Food Chemistry: X 36 (2026) 103878

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x

Effects of blending argan oil with walnut and olive oils: Modeling chemical quality, oxidative stability, and sensory acceptability

Abderrahim Asbbane [a], Moussa Nid Ahmed [a], Mohamed Adnan [a], Wissal Chouacha [a], Abdelhakim Bouyahya [b,*], Waleed Al Abdulmonem [c,*], Mohammed Alorini [c], El Hassan Sakar [d], Angelo Maria Giuffrè [e], Said Gharby [a,*]

[a] Biotechnology, Analytical Sciences and Quality Control Team, Polydisciplinary Faculty of Taroudant, Ibn Zohr University, Agadir, Morocco
[b] Laboratory of Human Pathologies Biology, Department of Biology, Faculty of Sciences, Mohammed V University in Rabat, Rabat 10106, Morocco
[c] Department of Pathology, College of Medicine, Qassim University, Buraydah, Saudi Arabia
[d] Laboratory of Biology, Ecology, and Health, FS, Abdelmalek Essaadi University, Tetouan, Morocco
[e] Department AGRARIA, University of Studies "Mediterranea" of Reggio Calabria, 89124 Reggio Calabria, Italy

ARTICLE INFO

Keywords:
Argan
Blending
Blend oil
Olive
Oxidative stability
Shelf-life
Walnut

ABSTRACT

Vegetable oil blending is widely applied to enhance oxidative stability and chemical quality. In this work, the effects of blending argan oil with olive and walnut oils were investigated with the dual objectives of improving oil stability and nutritional attributes while providing compositional insights relevant to authenticity assessment. Five blended oil formulations were prepared and compared with individual oils used as negative controls. Oil quality indices, pigment content, fatty acid composition, saponification and iodine values, nutritional and sensory profiles, were determined. Oxidative stability was evaluated using induction period measurements. All blended oils met the quality parameters within recommended standards, with free fatty acids below 6% and peroxide values below 6 mEq O_2/kg. The AOW5 blend (argan: 55%, olive: 40%, walnut: 5%) showed notably higher pigment content and the highest oxidative stability (induction period of 18.23 h). Fatty acid analysis revealed monounsaturated fatty acid levels exceeding 50% in all blends, indicating favorable nutritional profiles. Overall, blending argan oil with olive and walnut oils enhanced oxidative stability and maintained high nutritional quality, supporting the potential of controlled blending strategies for value enhancement while emphasizing the need for robust analytical characterization to distinguish quality improvement from fraudulent practices.

1. Introduction

Vegetable oils (VOs) are a major constituent of the human diet and play essential roles in food product formulation (Asbbane, Bousaid, et al., 2024). Although vegetable oils possess valuable functional, nutritional, and sensory properties, achieving all these qualities along with enhanced oxidative stability in a single oil remains a challenge (Hashempour-Baltork et al., 2016). Through processes such as interesterification, hydrogenation and fractionation can improve nutritional properties and stability of VOs. However, these methods have limitations, including high equipment and investment costs, and hydrogenation can produce harmful trans isomers. Blending, on the other hand, is an effective method for producing functional oils, that are balanced in fatty acids and beneficial to health (Hashempour-Baltork et al., 2016; O'Brien, 2008).

Argan oil (AO) is a highly valued virgin oil extracted from argan kernels. Roasted kernels provide an edible oil, while unroasted kernels provide a beauty oil, both types are obtained by mechanical pressing of carefully prepared kernels following a rigorous and standardized process (Gharby, Guillaume, et al., 2021; Guillaume et al., 2019). Approximately, 2.5 kg of kernel are needed to obtain 1 L of AO (Asbbane et al., 2025). AO contains almost 99% glycerides, mainly composed of fatty acids (FAs), with unsaturated fatty acids (UFAs) accounting for about 80% of the total (Gharby et al., 2011; Hallouch, Ibourki, Asbbane, et al., 2025).

Olive oil (OO) is a crucial part of the Mediterranean diet. Its use has numerous health properties (Sakar et al., 2022). World production of OO is estimated at 3,375,500 tons, according to the latest version of the

* Corresponding authors.
E-mail addresses: boyahyaa-90@hotmail.fr (A. Bouyahya), Dr.waleedmonem@qu.edu.sa (W. Al Abdulmonem), s.gharby@uiz.ac.ma (S. Gharby).

https://doi.org/10.1016/j.fochx.2026.103878
Received 21 November 2025; Received in revised form 14 March 2026; Accepted 16 April 2026
Available online 19 April 2026

International Olive Council (IOC, 2024). OO contains many substances including tocopherols, polyphenols, sterols, carotenoids, squalene, triterpenes, and volatile compounds. The major fatty acid in OO is oleic acid (55–83%), which is a monounsaturated fatty acid (MUFA) belonging to the oleic (ω9 group) (Gagour, Hallouch, A. Asbbane, et al., 2024). OO has a higher meaningful level of linoleic acid (2.50–21%) and polyunsaturated fatty acids (PUFAs) from the ω6 group. Higher UFAs in OO are related to many biological characteristics (Gharby, Hajib, et al., 2021).

