.015 ± 0.001^{a}	18.024 ± 0.001^{c}	21.45 ± 0.014^{d}	22.935 ± 0.007^{e}	24.06 ± 0.014^{f}	27.112 ± 0.0021^{g}	31.148 ± 0.004^{b}
	C18:3	55.493 ± 0.004^{a}	42.014 ± 0.004^{c}	31.915 ± 0.007^{d}	27.365 ± 0.007^{e}	19.735 ± 0.007^{f}	9.202 ± 0.000^{g}	0.160 ± 0.00^{b}
	C20:0	0.165 ± 0.007^{a}	0.203 ± 0.003^{c}	0.2 ± 0.00^{d}	0.306 ± 0.003^{e}	0.315 ± 0.002^{f}	0.360 ± 0.014^{g}	0.405 ± 0.001^{b}
W_2	**C16:0**	5.214 ± 0.003^{a}	6.804 ± 0.002^{c}	8.75 ± 0.071^{d}	9.371 ± 0.003^{e}	10.349 ± 0.0014^{f}	11.610 ± 0.014^{g}	13.725 ± 0.007^{b}
	C18:0	4.755 ± 0.007^{a}	5.633 ± 0.018^{c}	5.529 ± 0.001^{d}	5.585 ± 0.021^{e}	5.764 ± 0.000^{f}	5.935 ± 0.007^{g}	6.356 ± 0.008^{b}
	C18:1	18.985 ± 0.007^{a}	33.370 ± 0.014^{c}	31.049 ± 0.003^{d}	34.316 ± 0.36^{e}	36.277 ± 0.049^{f}	41.632 ± 0.003^{g}	47.97 ± 0.014^{b}
	C18:2	15.275 ± 0.007^{a}	18.15 ± 0.014^{c}	21.72 ± 0.014^{d}	23.115 ± 0.007^{e}	24.460 ± 0.0141^{f}	27.91 ± 0.014^{g}	30.715 ± 0.007^{b}
	C18:3	55.67 ± 0.00^{a}	42.46 ± 0.014^{c}	32.35 ± 0.014^{d}	28.240 ± 0.001^{e}	21.341 ± 0.0014^{f}	10.495 ± 0.007^{g}	0.092 ± 0.001^{b}
	C20:0	0.175 ± 0.007^{a}	0.206 ± 0.002^{a}	0.207 ± 0.028^{a}	0.310 ± 0.001^{c}	0.33 ± 0.005^{d}	0.38 ± 0.00^{e}	0.405 ± 0.001^{b}
W_3	**C16:0**	5.240 ± 0.001^{a}	6.858 ± 0.0035^{c}	8.801 ± 0.001^{d}	9.710 ± 0.014^{e}	10.465 ± 0.007^{f}	11.935 ± 0.007^{g}	13.805 ± 0.007^{b}
	C18:0	4.950 ± 0.014^{a}	5.679 ± 0.0014^{c}	5.581 ± 0.001^{d}	5.77 ± 0.00^{e}	5.82 ± 0.014^{f}	6.11 ± 0.001^{g}	6.380 ± 0.028^{b}
	C18:1	18.735 ± 0.021^{a}	24.555 ± 0.0071^{c}	31.7 ± 0.00^{d}	34.905 ± 0.007^{e}	36.835 ± 0.021^{f}	42.419 ± 0.002^{g}	48.525 ± 0.002^{b}
	C18:2	15.235 ± 0.007^{a}	18.330 ± 0.0283^{c}	21.773 ± 0.004^{d}	23.220 ± 0.014^{e}	24.525 ± 0.021^{f}	27.545 ± 0.629^{g}	30.925 ± 0.007^{b}
	C18:3	55.755 ± 0.007^{a}	44.405 ± 0.0071^{c}	32.395 ± 0.007^{d}	28.63 ± 0.014^{e}	21.919 ± 0.001^{f}	11.315 ± 0.007^{g}	0.088 ± 0.00^{b}
	C20:0	0.17 ± 0.014^{a}	0.208 ± 0.0113^{a}	0.215 ± 0.007^{a}	0.325 ± 0.007^{a}	0.32 ± 0.014^{a}	0.397 ± 0.002^{c}	0.410 ± 0.001^{b}
W_4	**C16:0**	5.415 ± 0.007^{a}	7.635 ± 0.0071^{c}	9.193 ± 0.002^{d}	10.355 ± 0.0071^{e}	10.83 ± 0.014^{f}	12.29 ± 0.000^{g}	13.819 ± 0.002^{b}
	C18:0	5.071 ± 0.001^{a}	5.875 ± 0.0071^{c}	5.595 ± 0.007^{d}	5.945 ± 0.021^{e}	5.910 ± 0.00^{f}	6.158 ± 0.002^{g}	6.835 ± 0.049^{b}
	C18:1	18.865 ± 0.021^{a}	27.262 ± 0.0028^{c}	32.955 ± 0.007^{d}	34.935 ± 0.021^{e}	38.125 ± 0.021^{f}	44.093 ± 0.000^{g}	49.19 ± 0.014^{b}
	C18:2	15.375 ± 0.007^{a}	18.72 ± 0.014^{c}	21.83 ± 0.014^{d}	23.75 ± 0.014^{e}	24.63 ± 0.014^{f}	28.063 ± 0.002^{g}	31.695 ± 0.028^{b}
	C18:3	55.925 ± 0.007^{a}	44.954 ± 0.019^{c}	33.47 ± 0.014^{d}	30.755 ± 0.007^{e}	22.43 ± 0.007^{f}	11.698 ± 0.003^{g}	0.067 ± 0.001^{b}
	C20:0	0.205 ± 0.001^{a}	0.225 ± 0.0071^{a}	0.219 ± 0.002^{a}	0.330 ± 0.00^{d}	0.355 ± 0.007^{e}	0.397 ± 0.001^{f}	0.448 ± 0.004^{b}

Results are expressed as the mean values ± standard deviation of the three replicates (mean ± SD, n = 3); (a − g) different letters within a row indicate significant statistical differences ($p < 0.05$).

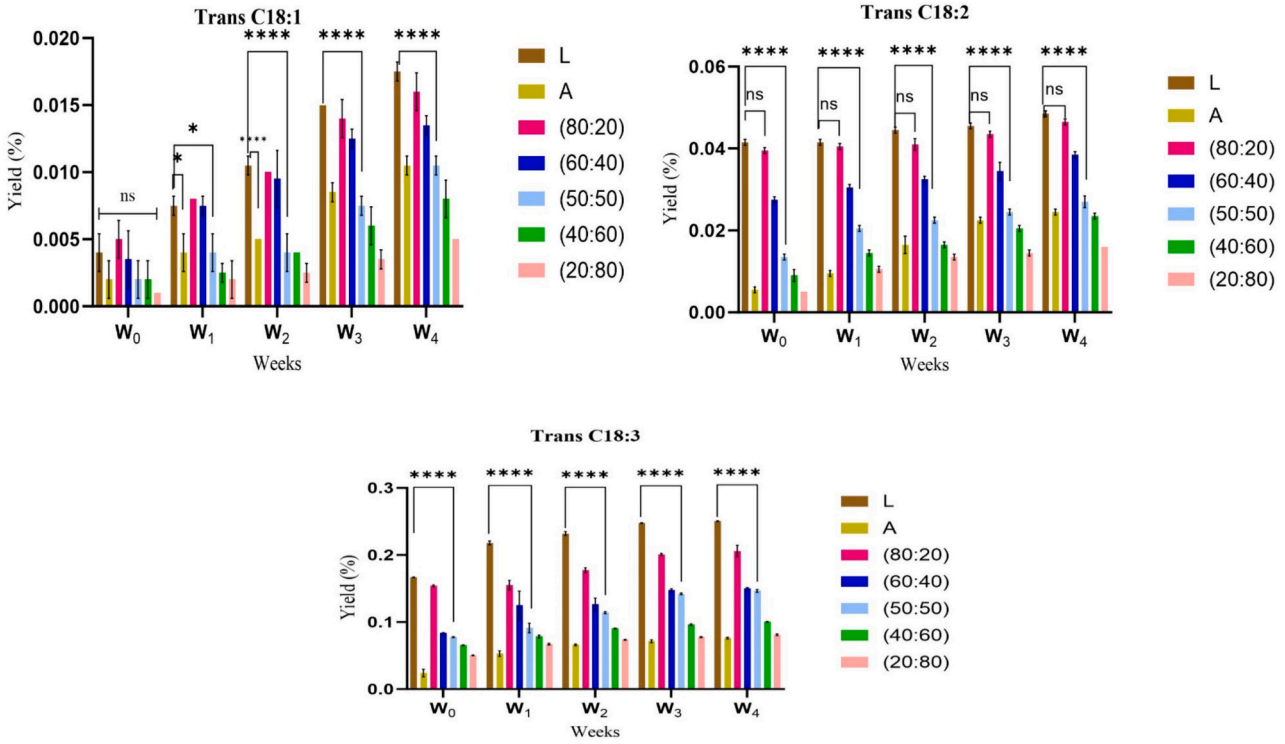

Fig. 1. Trans fatty acid composition of pure LO, AO, and blended oils.