Walnut oil (WO) is extracted from walnut kernels (Pan et al., 2020). WO has a rich fatty acid composition and is abundant in trace elements, which contribute significantly to human health (Ma et al., 2024). WO contains 70.39% ω-3 and 14.41% ω-6 FAs. It is valuable functional element that can be used as an additive, especially in food enhancement, to balance the ω3/ω6 ratio and raise the ω-3 levels in food products due to its high PUFAs concentration. Its application is nevertheless limited, as it is an unstable oil. Therefore, it is not suitable for high-temperature cooking like some other edible oils, but it can be blended with other saturated oils to improve its stability (Djikeng et al., 2024).

The blended method is used to formulate a balanced oil that is obtained from two or more VOs to meet the range required by consumers. Moreover, the levels of FAs in formulated oils are likely formulated to meet the requirements of the human body. Those oils can also contain higher levels of bioactive compounds, resulting in high quality oils, with excellent physical and biochemical characteristics, and the highest nutritional profiles (Pan et al., 2020). Blending oils is a method applied to modify the fatty acid composition in order to improve the nutritional attributes, sensory quality, oxidative stability and market value of the product. The oil manufacturing industry often applies a blending process to formulate balanced oils with better stability and greater functional properties (Fadda et al., 2022). Blending oils with good stability and important nutritional properties is an effective way to reduce oxidation (Gharby et al., 2025).

Oil blending has been widely applied as an effective strategy to optimize the omega-6/omega-3 ratio and to enhance oxidative stability through a specific MUFA/PUFA balance, with most studies focusing on binary mixtures, particularly those involving olive oil (González et al., 2023; Monfreda et al., 2012; Roiaini et al., 2015; Terpinc et al., 2026; Torri et al., 2019). AO is characterized by a high level of UFAs and tocopherols, whereas WO is rich in PUFAs but exhibits limited oxidative stability. OO, in turn, is distinguished by its high oleic acid and phenolic compound contents. Despite the nutritional and functional complementarity of these oils, their ternary blending has not yet been systematically investigated. To the best of our knowledge, no study has evaluated the combined effect of argan, olive, and walnut oils on fatty acid composition, bioactive compounds, and oxidative stability within a single lipid system. Therefore, the present work proposes an original ternary blending approach to formulate and characterize argan, olive and walnut oil mixtures with enhanced nutritional and functional properties.

2. Materiel and methods

2.1. Oil extraction

Argan oil (AO) was prepared by women's cooperatives in Taitmatine (Taroudant, Morocco) and obtained by mechanical extraction (SMIR Technotour, Agadir, Morocco). Olive oil (OO) was purchased from the local commercial market in Agadir, Morocco, and identified as extra virgin OO. Walnut oil (WO) was extracted in the BISACQ research laboratory of the Polydisciplinary Faculty of Taroudant (Morocco) using a mechanical cold-press method. All oils were immediately transferred into 250 mL dark glass bottles and stored at 4 °C until blending and further analyses.

2.2. Oil blends preparation

Oil blends were prepared by mixing argan oil (AO), olive oil (OO), and walnut oil (WO) at predefined ratios (AOW1-AOW5), as detailed in Table S1 (Supplementary Material). The blending ratios were established based on the recommended daily intake of the predominant fatty acid in each individual oil. The required volumes of each oil were accurately measured and combined at room temperature under gentle stirring for 20 min using a magnetic stirrer (BIOBASE MS-M-S10) until visually homogeneous. No phase separation was observed during or after blending. The blends were prepared immediately before analysis, transferred into dark glass bottles, and stored at 4 °C until further analyses.

2.3. Quality indices

2.3.1. Free fatty acids (FFA)

FFA or acidity was evaluated in the studied oil according to the protocol detailed in ISO 660 (2020). Five grams of each oil were placed into a 250 mL beaker. Thereafter, 80 mL of absolute ethanol was introduced, additionally, a few drops of phenolphthalein were added as an indicator color. The mixture was titrated with NaOH (0.1 N). FFA of pure and blended oils was expressed as g of oleic acid /100 g.

2.3.2. Peroxide value (PV)

PV was evaluated according to ISO 3960 (2017). Firstly, 5 g of the sample was dissolved in a solution of acetic acid and isooctane (6:4, *v*/v), after adding one milliliter of a supersaturated solution of KI. After 1 min of stirring, 75 mL of H_2O was added and the mixture was titrated with $Na_2O_3S_2$ (0.01 N), with starch as an indicator color. The equivalence point was obtained when the blue color disappeared. PV is expressed in milli-equivalents of active oxygen per kilogram of oil (mEq O_2 /kg).

2.3.3. Para anisidine value (p-AV)

The *p*-AV was assessed according to ISO 6885 (2016). Firstly, 1.00 ± 0.01 g of sample was diluted to 25 mL with isooctane (solution A), and the absorbance (Ab) was read at 350 nm. After, five milliliters of this solution were reacted with one milliliter of anisidine reagent (solution B). The absorbance (As) was again read at 350 nm, after 10 min in darkness, using a SCILOGEX SP- UV1100 spectrometer. The *p*-AV is calculated following this formula:

$$p-\mathrm{AV}=\frac{25\times(1.2\,\mathrm{As}-\mathrm{Ab})}{\mathrm{m}}$$

Ab and As: absorbance of solution A and B, respectively. m: mass of studied oil (g). 25: volume of isooctane to dilute the sample, and 1.2: correction factor for dilution of the solution with 1 mL of *p*ara anisidine.

2.3.4. UV extinction coefficients (K_{232}, K_{270})

K_{232} and K_{270} were obtained in accordance with ISO 3656 (2011). These coefficients were expressed as the absorption of a mixture of oil with cyclohexane (1%). The extinction coefficients K_{232} and K_{270} can be used to evaluate the existence of primary and secondary oxidation products, respectively.

2.3.5. Total oxidation value (TOTOX) and integral oxidation value (INTOX)

The total oxidation index is a parameter to evaluate the oxidative stability (Oubannin et al., 2022). It is obtained using the following equation:

$$\mathbf{TOTOX}=\mathbf{2}\times\mathbf{PV}+\boldsymbol{p}\textbf{-AV}.$$

The integral oxidation focuses on prioritizing the formation of secondary oxidation compounds. This indicator is determined using the following equation:

$$\mathbf{INTOX}=\mathbf{PV}+(\mathbf{2}\times\boldsymbol{p}\textbf{-AV})$$

2.4. Pigment content

The pigment (carotenoid and chlorophyll) contents of pure and blended oils were obtained following the established protocol (Nid Ahmed et al., 2024). Briefly, 7.5 g of the sample was diluted with cyclohexane (25 mL). The quantity of pigments was obtained by reading the absorbance at 470 and 670 nm based on formulas as follows:

$$\textbf{Carotenoids}\left(\mathbf{mg/Kg}\right)=\frac{\mathbf{A_{470}\times 10^6}}{\mathbf{2000\times 100\times L}}$$

$$\textbf{Chlorophylls}\left(\mathbf{mg/Kg}\right)=\frac{\mathbf{A_{670}\times 10^6}}{\mathbf{613\times 100\times L}}$$

A: absorbance and L: spectrophotometric cell diameter (10 mm).

2.5. Bioactive compounds

The extraction of bioactive substances was carried out using the method detailed by Oubannin, Asbbane, Goh, et al. (2024), with slight modifications.

Firstly, five grams of each oil was placed in a tube. After, 20 mL of a mixture of hexane and 80% of methanol (50:50, *v*/v) was added. The solution was energetically vortexed and then centrifuged for 15 min at 3500 rpm. The polar phase or micellar dispersions (in the bottom) was recuperated, and then submitted to phytochemical assays.

2.5.1. Total phenolic compound (TPC)

TPC was evaluated based on the Folin–Ciocalteu assay (Bijla et al., 2021). Briefly, 0.5 mL of micellar dispersions was reacted with 2.5 mL of Folin-Ciocalteu solution (10%). Then 2 mL of Na_2CO_3 (7.5%) was added and after two hours in darkness. The absorption was read at 765 nm. TPC was expressed as mg gallic acid equivalents per g of micellar dispersions (mg GAE/g MP).

2.5.2. Total flavonoid compound (TFC)

TFC of the oils was evaluated using a colorimetric assay (Gagour, Hallouch, Asbbane, et al., 2024). In a 10 mL test flask, one milliliter of micellar dispersions was reacted with 300 μL of $NaNO_2$ (5%) and allowed to stand for five minutes. The solution was then added to 300 μL of $AlCl_3$ (10%), then one milliliter of NaOH (2 N) was added to the solution, which was then filled to the mark with H_2O after six minutes. The absorbance was read at 415 nm. TFC was expressed as mg quercetin equivalent per g micellar dispersions (mg QE/g MP).