proportion of LO exceeds 50%, the PUFA content becomes higher due to the high linolenic acid content (55.373 ± 0.006). As the PUFA/SFA ratio is generally considered an indicator of oxidative stability, then a low ratio indicates improved stability in blended oils (Karupaiah & Sundram, 2013), and therefore increased postprandial HDLC (Bhatnagar, Prasanth Kumar, Hemavathy, & Gopala Krishna, 2009). Pure oils show a PUFA/SFA ratio of 3.9 (AO) to 9.22 (LO), and blended oils vary within this range, approaching the value of the high-proportion oil,

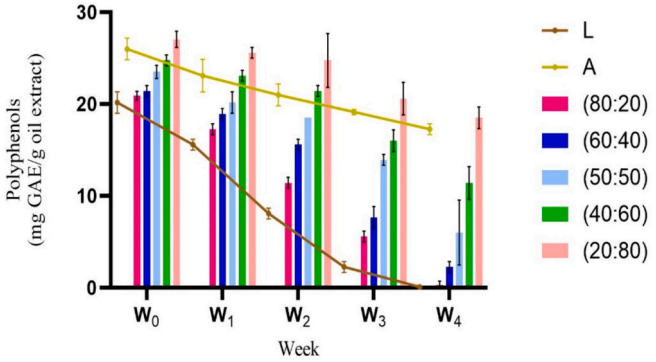

Fig. 2. Total polyphenols content of pure LO, AO, and blended oils.

overall, not mentioning a large difference between the controls and the 4th week oils.

3.2. *Trans fatty acids during oxidation*

Various factors, including genetic variations in the seeds, differences in oil processing, different harvest dates or different extraction procedures result in FA compositions that differ from one oil to another (Boskou, Blekas, & Tsimidou, 2006), hence trans fatty acids appear in oils with high amounts of unsaturated fatty acids through their exposure to high temperatures or depending on the extraction methods used, which increases the oil's oxidative sensitivity (Zarrouk et al., 2019), thus unsaturated fatty acids (UFAs) with more double bonds are more isomerized and double bonds near the methyl end are more susceptible to thermal isomerization (Liu et al., 2021).

Trans C18:3 FAs have been determined to be the main TFA isomers in linseed oils, resulting from exposure of the oil to high environmental temperatures which would lead to the formation of large quantities of C18:3 TFAs, as already confirmed by the literature (Kong, Du, Chen, Cai, Xie, & Shen). In our study, C18:3 FAT is most abundant in LO and AO, at 0.167% and 0.020% respectively in their initial states, and during high-temperature oxidation the content increases from 0.22% and 0.056% in week 1 to 0.251% and 0.077% in week 4. LO's high FAT C18:3 content forces its oxidation easily and would lead the mixtures (80: 20) and (60: 40) and (50: 50) to oxidize reaching 0.212 and 0.151 and 0.148 and as soon as AO exceeds 50% of the blend, the content would drop to 0.08 for the (20: 80) blend. Trans linolenic C18:2 isomers increase with oxidation of pure oils and blends, ranging from 0.041% to 0.049% for LO, from 0.006 to 0.025% for AO, the 1st blend of (80: 20) shows no significant difference with pure LO for 5 weeks, while the blend (50: 50) shows a slow increase and approaches the acid content in AO. For trans C18:1, at week 0 all oils show no significant difference between themselves and LO, and from week 1, the content increases rapidly in LO and the blends (80: 20) and (60: 40), while in AO the content increases

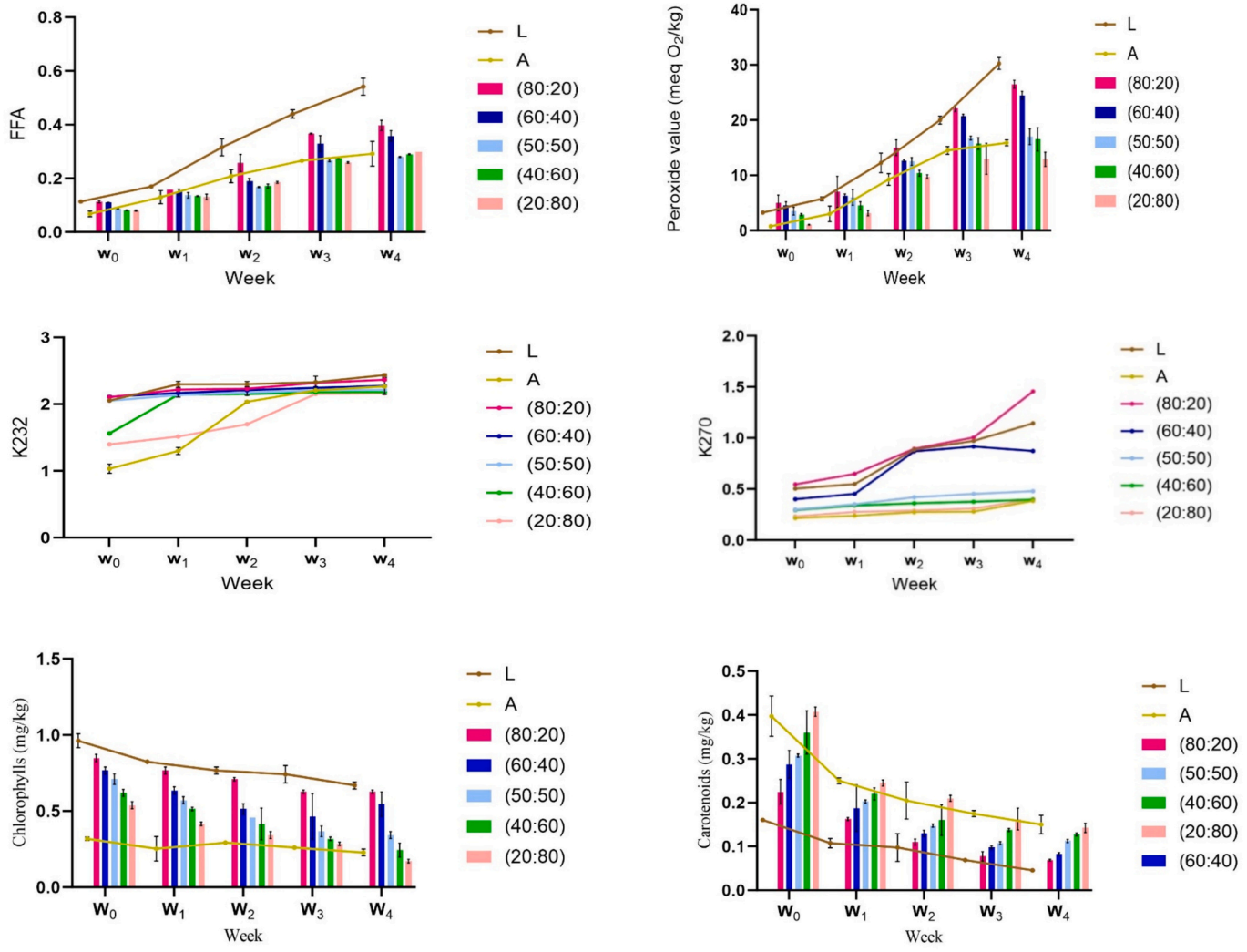

Fig. 3. Physicochemical properties of pure LO, AO, and blended oils.

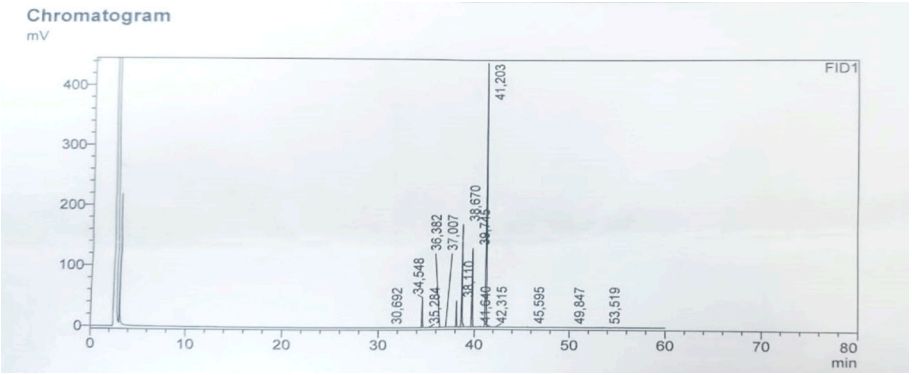

Fig. 4. : Fatty acid chromatogram of *Linum usitatissimum* control oil of week 4 (LO, W4).

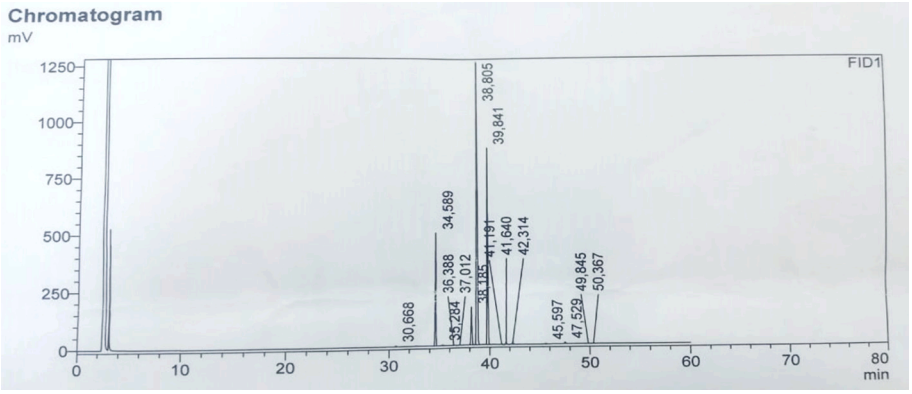

Fig. 5. : Fatty acid chromatogram of Argania spinosa control oil of week 4 (AO, W4).

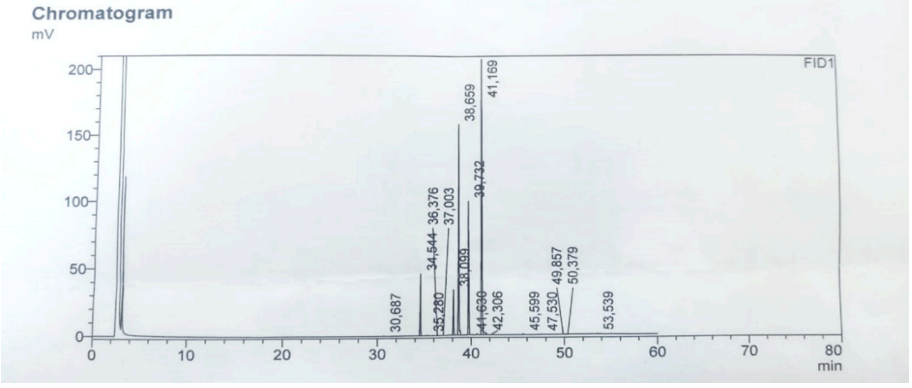

Fig. 6. : Fatty acid chromatogram of (80:20) proportion of week 4 ((80:20), W4).

slowly, giving the power to lower trans C18:1 in the rest of the blends.

In studies comparing linseed varieties, trans linolenic C18:3 isomers range from 0.39% to 0.23% and trans linolenic C18:2 isomers range from 0.041% to 0.05% (Moknatjou et al., 2015), and studying the oil quality of argan seeds from different Moroccan regions, trans C18:1 and trans C18:2 isomers are below 0.05%, and trans C18:3 isomers range from 0.06% to 0.09% (Miklavčič et al., 2020).

3.3. Fatty acid characteristics

Diets with a PUFA/SFA ratio of <0.45 tend to raise blood cholesterol levels, making them inappropriate (Department of, H., and Social, S., 1984). Initially, linseed oil shows a high content of ∑PUFA 70% than ∑MUFA 19% while argan oil shows a high content of ∑MUFA 48% followed by ∑PUFA 31% and 19% SFA, giving high PUFAs/SFAs and ω_3/ω_6 ratios for LO than AO respectively (9.37–3.69) and (3.98–0.004) (Table 2). Results confirm our results for LO (Choo, Birch, & Dufour, 2007; Herchi et al., 2014; Tańska, Roszkowska, Skrajda, & Dąbrowski, 2016), and others for AO (Miklavčič et al., 2020) and oil formulations with a high proportion of LO have high ratios, as demonstrated by oxidation studies on linseed oil, (da Silva Moura, da Silva, & Braga, 2023; Hashempour-Baltork et al., 2018; Joshi, Hegde, & Zanwar, 2022). After 28 days of oxidation at 60 °C, the oils showed a slight decrease in ratios, as already mentioned above (Mikołajczak, Pilarski, Gęsiński, & Tańska, 2023; Pan et al., 2020).

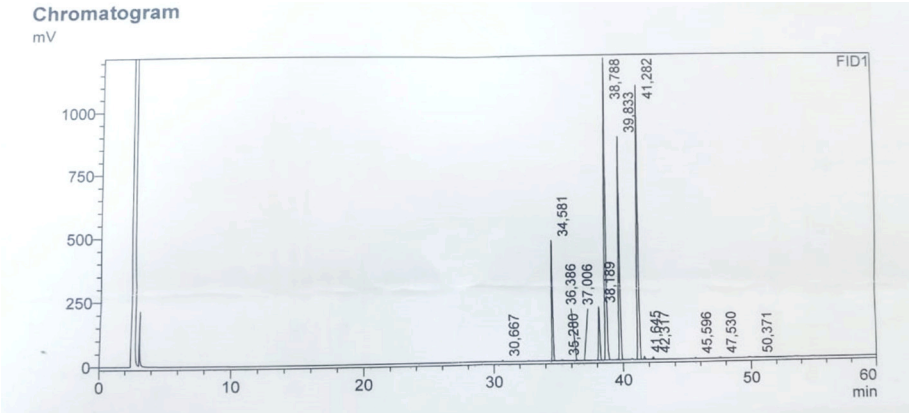

Fig. 7. : Fatty acid chromatogram of (60:40) proportion of week 4 ((60:40), W4).

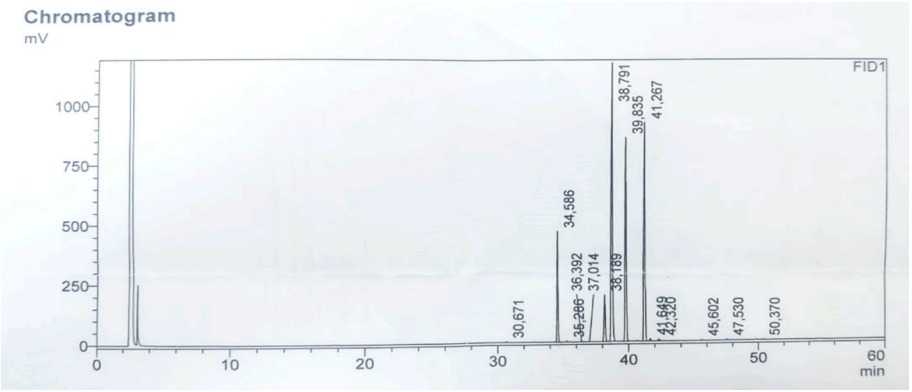

Fig. 8. : Fatty acid chromatogram of (50:50) proportion of week 4 ((50:50), W4).

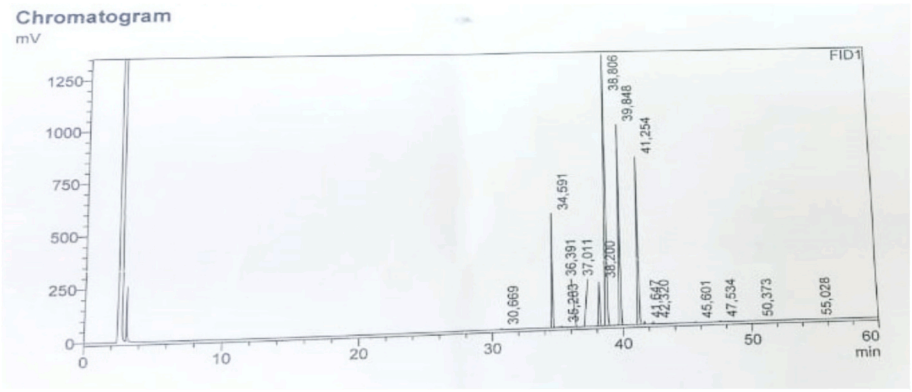

Fig. 9. : Fatty acid chromatogram of (40:60) proportion of week 4 ((40:60), W4).

3.4. Nutritional indexes

The nutritional quality of oils has been assessed by nutritional indexes such as AI, TI, HH, COX, OS, these indexes evaluate the nutritional quality of oils according to their fatty acid composition are presented in Table 3. AI and TI can be used as predictors or risk factors for cardiovascular disease. These indexes should therefore be kept at low levels as part of a healthy daily diet (Hashempour-Baltork et al., 2018).

Due to the higher PUFA content in LO than AO, AI and TI are lower for LO (0.002; 0.001) than AO (0.019; 0.037), approximately to the results that compare between linseed, sesame and olive oil and show respectively for AI (0.00; 0.13; 0.15) and for TI (0.04; 0.26; 0.38) (Hashempour-Baltork et al., 2018), as well as higher values cited for linseed oil (0.07 and 0.07) and sesame oil (0.69 and 0.13) (Guimarães et al., 2013). Formulation of (80: 20)blend had the lowest AI and TI values (0.003 and 0.001), while the (20: 80) blend had the highest values (0.012 and 0.011) of all the blends. Consequently, as the proportion of LO in the blend increased, the AI and TI values decreased, which was confirmed by blending LO with avocado oil (da Silva Moura et al., 2023) and LO with olive oil and sesame oil (Hashempour-Baltork et al., 2018).