2.5.3. Ferric reducing antioxidant power test (FRAP)

The antioxidant capacity of the studied oils was evaluated by the FRAP test (Ait Bouzid et al., 2023). The FRAP reagent, containing (2, 4, 6-tripyridyl-*s*-triazine), $FeCl_3$ and acetate buffer, are reacted with H_2O and the micellar dispersions. The absorbance was measured at 595 nm after 30 min. FRAP was expressed as mg Trolox equivalents per g of micellar dispersions (mg TE/g MP).

2.5.4. Radical scavenging activity by DPPH test

Briefly, 4 mL of micellar dispersions was reacted with 0.8 mL of a methanolic DPPH (0.2 mM). After 30 min in the dark, the absorbance was read at 517 nm. A control is prepared by adding 0.4 mL of DPPH to 2 mL of methanol, with ethanol serving as the blank (Hallouch, Ibourki, Bijla, et al., 2025).

2.6. Fatty acids composition (FAC)

FAC was analyzed according to the official analytical protocol (ISO 12966-2, 2017). Fatty acids (FAs) were converted into their fatty acid methyl esters (FAME) and FAC was obtained as their corresponding methyl esters by gas chromatography (GC - Agilent 6890). Firstly, 100 mg of the oil was reacted with two milliliters of isooctane and added 0.1 mL of methanolic KOH solution (2 N), after stirred for one minute. Next, 2 mL saturated NaCl (40%) was added after two minutes. The organic phase was recovered and dried with sodium bisulfate; 1 µL of extract was injected. The apparatus was equipped with a DB 23 AG-TRANS capillary column (60 m × 320 µm × 0.25 µm). FID detector and injector temperatures were both set at 260 °C. Carrier gas used is Helium at a flow rate of 0.8 mL/min and a pressure of 20.12 psi. FAME are expressed as relative percentage of the area of each peak.

2.7. Iodine value (IV) and saponification value (SV)

IV can determine the degree of unsaturation, this index is obtained from the percentage of UFA following the theoretical expression (Asbbane et al., 2025):

IV (g I_2/100 g) = (% C16:1 × 1.001) + (% C18:1 × 0.899) + (% C18:2 × 1.814) + (% C18:3 × 2.737).

SV is evaluated using the FAs applied to the formula published by Asbbane, Hallouch, et al. (2024):

SV (mg KOH/g of oil) = 3 × n × 56 × 1000 (with $n = 1 / M_{TG}$)

$$\boldsymbol{M_{TG}}=\boldsymbol{mean\ molecular\ weight}\times\mathbf{3})+\mathbf{92.09}-(\mathbf{3}\times\boldsymbol{molecular\ weight}(\boldsymbol{H_2O}))$$

2.8. Nutritional quality indices

Nutritional properties of the FAs present in the studied oils were assessed using the parameters described in **Table S2**. These indices were calculated based on FAs, following the equations published by Lakhlifi El Idrissi et al. (2024).

2.9. Calculated oxidizability value (COX) and oxidative susceptibility (OS)

COX is a measure of oil's susceptibility to oxidation. This index is estimated using a theoretical formula based on UFAs. This calculation method provides a quantitative evaluation of an oil's oxidizability, helping to understand and predict its oxidative stability and shelf life. The formula applied to esteemed COX is (Ait Bouzid et al., 2024):

$$\mathbf{COX}=\frac{\mathbf{1\times(C16{:}1+C18{:}1+C20{:}1)+10.3\times(C18{:}2)+21.6\times(C18{:}3+C20{:}3)}}{\mathbf{100.}}$$

Oxidative susceptibility (OS) was obtained using the UFAs levels, following this equation (Ait Nouisse et al., 2025):

OS = %MUFA + (%C18:2 × 45) + (%C18:3 × (100)

2.10. Rancimat test

The state of oil's oxidative stability was determined using the Rancimat apparatus. Firstly, three grams of oil were placed in tubes and exposed to higher temperatures 383, 393, 403 and 413 K while maintaining a constant airflow (20 L/h) (Gharby et al., 2016). The decomposition products resulting from oxidation were transported by continuous air flow to a measuring cell filled with distilled water. The change in conductivity caused by the volatile substances generated during oxidation was continuously monitored. The inflection point in the recorded curve, when the sample lost its resistance to oxidation, was proposed as the induction period (IP) (Harkaoui et al., 2023).

2.11. Kinetic data analysis

The kinetic data for the different samples were obtained using the following methods (Gagour, Ahmed, et al., 2022).