The hypocholesterolemic and hypercholesterolemic fatty acids index (h/H) corresponds to the specific effects of fatty acids on cholesterol metabolism, and high index values are desirable for nutritional purposes. The HH index corresponds to the specific effects of fatty acids on cholesterol metabolism, and high index values are desirable for

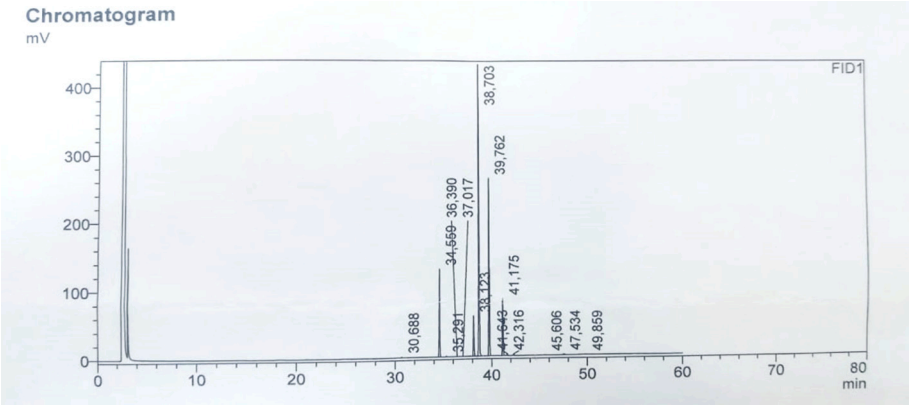

Fig. 10. : Fatty acid chromatogram of (20:80) proportion of week 4 ((20:80), W4).

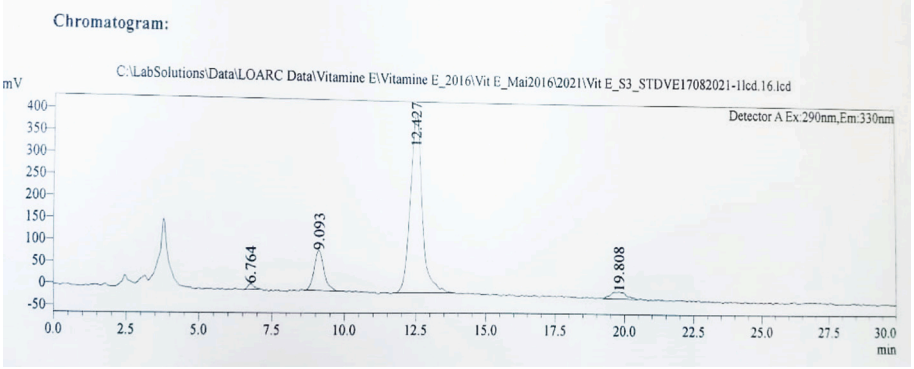

Fig. 11. : Tocopherol chromatogram of (60:40) proportion of week 4 ((60:40), W4).

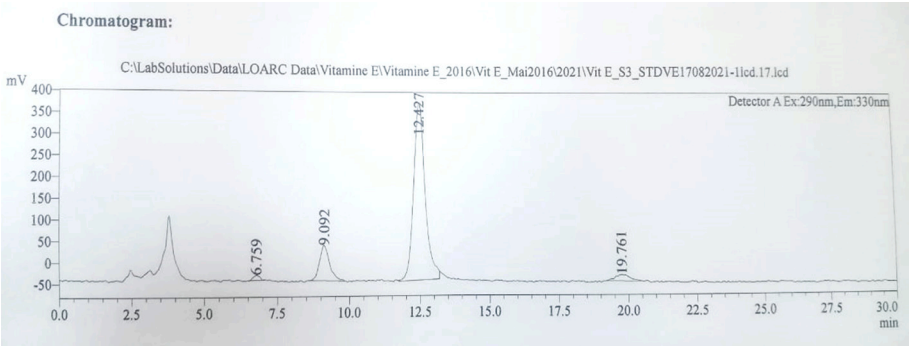

Fig. 12. : Tocopherol chromatogram of (50:50) proportion of week 4 ((50:50), W4).

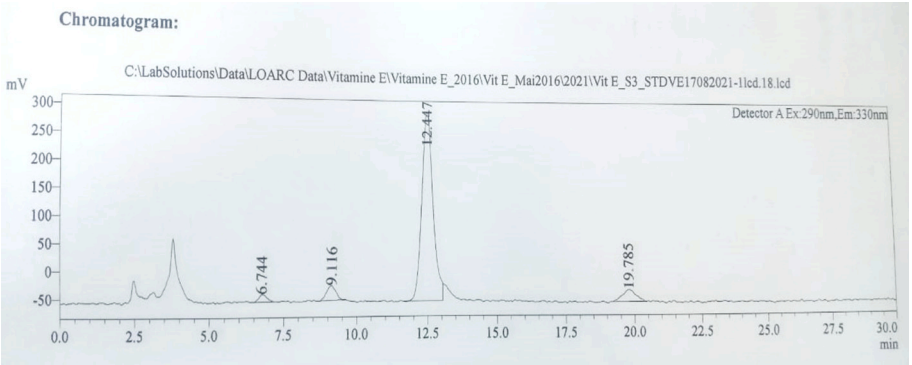

Fig. 13. : Tocopherol chromatogram of (20:80) proportion of week 4 ((20:80), W4).

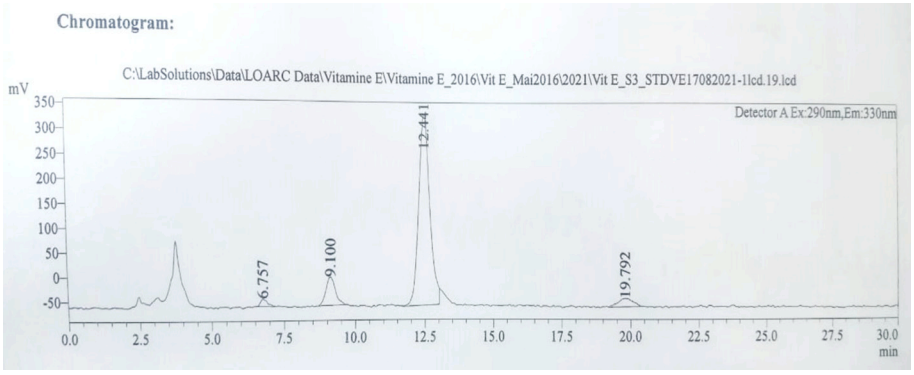

Fig. 14. : Fatty acid chromatogram of (40:60) proportion of week 4 ((40:60), W4).

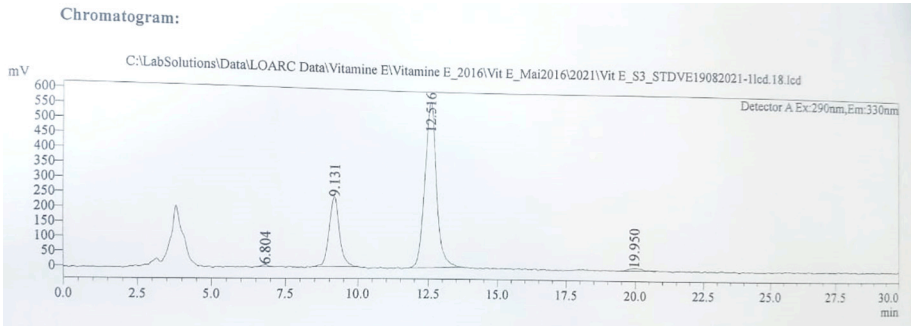

Fig. 15. : Tocopherol chromatogram of *Linum usitatissimum* control oil of week 4 (LO, W4).

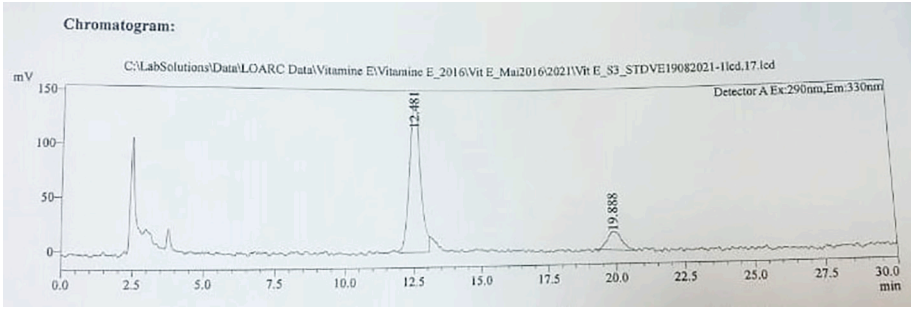

Fig. 16. : Tocopherol chromatogram of Argania spinosa control oil of week 4 (LO, W4).

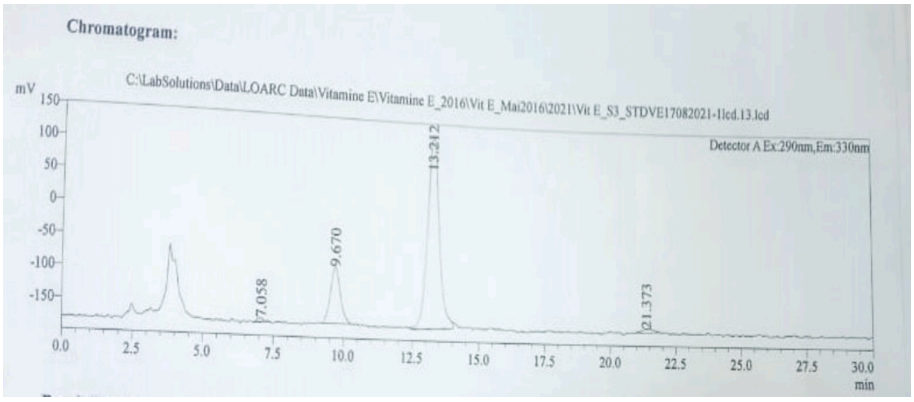

Fig. 17. Tocopherol chromatogram of (80:20) proportion of week 3 ((80:20), W3).