The rate constant of reaction (k) for lipid oxidation of oils was calculated as the inverse of IP

$$\mathbf{k}=\frac{\mathbf{1}}{\mathbf{IP}} \quad (1)$$

The temperature coefficient (T_{coeff}, K^{-1}) was determined based on the slope of the linear formula (2) between ln (k) and T:

$$\mathbf{ln(k) = aT + b} \quad (2)$$

The temperature acceleration factor (Q_{10}), was determined using the formula (3):

$$\mathbf{Q_{10} = e^{-10\times T_{coeff}}} \quad (3)$$

The influence of temperature (T) on the rate of lipid oxidation (k) was illustrated using the Arrhenius formula (4):

$$\mathbf{ln(k) = lnA - \frac{Ea}{RT}} \quad (4)$$

A: frequency factor (h^{-1}), Ea: activation energy (kJ/mol), R: molar gas constant (8.314 $J.K^{-1}.mol^{-1}$).

The activation enthalpies (ΔH) and entropies (ΔS) were calculated using the following eq. (5):

$$\mathbf{ln\left(\frac{k}{T}\right) = ln\left(\frac{k_B}{h}\right) + \left(\frac{\Delta S}{R}\right) - \left(\frac{\Delta H}{RT}\right)} \quad (5)$$

where k_B: Boltzmann constant (1.380×10^{-23} J/K), h: Planck's constant (6.63×10^{-34} J s).

The shelf-life prediction of studied samples at 20, 25, 30 and 35 °C was obtained by linear regression of ln (IP) versus T using the following eq. (6):

$$\mathbf{ln(IP) = a(T) + b} \quad (6)$$

2.12. Sensory panel

The sensory panel consisted of 15 trained assessors (6 females and 9 males), aged 22–50 years, all non-smokers and regular consumers of argan, olive and walnut oils. The panel included a professor specializing in vegetable oil sensory analysis. As all tested products were edible oils and posed no health risk, formal ethical committee approval was not required according to institutional guidelines. Nevertheless, all participants were fully informed about the goals and methods of the study and provided written informed consent before participation. The study was carried out with anonymity and voluntary involvement guaranteed by ethical guidelines for research involving human subjects.

2.13. Sensory evaluation procedure

Sensory analysis was conducted in accordance with standardized protocols previously applied to argan and olive oils (Gagour et al., 2025; Oubannin, Asbbane, Hallouch, et al., 2024, with adaptation to accommodate blended oil samples. Eight oil samples (three pure oils and five blended oils) were evaluated. Samples were presented at 22 ± 2 °C in standardized amber glass cups, each coded with a random three-digit number to avoid identification bias. The following sensory attributes were assessed: color, odor, flavor intensities and rancidity. Each attribute was evaluated using a structured 4-point intensity scale: 0 = absent, 1 = weak, 2 = moderate, 3 = strong, 4 = very strong. Assessors recorded their scores independently.

2.14. Statistical analysis

The mean ± standard deviation (SD) of three replicates is used to express all values. One-way analysis of variance (ANOVA) was used to assess statistical differences between samples, and Tukey's post hoc test was used at a significance level of $p < 0.05$ to investigate the associations between variables. Multivariate studies were conducted such as principal component analysis (PCA) and correlation matrix analysis. OriginPro software (version 2025) was used for statistical analysis and graphical representations.

3. Results and discussion

3.1. Quality indices

3.1.1. Free fatty acids

Free fatty acid (FFA) is widely used as an indicator of oil quality and mainly reflects the degree of hydrolytic degradation. FFA are generated through the cleavage of ester bonds in triacylglycerols, resulting in the release of fatty acids via enzymatic hydrolysis or chemical hydrolysis (Ahmed et al., 2024; Mahesar et al., 2014). Fig. 1**-A** showed that pure AO had the highest value of FFA (0.75 ± 0.04 g/100 g) and extra virgin OO had the lowest (0.21 ± 0.01 g/100 g), while, there was no significant difference in the blended oils. The FFA values of the studied blend oils are in accordance with the SNIMA Standards (SNIMA, 2003). The FFA of pure OO is in line with other studies (Torres et al., 2011). FFA of OO falls within the IOC standard range (<0.80) (IOC, 2021). Therefore, FFA values mainly represent hydrolytic deterioration, rather than oxidative degradation, which involves lipid peroxidation and is better assessed using oxidation parameters.

3.1.2. Primary oxidation

PV and K_{232}, which are markers of the presence of primary oxidation products (hydroperoxides or peroxides) in vegetable oils, can be used to evaluate the oxidation status of the oils under study (Gharby et al., 2025).

Peroxide value (PV) and specific extinction (K_{232})

Fig. 1**-B** shows that AO recorded the lowest value in PV (0.95 ± 0.09 mEq O_2/kg), while olive oil showed the highest value (5.90 ± 0.07 mEq O_2/kg). All blended oils had a PV lower than OO. The acceptable PV range for OO is 20 mEq O_2 /kg (Gagour, Ibourki, Antari, et al., 2024), for AO and WO is 15 mEq O_2 /kg (Codex Alimentarius, 2023; Gharby & Charrouf, 2022).