Table 2
Fatty acid characteristics of pure LO, AO, and blended oils.

Weeks		L	(80:20)	(60:40)	(50:50)	(40:60)	(20:80)	A
W_0	∑SFA	9.623 ± 0.022 [a]	11.134 ± 0.001[c]	13.967 ± 0.035[d]	14.411 ± 0.031[e]	14.313 ± 0.057[f]	16.962 ± 0.035[g]	19.952 ± 0.070[b]
	∑MUFA	19.831 ± 0.022 [a]	24.535 ± 0.025 [c]	30.545 ± 0.023[d]	33.183 ± 0.042[e]	35.514 ± 0.009[f]	42.02 ± 0.011 [g]	48.229 ± 0.010[b]
	∑PUFA	70.378 ± 0.013 [a]	60.004 ± 0.00 [c]	52.96 ± 0.028 [d]	49.8 ± 0.014 [e]	42.64 ± 0.014 [f]	36.16 ± 0.028 [g]	31.205 ± 0.035[b]
	PUFAs/SFAs	9.373 ± 0.022 [a]	7.592 ± 0.001 [c]	5.978 ± 0.015 [d]	5.758 ± 0.014 [e]	5.46 ± 0.022 [f]	4.609 ± 0.012 [g]	3.981 ± 0.012 [b]
	ω_3/ω_6	3.69 [a]	2.332 [c]	1.487 [d]	1.19 [e]	0.808 [f]	0.336 [g]	0.004 [b]
W_1	∑SFA	9.804 ± 0.001 [a]	11.969 ± 0.004 [c]	14.142 ± 0.004[d]	14.545 ± 0.026[e]	15.059 ± 0.015[f]	17.762 ± 0.022[g]	20.097 ± 0.007[b]
	∑MUFA	19.951 ± 0.008 [a]	24.697 ± 0.000 [c]	31.364 ± 0.006[d]	34.042 ± 0.01 [e]	36.575 ± 0.018[f]	42.198 ± 0.006[g]	48.456 ± 0.004
	∑PUFA	70.507 ± 0.004 [a]	60.037 ± 0.005 [c]	53.365 ± 0.007[d]	50.3 ± 0.014 [e]	43.795 ± 0.021[f]	36.313 ± 0.003[g]	31.307 ± 0.004[b]
	PUFAs/SFAs	9.226 ± 0.002 [a]	7.079 ± 0.002 [c]	5.991 ± 0.002 [d]	5.798 ± 0.009 [e]	5.336 ± 0.003 [f]	4.42 ± 0.006 [g]	3.968 ± 0.002 [b]
	ω_3/ω_6	3.695 [a]	2.33 [c]	1.487 [d]	1.193 [e]	0.82 [f]	0.339 [g]	0.0051 [b]
W_2	∑SFA	10.256 ± 0.006 [a]	12.778 ± 0.022 [c]	14.638 ± 0.067	15.4 ± 0.014 [e]	16.617 ± 0.009[f]	18.117 ± 0.008[g]	20.698 ± 0.018[b]
	∑MUFA	19.262 ± 0.005 [a]	33.669 ± 0.037 [c]	31.428 ± 0.007[d]	34.689 ± 0.362[e]	36.649 ± 0.001[f]	42.161 ± 0.001[g]	48.519 ± 0.032[b]
	∑PUFA	70.945 ± 0.007 [a]	60.61 ± 0.028 [c]	54.07 ± 0.028 [d]	51.354 ± 0.008[e]	45.801 ± 0.016[f]	38.405 ± 0.007[g]	30.807 ± 0.006[b]
	PUFAs/SFAs	8.795 ± 0.005 [a]	7.377 ± 0.008 [c]	5.84 ± 0.025 [d]	5.587 ± 0.028 [e]	4.961 ± 0.004 [f]	4.446 ± 0.002 [g]	3.832 ± 0.002 [b]
	ω_3/ω_6	3.644 [a]	2.339 [c]	1.489 [d]	1.221 [e]	0.872 [f]	0.376 [g]	0.0029 [b]
W_3	∑SFA	10.468 ± 0.031 [a]	12.891 ± 0.020 [c]	14.758 ± 0.003[d]	15.964 ± 0.006[e]	16.778 ± 0.037[f]	18.634 ± 0.008[g]	20.795 ± 0.028[b]
	∑MUFA	19.021 ± 0.015 [a]	24.886 ± 0.013 [c]	32.099 ± 0.008[d]	35.295 ± 0.011[e]	37.222 ± 0.022[f]	42.952 ± 0.010[g]	49.096 ± 0.021[b]
	∑PUFA	70.99 ± 0.00 [a]	62.735 ± 0.021 [c]	54.167 ± 0.011[d]	51.85 ± 0.028 [e]	46.444 ± 0.020[f]	38.86 ± 0.622 [g]	31.013 ± 0.007[b]
	PUFAs/SFAs	8.598 ± 0.024 [a]	6.797 ± 0.013 [c]	5.845 ± 0.001 [d]	5.458 ± 0.001 [e]	4.986 ± 0.009 [f]	4.39 ± 0.032 [g]	3.852 ± 0.007 [b]
	ω_3/ω_6	3.659 [a]	2.422 [c]	1.487 [d]	1.232 [e]	0.893 [f]	0.41 [g]	0.0028 [b]
W_4	∑SFA	10.811 ± 0.009 [a]	13.903 ± 0.007 [c]	15.165 ± 0.004[d]	16.789 ± 0.030[e]	17.271 ± 0.021[f]	19.034 ± 0.007[g]	21.325 ± 0.036[b]
	∑MUFA	19.166 ± 0.014 [a]	27.596 ± 0.001 [c]	33.366 ± 0.007[d]	35.363 ± 0.023[e]	38.542 ± 0.016[f]	44.631 ± 0.007[g]	49.812 ± 0.013[b]
	∑PUFA	71.3 ± 0.014 [a]	63.673 ± 0.005 [c]	55.3 ± 0.028 [d]	54.505 ± 0.007[e]	47.06 ± 0.042 [f]	39.76 ± 0.001 [g]	31.762 ± 0.006[b]
	PUFAs/SFAs	8.367 ± 0.004 [a]	6.564 ± 0.004 [c]	5.846 ± 0.003 [d]	5.352 ± 0.008 [e]	4.956 ± 0.004 [f]	4.433 ± 0.002 [g]	3.825 ± 0.007 [b]
	ω_3/ω_6	3.637 [a]	2.401 [c]	1.533 [d]	1.294 [e]	0.91 [f]	0.416 [g]	0.0021 [b]

Results are expressed as the mean values ± standard deviation of the three replicates (mean ± SD, n = 3); (a − g) different letters within a row indicate significant statistical differences ($p < 0.05$).

nutritional purposes. HH is more strongly present in LO (18.85) than in AO (5.95), and studies show that pure LO reaches (13.24) (Gharby et al., 2018) and (14.85) (Guimarães, et al., 2013), leading to higher values in blends (80: 20) and (60: 40) than in the rest of the oils, from 14.40 (80: 20) to 7.05 (20: 80), an effect similar to the literature (Hashempour-Baltork et al., 2018).

The oxidizability (COX) and oxidative susceptibility (OS) indexes determine the oxidative stability of the oil, so the OS index and the COX index should be as low as possible to indicate that the fatty acids are less likely to oxidize and therefore the oil is stable against oxidation.

Oxidizability (COX value) is a factor indicating the oxidative stability of oils and fats, determined on the basis of UFAs, a lower COX value indicates greater oil stability (Hassanein et al., 2022). AO recorded the lowest COX value (3.7), indicating lower auto-oxidation in the oil, while LO recorded the highest COX value (13.7), similar to the results found (Plaha et al., 2023; Symoniuk, Ratusz, & Krygier, 2017). The values examined in our study for LO (<14) are lower than the COX value reported in the linseed oil studied (Hassanein et al., 2022), so they fall within the range of results found between 12.03 and 15.40 (Herchi et al., 2014; Symoniuk et al., 2017), and in a study including all linum species, all oils reached COX value <15 (Plaha et al., 2023). However, pure LO and blends (80: 20, 60: 40, 50: 50) with Cox > 9 are prone to auto-oxidation, and have comparatively low oxidative stability, meaning that these oils are susceptible to oxidation by external factors, while the blend (40: 60) admits a value of 5, which is the best COX value observed among the blends, while AO is characterized by the lowest COX value, which favours it by high oxidative stability and in turn favours the blend (20: 80) with a low COX value (5.17). And the OS index, which initially reaches 6232.407 for pure LO and a low value of 1459.329 for pure AO, clearly explains LO's high oxidative susceptibility, since its high value varies from 6232 to 6303 between week 0 and week 4 (Herchi et al., 2014). However, the OS value indicates the susceptibility of AO oil and blends (40: 60; 20: 80) against oxidation, and strong autoxidation is shown for pure LO and other blends. Due to the low COX and OS values determined for AO and oils (50: 50, 60: 40, 20: 80), it appears that they may be suitable for human nutrition, conversely for LO and oils (80: 20; 60: 40) which are highly sensitive to autoxidation.

3.5. Tocopherols content during oxidation

Tocopherol is present in plants in four forms (α-, β-, γ- and δ-), having antioxidant activity that protects polyunsaturated fatty acids (PUFAs) against oxidative deterioration so it has some nutritional importance as well as biological activity that protects cells against oxidative stress (Hajib et al., 2021; Tavakoli et al., 2018; Wang et al., 2024).

According to Table 4, the tocopherol composition of AO was found to be significant to that of LO, and its total tocopherol content was 786.710 ± 0.806 mg/kg, close to 749.38 mg/kg and 768.93 ± 0.05 g mg/kg respectively (El Idrissi et al., 2023; Kouidri, Saadi, Noui, & Medjahed, 2015) and very high than that found in the literature 236.86 ± 3.16 mg/kg (Pan et al., 2020; Zhou et al., 2017). LO's tocopherol content profiles appear impressive compared to the bibliography, even its high total content of 582.638 ± 0.693 mg/kg, which exceeds 73.65 mg/kg (Oomah, Kenaschuk, & Mazza, 1997), but lower compared to 1065.2 ± 1.14 mg/kg (Mikołajczak et al., 2023), 34,700 ± 0.28 mg/kg (Khattab & Zeitoun, 2013).

γ-tocopherols is the major compounds identified for LO (570.927 ± 0.2 mg/kg) and AO (687.485 ± 0.785 mg/kg) followed by δ-tocopherols (6.733 ± 0.033 mg/kg) and (51.035 ± 0.163 mg/kg) then α-tocopherols (5.421 ± 0.1 mg/kg) and (48.190 ± 0.184 mg/kg) respectively, as already proven in the literature (El Kharrassi et al., 2018; Kouidri et al., 2015; Mikołajczak et al., 2023; Zeng et al., 2022).

In all five blended oils, total tocopherol content increased as the proportion of AO increased, and there were consistent differences between oil blends. As the number of days of oxidation increased, tocopherol levels tended to decrease, In addition, the degrees of tocopherol loss were different for each isomer within 28 days of storage, in particular for γ-tocopherol, which decreased very rapidly in pure LO oil from 570.927 ± 0.2 mg/kg to 117.615 ± 7.14 mg/kg and those mixed at (80: 20; 60: 40) varied from (305.955 ± 0.120 mg/kg; 346.075 ± 0.431 mg/kg) to (135.280 ± 0.071 mg/kg; 160.201 ± 0.005 mg/kg) respectively, while pure AO and the rest of the oils remained remarkably stable over day 28, with AO losing almost half its γ-tocopherol content from 687.485 ± 0.785 to 357.147 ± 0.004 mg/kg, while pure AO and the rest of the oils remained remarkably stable over the course of day 28, with AO losing almost half its γ-tocopherol content from 687.485 ±

Table 3
Lipid health indices of pure LO, AO, and blended oils.

Weeks		L	(80:20)	(60:40)	(50:50)	(40:60)	(20:80)	A
W_0	**AI**	0.002 ± 0.00^{a}	0.003 ± 0.00 ^{a}	0.005 ± 0.00 ^{d}	0.006 ± 0.00^{e}	0.008 ± 0.00^{f}	0.012 ± 0.00^{g}	0.019 ± 0.00^{b}
	TI	0.001 ± 0.00 ^{a}	0.001 ± 0.00 ^{a}	0.002 ± 0.00 ^{d}	0.003 ± 0.00 ^{e}	0.005 ± 0.00 ^{f}	0.011 ± 0.00 ^{g}	0.037 ± 0.00 ^{b}
	HH	18.852 ± 0.11 ^{a}	14.401 ± 0.019^{c}	9.917 ± 0.007^{d}	9.098 ± 0.004 ^{e}	8.517 ± 0.003 ^{f}	7.056 ± 0.004 ^{g}	5.958 ± 0.001 ^{b}
	COX	13.702 ± 0.001 ^{a}	11.169 ± 0.00 ^{c}	9.336 ± 0.004 ^{d}	8.516 ± 0.001 ^{e}	6.898 ± 0.002 ^{f}	5.17 ± 0.002 ^{g}	3.706 ± 0.004 ^{b}
	OS	6232.407 ± 0.932^{a}	5034.743 ± 0.013^{c}	4155.595 ± 2.027^{d}	3762.759 ± 0.983^{e}	3002.89 ± 1.016 ^{f}	2169.995 ± 0.90 ^{g}	1459.329 ± 1.989^{b}
W_1	**AI**	0.002 ± 0.00 ^{a}	0.003 ± 0.00 ^{a}	0.005 ± 0.00 ^{d}	0.006 ± 0.00 ^{e}	0.008 ± 0.00 ^{f}	0.013 ± 0.00 ^{g}	0.0195 ± 0.00 ^{b}
	TI	0.001 ± 0.00 ^{a}	0.001 ± 0.00 ^{a}	0.002 ± 0.00 ^{d}	0.003 ± 0.00 ^{e}	0.005 ± 0.00 ^{f}	0.011 ± 0.00 ^{g}	0.037 ± 0.00 ^{b}
	HH	18.560 ± 0.025 ^{a}	13.079 ± 0.00 ^{c}	10.017 ± 0.003 ^{d}	9.225 ± 0.00 ^{e}	8.652 ± 0.005 ^{f}	6.83 ± 0.005 ^{g}	5.960 ± 0.004 ^{b}
	COX	13.730 ± 0.00 ^{a}	11.175 ± 0.00 ^{c}	9.412 ± 0.00 ^{d}	8.609 ± 0.002 ^{e}	7.103 ± 0.003 ^{f}	5.197 ± 0.00 ^{g}	3.722 ± 0.00 ^{b}
	OS	6244.904 ± 0.384^{a}	5037.127 ± 0.417^{c}	4188.115 ± 0.077^{d}	3802.617 ± 1.035^{e}	3092.775 ± 1.361^{f}	2182.366 ± 0.160 ^{g}	1466.094 ± 0.162^{b}
W_2	**AI**	0.002 ± 0.00	0.003 ± 0.00	0.005 ± 0.00	0.006 ± 0.00 ^{e}	0.008 ± 0.00 ^{f}	0.012 ± 0.00 ^{g}	0.021 ± 0.00 ^{b}
	TI	0.001 ± 0.00	0.001 ± 0.00	0.002 ± 0.00	0.003 ± 0.00 ^{e}	0.005 ± 0.00 ^{f}	0.010 ± 0.00 ^{g}	0.04 ± 0.00 ^{b}
	HH	17.134 ± 0.016	13.703 ± 0.00	9.649 ± 0.069	9.090 ± 0.031 ^{e}	7.855 ± 0.002 ^{f}	6.825 ± 0.006 ^{g}	5.683 ± 0.002 ^{b}
	COX	13.788 ± 0.00	11.375 ± 0.004	9.535 ± 0.004	8.824 ± 0.002 ^{e}	7.492 ± 0.001 ^{f}	5.558 ± 0.00 ^{g}	3.663 ± 0.00 ^{b}
	OS	6273.638 ± 0.313	5096.419 ± 2.087	4243.828 ± 2.043	3898.814 ± 0.027^{e}	3271.450 ± 0.777^{f}	2347.611 ± 0.069 ^{g}	1439.895 ± 0.144^{b}
W_3	**AI**	0.002 ± 0.00	0.003 ± 0.00	0.005 ± 0.00	0.006 ± 0.00 ^{e}	0.008 ± 0.00 ^{f}	0.012 ± 0.00 ^{g}	0.020 ± 0.00 ^{b}
	TI	0.001 ± 0.00	0.001 ± 0.00	0.002 ± 0.00	0.003 ± 0.00 ^{e}	0.004 ± 0.00 ^{f}	0.010 ± 0.00 ^{g}	0.040 ± 0.00 ^{b}
	HH	17.005 ± 0.001	12.618 ± 0.011	9.669 ± 0.001	8.856 ± 0.009 ^{e}	7.88 ± 0.002 ^{f}	6.744 ± 0.048 ^{g}	5.710 ± 0.002 ^{b}
	COX	13.800 ± 0.00	11.725 ± 0.001	9.557 ± 0.001	8.925 ± 0.004 ^{e}	7.629 ± 0.002 ^{f}	5.705 ± 0.063 ^{g}	3.690 ± 0.00 ^{b}
	OS	6280.097 ± 0.374	5290.237 ± 0.579	4251.362 ± 0.857	3943.196 ± 2.04 ^{e}	3332.748 ± 0.835^{f}	2413.977 ± 27.622^{g}	1449.521 ± 0.339^{b}
W_4	**AI**	0.002 ± 0.00	0.003 ± 0.00	0.005 ± 0.00	0.006 ± 0.00 ^{e}	0.008 ± 0.00 ^{f}	0.012 ± 0.00 ^{g}	0.020 ± 0.00 ^{b}
	TI	0.001 ± 0.00	0.001 ± 0.00	0.002 ± 0.00	0.003 ± 0.00 ^{e}	0.004 ± 0.00 ^{f}	0.009 ± 0.00 ^{g}	0.039 ± 0.00 ^{b}
	HH	16.526 ± 0.019	11.775 ± 0.010	9.506 ± 0.001	8.563 ± 0.003 ^{e}	7.782 ± 0.007 ^{f}	6.759 ± 0.00 ^{g}	5.797 ± 0.002 ^{b}
	COX	13.852 ± 0.002	11.911 ± 0.002	9.808 ± 0.004	9.439 ± 0.00 ^{e}	7.763 ± 0.007 ^{f}	5.858 ± 0.00 ^{g}	3.771 ± 0.00 ^{b}
	OS	6303.541 ± 1.039	5365.346 ± 1.274	4362.716 ± 2.043	4179.613 ± 0.048^{e}	3389.892 ± 0.44 ^{f}	2477.216 ± 0.219 ^{g}	1482.788 ± 0.190^{b}

Results are expressed as the mean values ± standard deviation of the three replicates (mean ± SD, n = 3); (a − g) different letters within a row indicate significant statistical differences ($p < 0.05$).