In addition, K_{232} can show the existence of primary oxidation products, and this measurement can be used to check the PV (Gagour, Oubannin, et al., 2022). The highest K_{232} was recorded with OO. No significant difference in K_{232} was observed among the blend oils (AOW1, AOW2 and AOW5). Generally, K_{232} and PV values follow the same trend when oils are blended. The PV and K_{232} of pure OO are in line with those published in the literature (Torres et al., 2011).

The low PV and K_{232} of AO imply that the level of hydroperoxides, identified as primary oxidation products, is very low, suggesting better oxidative stability than OO. In fact, tocopherols and phenolic compounds, in which AO is rich, are the natural antioxidants that inhibit the formation of hydroperoxides once released in lipid oxidation. The results for the blended oils with these intermediate values likely reflect both the dilution effect of the oils and the antioxidants' protective role of AO, which may reduce the formation of primary oxidation compounds in the mixtures.

3.1.3. Secondary oxidation

The *p*-AV and K_{270} are used to estimate secondary oxidation compounds (ketones or aldehydes) (Oubannin et al., 2022).

Para anisidine value and specific extinction (K_{270})

The *p*-AV is an indicator of the existence of secondary oxidation compounds (Asbbane, Hallouch, et al., 2024). Fig. 1**-C** shows the *p*-AV and K_{270} values for pure and blended oils. AOW4 recorded the lowest *p*-AV (0.47 ± 0.01), while WO had the highest (3.51 ± 0.01). The highest value was found for pure WO, indicating extensive degradation of oxidized UFA. The blended oils (AOW2; AOW3; AOW4 and AOW 5) showed lower values than the pure oils. K_{270} recorded high values in AO and WO. In addition, all blended oils showed lower values than the two pure oils (AO and WO). K_{270} of OO is similar to other olive oil samples (Asgari et al., 2017; Gagour, Hallouch, Asbbane, et al., 2024).

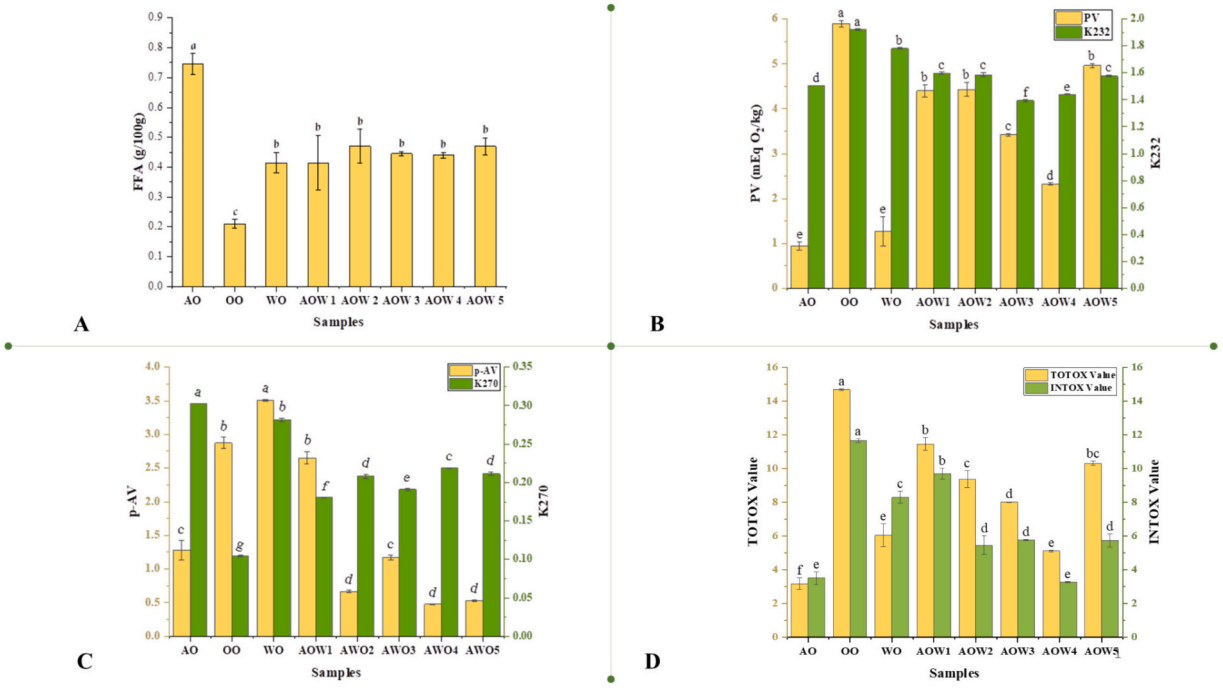

Fig. 1. Quality indices of pure and blended oils (A: Acidity. B: K_{232} and PV. C: K_{270} and *p*-AV. D: TOTOX and INTOX values)

3.1.4. Total oxidation value (TOTOX) and integral oxidation value (INTOX)

To give an overall picture of the oxidation vegetable oils, a value combining the information from the PV and the *p*-AV has been developed.

Fig. 1**-D** shows the chemical oxidation indicators of TOTOX and INTOX. A significant difference is shown for pure and blended oils. AO recorded low TOTOX and INTOX values, while, OO recorded a high value, which may be linked to the conditions under which the oil is extracted. AOW4 is a blended oil had low values for these two parameters.

3.2. Pigment content

Oil quality is influenced by pigment content, whose high antioxidant capacity improves the stability of oils and protects them from deterioration (Oubannin, Asbbane, Hallouch, et al., 2024). Fig. 2 shows variations in pigment content for pure and blended oils. A significant increase in pigment was shown in all blended oils. AOW5 recorded a high chlorophyll and carotenoid value, followed by AOW2, while AO and OO recorded the lowest chlorophyll value. AO and WO had the lowest carotenoid value. The pigment level depends on the degree of ripeness or the oil extraction technique (Symoniuk et al., 2022). It is well known that chlorophylls accelerate oxidation, while carotenoids tend to slow it down (Symoniuk et al., 2017).

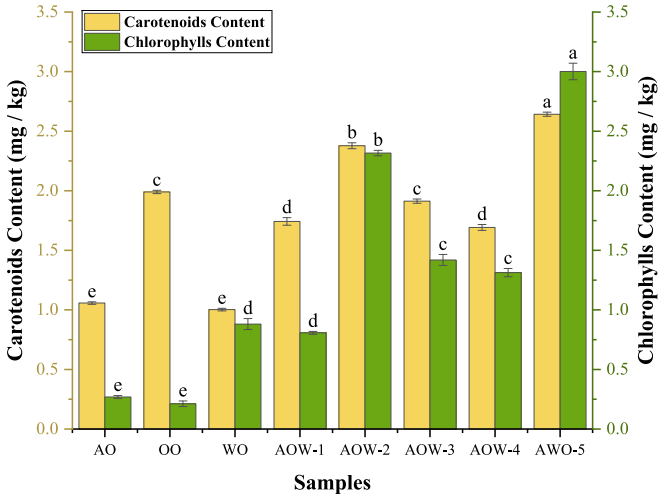

Fig. 2. Pigment content of pure and blended oils.

3.3. Fatty acids composition

The most important and abundant constituents of VOs are fatty acids. Oxidative stability, nutritional and cosmetic qualities are strongly associated with FAs (Bijla et al., 2022). The studied oils showed diversity in their fatty acid composition (Table 1). The FAs found in the oils were oleic, linoleic and palmitic acids with 47.34, 34.48 and 13.08 g/100 g (AO); 66.97, 12.18 and 15.60 g/100 g (OO) and 18.43, 59.36 and 6.67 g/100 g (WO), respectively. Additionally, WO contained a high level of C18:2 and C18:3 “59.36 and 13.43 g/100g, respectively”. All Blended oils had a higher level of C18:0 than OO and WO.

Some individual FAs for AO are similar to those published by Gharby, Hajib, et al. (2021). Blending different VOs can affect FAC and increase the amount of natural antioxidants and bioactive molecules in the blends and, therefore, can enhance the nutritional profile and the oxidative stability of oils (Hashempour-Baltork et al., 2016).

No significant difference in SFA between AO and OO. All blended oils had higher levels of SFA and MUFA than WO. The studied blended oils recorded more than 50 g/100 in MUFA. WO has an appreciably higher PUFA and UFA level, mainly due to linoleic and α-linolenic acids. Blended oils had higher PUFA and UFA levels than OO. UFA of WO are similar to those of walnut oil extracted by cold press (90.74 g/100 g) (Ma et al., 2024). The levels of SFAs, MUFAs, PUFAs and UFAs in OO were very close to those of extra virgin olive oil (Asgari et al., 2017).

The SFA/UFA ratio was used as an indicator of oil quality**.** PUFAs are more sensitive to oxidation, whereas SFAs have a high stability (Arslan et al., 2017). MUFA/PUFA and UFA/SFA in blended oils are higher than those in AO. PUFA/ SFA is generally regarded as an indicator of an oil's susceptibility to oxidation. (Al-Amrousi, 2024)**.** There was no significant

Table 1
Fatty acid composition (g/100 g), IV and SV of pure and blended oils.