Table 4
Tocopherols content (mg/kg) of pure LO, AO, and blended oils.

Weeks	tocopherols	LO	(80: 20)	(60: 40)	(50: 50)	(40: 60)	(20: 80)	AO
W_0	**α-tocopherols**	5.421 ± 0.1^{a}	6.116 ± 0.006^{a}	11.738 ± 0.049^{c}	28.419 ± 0.021^{d}	37.267 ± 0.091^{e}	39.933 ± 0.098^{f}	48.190 ± 0.184^{b}
	γ-tocopherols	570.927 ± 0.2^{a}	305.955 ± 0.120^{c}	346.075 ± 0.431^{d}	385.155 ± 0.078^{e}	428.707 ± 0.006^{f}	444.248 ± 0.003^{g}	687.485 ± 0.785^{b}
	δ-tocopherols	6.733 ± 0.033^{a}	8.092 ± 0.001^{c}	16.638 ± 0.007^{d}	19.277 ± 0.004^{e}	21.353 ± 0.004^{f}	24.873 ± 0.04^{g}	51.035 ± 0.163^{b}
	Total	582.638 ± 0.693^{a}	320.163 ± 0.116^{c}	374.451 ± 0.488^{d}	432.851 ± 0.095^{e}	487.327 ± 0.093^{f}	509.054 ± 0.141^{g}	786.710 ± 0.806^{b}
W_1	**α-tocopherols**	2.970 ± 0.057^{a}	3.307 ± 0.005^{a}	6.640 ± 0.113^{a}	21.973 ± 0.018^{a}	27.785 ± 0.035^{a}	32.815 ± 0.008^{a}	36.519 ± 0.107^{a}
	γ-tocopherols	408.477 ± 0.423^{a}	289.955 ± 0.008^{a}	318.896 ± 0.147^{a}	391.828 ± 0.02^{b}	369.393 ± 0.007^{a}	416.079 ± 0.037^{a}	561.019 ± 0.129^{a}
	δ-tocopherols	6.328 ± 0.094^{a}	8.410 ± 0.001^{a}	14.853 ± 0.011^{a}	18.092 ± 0.054^{a}	18.765 ± 0.008^{a}	23.838 ± 0.021^{a}	25.257 ± 0.161^{a}
	Total	417.775 ± 0.460^{a}	301.671 ± 0.013^{a}	340.339 ± 0.271^{a}	361.828 ± 0.032^{b}	415.943 ± 0.036^{a}	472.731 ± 0.024^{a}	622.794 ± 0.182^{a}
W_2	**α-tocopherols**	2.516 ± 0.149^{a}	2.863 ± 0.007^{a}	4.978 ± 0.018^{c}	17.628 ± 0.021^{d}	18.566 ± 0.021^{e}	27.209 ± 0.006^{f}	32.04 ± 0.135^{b}
	γ-tocopherols	317.101 ± 0.326^{a}	216.165 ± 0.021^{c}	236.259 ± 0.001^{d}	318.2 ± 0.014^{e}	333.164 ± 0.005^{f}	405.728 ± 0.021^{g}	479.01 ± 0.206^{b}
	δ-tocopherols	5.802 ± 0.1^{a}	7.088 ± 0.004^{c}	13.160 ± 0.014^{d}	15.730 ± 0.31^{e}	16.205 ± 0.021^{f}	20.142 ± 0.006^{g}	24.064 ± 0.073^{b}
	Total	325.419 ± 0.575^{a}	226.116 ± 0.032^{c}	254.397 ± 0.005^{d}	351.558 ± 0.293^{e}	367.935 ± 0.037^{f}	453.078 ± 0.033^{g}	535.114 ± 0.001^{b}
W_3	**α-tocopherols**	1.211 ± 0.081^{a}	1.685 ± 0.106^{c}	3.145 ± 0.007^{d}	11.33 ± 0.007^{e}	13.2 ± 0.028^{f}	20.603 ± 0.002^{g}	26.69 ± 0.198^{b}
	γ-tocopherols	226.005 ± 0.049^{a}	190.266 ± 0.062^{c}	187.509 ± 0.001^{d}	248.840 ± 0.057^{e}	272.701 ± 0.005^{f}	368.324 ± 0.002^{g}	408.797 ± 0.037^{b}
	δ-tocopherols	5.497 ± 0.05^{a}	6.25 ± 0.014^{c}	13.49 ± 0.014^{d}	15.741 ± 0.005^{e}	17.071 ± 0.087^{f}	19.968 ± 0.003^{g}	23.5 ± 0.03^{b}
	Total	232.713 ± 0.082^{a}	198.201 ± 0.182^{c}	204.144 ± 0.023^{d}	275.911 ± 0.069^{e}	302.972 ± 0.11^{f}	398.894 ± 0.003^{g}	458.987 ± 0.204^{b}
W_4	**α-tocopherols**	0.611 ± 0.054^{a}	0.979 ± 0.017^{a}	2.034 ± 0.004^{a}	8.859 ± 0.004^{c}	10.117 ± 0.005^{d}	18.871 ± 0.013^{e}	19.001 ± 0.006^{b}
	γ-tocopherols	117.615 ± 7.14^{a}	135.280 ± 0.071^{c}	160.201 ± 0.005^{d}	213.115 ± 0.008^{e}	244.604 ± 0.012^{f}	330.98 ± 0.008^{g}	357.147 ± 0.004^{b}
	δ-tocopherols	4.637 ± 0.03^{a}	5.97 ± 0.028^{a}	13.642 ± 0.002^{c}	14.71 ± 0.002^{d}	17.893 ± 0.003^{e}	18.151 ± 0.004^{f}	16.86 ± 0.042^{b}
	Total	122.863 ± 7.225^{a}	142.229 ± 0.06^{c}	175.877 ± 0.001^{d}	236.684 ± 0.006^{e}	312.613 ± 0.02^{f}	368.001 ± 0.009^{g}	393.008 ± 0.052^{b}

Results are expressed as the mean values ± standard deviation of the three replicates (mean ± SD, n = 3); (a − g) different letters within a row indicate significant statistical differences ($p < 0.05$).

0.785 to 357.147 ± 0.004 mg/kg, and the oils at (20: 80; 40: 60 and 50: 50) decreasing in γ-tocopherol content as the proportion of AO decreases, while remaining better than LO.

As for α-tocopherols, it is strongly reduced in all oils, but a remarkable difference is revealed for pure LO oils ranging from 5.421 ± 0.1 on day 0 to 0.611 ± 0.054 on day 28 and blended oils at proportions (80: 20; 60: 40) vary from (6.116 ± 0.006; 11.738 ± 0.049) from day 0 to (0.979 ± 0.017; 2.034 ± 0.004) on day 28, while AO oils and oils with an AO proportion >50% retain interesting levels of α-tocopherols: 19 mg/kg (AO),18 mg/kg (20:80), 10 mg/kg (40: 60), 8 mg/kg (50: 50). This phenomenon is consistent with previous studies (Pan et al., 2020), in which α-tocopherol is a source of the hydrogen atoms to reduce peroxyl radicals at a higher rate than the γ- and δ-homologues.

Other works have presented similar studies on different vegetable oils and reached identical results and interpretations concerning the oxidation of tocopherols and fatty acids in pure oils, as well as the stability of mixtures with different proportions (Pan et al., 2020; Prakash, Naik, & Yadav, 2020).

3.6. Total polyphenols content

The polyphenol content of pure control oils reaches 20 mg GAE /100 g oil for LO, and different values have been found in the bibliography 38.46 mg GAE /100 g oil (Hamed & Abo-Elwafa, 2012), 0.27 mg GAE/ 100 g seeds (Fruehwirth et al., 2020), 2.85 mg of GAE per 10 g of oil (Kostadinovik & Mitrev, 2013), 72.54 mg of GAE/kg oil (Kostadinović Veličkovska, Brühl, Mitrev, Mirhosseini, & Matthäus, 2015), and 26 mg GAE/g oil for pure AO, which is on the order of 23 to 21 mg GAE/g oil

(El Idrissi et al., 2023).

These oils show a decrease during oxidation where AO goes from 26 to 17.5 mg GAE/g oil, while the sharp decrease seems to be for pure LO going from 20.16 to 0.00 mg GAE/g oil. The presence of AO in all blends gives higher polyphenol contents than pure LO (Hashempour-Baltork, Torbati, Azadmard-Damirchi, & Savage, 2017), so the seven oils during week 0 and the first week of oxidation show high polyphenol contents and from week 2 onwards the content of oils with proportions above 50% LO starts to drop until pure LO disappears and the oils (50: 50) and (80:20) become negligible in week 4, the same decrease is proven when increasing the quality of LO in the mixture in the literature (Hamed & Abo-Elwafa, 2012; Hashempour-Baltork et al., 2017).

3.7. Physicochemical properties

3.7.1. Free fatty acids

The acidity of vegetable oils is a qualitative parameter for defining triacylglycerol hydrolysis and free fatty acid (FFA) levels. All samples showed a significant increase ($p < 0.05$) in acidity.

Pure LO showed the highest acidity of all blends during 28 days of oxidation, ranging from 0.114% to 0.54%, percentages lower than those of studies that had the interest of comparing the stability of fresh and oxidized LO at 60 °C and found that acidity varied from 0. 695% to 0.76% (Mikołajczak et al., 2023)and a comparison between cold-press and hot-press extraction revealed that acidity rose from 0.595% to 0.735% (Zeng et al., 2022), while 0.96% was found for oil extracted by supercritical fluid (Khattab & Zeitoun, 2013). While pure AO varied between 0.0675% and 0.29%, also by effect of temperature it passed from the initial state 0.180% to 0.240% and from 0.22% to 6.54% (Belcadi-Haloui et al., 2018; Miklavčič et al., 2020). For blends, acidity appears low and increases slowly over 28 days as long as the proportion of AO is above 50%. Oils with a high FFA content become prone to oxidation and also reduce their smoking point, making them less suitable for food applications (World Health, 1994).

3.7.2. Peroxide value (PV)

Initially, the pure oils showed a wide difference in peroxide values, such as 2.9 for LO and 0.75 for AO, and by day 28 had reached 29.75 and 15.875 meq O_2/kg respectively. LO often had high peroxide values: 1.80 ± 0.14 meq O_2/kg (Choo et al., 2007; Herchi et al., 2014), 3.94 ± 0.31 meq O_2/kg (Pan et al., 2020), 5.42 ± 0.1 meq O_2/kg (Khattab & Zeitoun, 2013) and when subjected to oxidation at 60 °C it went from 0.39 ± 0.00 to 6.67 ± 0.09 meq O_2/kg (Mikołajczak et al., 2023). Whereas AO indicates PVs varying with roasting between 6.00 ± 0.035 and 7.08 ± 0.078 meq O_2/kg (Drouche, Castellano, Saidi, & Perez-Camino, 2022), and from 0.10 ± 0.01 to 0.16 ± 0.02 meq O_2/kg (Belcadi-Haloui et al., 2018) under different conditions.

With longer storage time, we observe an increase in the peroxide value of all oils, in particular the (80: 20) oil keeps a high PV 26.5 meq O_2/kg as high as pure LO 29.75 meq O_2/kg throughout the oxidation time, but the one mixed with (20: 80) shows the lowest PV 12.95 meq O_2/kg, while the two oils at (50: 50) and (40: 60) appear slower with a PV in the vicinity of pure AO. This means that the addition of AO inhibited the oxidation of LO oil, probably due to the high amount of tocopherol in AO.

3.7.3. Specific extinction coefficients (K232 and K270)

Oxidation of the side chains of PUFAs forms hydroperoxides of conjugated diene, which is a primary oxidation product (Weber, Bochi, Ribeiro, Victório, & Emanuelli, 2008). Conjugated dienes (CD) only appear with an absorption peak at around 232 nm (Ramadan & Wahdan, 2012). The higher the level of conjugated dienes in the edible oil, the poorer the oxidative stability (Mohdaly, Sarhan, Mahmoud, Ramadan, & Smetanska, 2010). As the number of days in storage progressed, all oils developed a trend towards linear growth of conjugated dienes, from which all final CD values were significantly higher than initial values. During storage, the maximum increase in CD was observed in LO, which rose from 2.055 to 2.437 higher than LO oxidized for 10 days, which rises from 0.18 e to 0.26 (Mikołajczak et al., 2023), and the minimum increase was observed in AO, which went from 1.0335 to 1.86, similar to the recent study (Pan et al., 2020) and lower than 3.25 ± 0.09 (Rabadán, Álvarez-Ortí, Pardo, & Alvarruiz, 2018). The CD values of the blended oils were between LO and AO, and the blended oils with a high proportion of AO showed a slow increase in CD value, except the oil at (80: 20) becomes lower than AO at week 2, plus the oils at (50: 50) and (40: 60) all three stabilize above AO from week 3 onwards.

Absorbance at 270 nm also showed variations according to storage conditions. Overall, it increased for LO from 0.5345 to 1.0035 > 0.20 (Choo et al., 2007; Herchi et al., 2014), and for AO from 0.2165 to 0.384 > 0.054 ± 0.001 (Belcadi-Haloui et al., 2018). A slow increase in K270 is noted for AO plus the three oils with proportions (20: 80; 40: 60; 50: 50) during the 28 days, while the two with high LO increase rapidly from the 2nd week onwards. Previous studies have reported that increasing the temperature and storage time of vegetable oils at 60 °C led to an increase in K232 and K270 (Belcadi-Haloui et al., 2018; Mikołajczak et al., 2023).

However, the acidity, PV and K270 values found only in pure AO and (20: 80) oil remained below the limits set by Moroccan standard NM 08.5.090 [22] characterizing argan oil quality:

Pure AO: Acidity (%) =0.29 < 0.8; PV = 14.25 < 15 meq O_2/kg; K270 = 0.304 < 0.35.

(20: 80) Oil: Acidity (%) =0.29 < 0.8; PV = 12.95 < 15 meq O_2/kg; K270 = 0.28 < 0.35.

3.8. Chlorophylls and carotenoids

Maximum chlorophyll content is noted for LO with 0.96 mg/kg in the initial oil state, rising to 0.67 mg/kg in the last week, and remains low compared to recent studies 2.34 mg/kg oil (Herchi et al., 2014), 5.76 mg/kg oil (Choo et al., 2007). And AO indicates the low content of all oils, ranging from 0.31 to 0.23 mg/kg in 4 weeks of oxidation, corresponding to 0.43–1.16 mg/kg (El Idrissi et al., 2023), 0.34 mg/kg (Bouchab et al., 2023), 0.32–0.43 mg/kg (Moradi, Gharachorloo, & Ghasemi Afshar, 2023). The chlorophyll content of the blends follows the decrease observed in the pure oils and remains close to the dominant oil content of each blend. Over 4 weeks, LO influences the content of oils at (80: 20) and (60: 40) with 0.62–0.54 mg/kg respectively, while AO decreases the content in the remaining oils from week 2 onwards to <0.3 mg/kg.

On the other hand, pure AO is quite rich in carotenoids at 0.4 mg/kg compared with LO at 0.16 mg/kg, and recently different results were found for AO (0.24 (Bouchab et al., 2023), 0.25–0.63 (El Idrissi et al., 2023), 12 mg/kg (Moradi et al., 2023) and others for LO (7.52 (Herchi et al., 2014), 0.69 (Mikołajczak et al., 2023), 9.21 (da Silva Moura et al., 2023). During oxidation, pure LO increases from 0.16 to 0.046 mg/kg, with a proven decrease from 0.69 to 0.48 mg/kg (Mikołajczak et al., 2023). As long as LO contains low levels of carotenoids, LO-rich blends suffer a similar deficiency to that seen when avocado oil blended with linseed oil in high proportions (da Silva Moura et al., 2023).

4. Conclusion

The LO and AO blends achieved the desired objectives by improving nutrition and functionality compared to those of LO, with the proportion of AO increasing, the oleic acid content in the blended oil increased, and the fatty acid composition was more balanced in the blends (50: 50; 40: 60; 20: 80), while the trans fatty acid content of the formulas (80: 20; 60: 40) increased due to the high C18:3 trans fatty acid content of pure linseed oil. After 28 days of accelerated oxidation at 60 °C, the tocopherol and carotenoid content of all seven oils progressively decreased, while the FFA, POV, K232 and K270 proprieties, and chlorophyll concentrations increased slightly, indicating that the quality of

the oils progressively deteriorated, but the proportionally blended oils (50: 50; 40: 60; 20: 80) produced lower concentrations of primary and secondary oxidation products and the lowest COX and OS factors recorded, indicating a significant increase in their oxidation stability.

Availability of data and materials

not applicable.

CRediT authorship contribution statement

Oumayma Belhoussaine: Writing – original draft, Investigation, Data curation. **Chaimae El Kourchi:** Writing – original draft, Software, Data curation. **Mohamed Amakhmakh:** Software, Investigation, Data curation. **Riaz Ullah:** Writing – review & editing, Resources, Investigation, Funding acquisition. **Zafar Iqbal:** Writing – review & editing, Resources, Investigation, Funding acquisition. **Khang Wen Goh:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Formal analysis. **Monica Gallo:** Investigation, Validation, Visualization, Writing – review & editing. **Hicham Harhar:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Abdelhakim Bouyahya:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation. **Mohamed Tabyaoui:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Data availability

No data was used for the research described in the article.

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Authors declare that there is no conflict of interest.

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