	AO	OO	WO	AOW1	AOW2	AOW3	AOW4	AOW5
C14:0	0.12 ± 0.01 ^{a}	0.02 ± 0.00 ^{cd}	0.01 ± 0.00 ^{d}	0.06 ± 0.01 ^{bcd}	0.06 ± 0.01^{bcd}	0.08 ± 0.01 ^{ab}	0.09 ± 0.01 ^{ab}	0.07 ± 0.01 ^{abc}
C16:0	13.08 ± 0.10 ^{bc}	15.60 ± 0.10 ^{a}	6.67 ± 0.10 ^{e}	13.10 ± 0.10 ^{b}	12.34 ± 0.10 ^{d}	12.75 ± 0.10 ^{bcd}	12.54 ± 0.10 ^{cd}	13.04 ± 0.10 ^{bc}
C16:1	ND	2.15 ± 0.10 ^{a}	ND	1.67 ± 0.10 ^{ab}	1.55 ± 0.10 ^{b}	1.39 ± 0.10 ^{b}	1.54 ± 0.10 ^{b}	1.61 ± 0.10 ^{b}
C18:0	4.28 ± 0.10 ^{a}	1.89 ± 0.10 ^{c}	1.99 ± 0.10 ^{c}	2.79 ± 0.10 ^{b}	2.82 ± 0.10 ^{b}	3.26 ± 0.10 ^{b}	3.25 ± 0.10 ^{b}	3.18 ± 0.10 ^{b}
C18:1	47.34 ± 0.10 ^{f}	66.97 ± 0.10 ^{a}	18.43 ± 0.10 ^{c}	52.91 ± 0.10 ^{c}	49.98 ± 0.10 ^{e}	50.31 ± 0.10 ^{de}	50.66 ± 0.10 ^{d}	53.92 ± 0.10 ^{b}
C18:2	34.48 ± 0.10 ^{b}	12.18 ± 0.10 ^{g}	59.36 ± 0.10 ^{a}	27.62 ± 0.10 ^{e}	31.07 ± 0.10 ^{c}	30.47 ± 0.10 ^{d}	30.79 ± 0.10 ^{cd}	26.82 ± 0.10 ^{f}
C18:3	0.05 ± 0.01 ^{e}	0.55 ± 0.01 ^{d}	13.43 ± 0.10 ^{a}	1.47 ± 0.10 ^{c}	2.02 ± 0.10 ^{b}	1.42 ± 0.10 ^{c}	0.74 ± 0.01 ^{d}	0.85 ± 0.01 ^{d}
C20:0	0.24 ± 0.01 ^{b}	0.38 ± 0.01 ^{a}	0.11 ± 0.01 ^{d}	0.13 ± 0.01 ^{d}	0.16 ± 0.01 ^{cd}	0.14 ± 0.01 ^{d}	0.15 ± 0.01 ^{d}	0.21 ± 0.01 ^{bc}
C22:0	0.4 ± 0.01 ^{a}	0.27 ± 0.01 ^{b}	ND	0.24 ± 0.01 ^{b}	ND	0.17 ± 0.01 ^{c}	0.24 ± 0.01 ^{b}	0.29 ± 0.01 ^{b}
SFA	18.12 ± 0.33 ^{a}	18.16 ± 0.33 ^{a}	8.78 ± 0.33 ^{d}	16.32 ± 0.33 ^{bc}	15.38 ± 0.33 ^{c}	16.40 ± 0.33 ^{bc}	16.27 ± 0.33 ^{bc}	16.79 ± 0.33 ^{b}
MUFA	47.34 ± 0.14 ^{d}	69.12 ± 0.28 ^{a}	18.43 ± 0.14 ^{e}	54.58 ± 0.28 ^{b}	51.53 ± 0.28 ^{c}	51.7 ± 0.28 ^{c}	52.2 ± 0.28 ^{c}	55.53 ± 0.28 ^{b}
PUFA	34.53 ± 0.16 ^{b}	12.73 ± 0.16 ^{g}	72.79 ± 0.28 ^{a}	29.09 ± 0.28 ^{e}	33.09 ± 0.28 ^{c}	31.89 ± 0.28 ^{d}	31.53 ± 0.16 ^{d}	27.67 ± 0.16 ^{f}
UFA	81.87 ± 0.30 ^{cd}	81.85 ± 0.44 ^{d}	91.22 ± 0.43 ^{a}	83.67 ± 0.57 ^{bcd}	84.62 ± 0.57 ^{b}	83.59 ± 0.57 ^{bcd}	83.73 ± 0.44 ^{bc}	83.20 ± 0.44 ^{bcd}
MUFA/PUFA	1.371 ± 0.002 ^{f}	5.430 ± 0.044 ^{a}	0.253 ± 0.001 ^{g}	1.876 ± 0.001 ^{c}	1.557 ± 0.001 ^{e}	1.621 ± 0.001 ^{d}	1.656 ± 0.001 ^{d}	2.007 ± 0.001 ^{b}
UFA/SFA	4.52 ± 0.07 ^{d}	4.51 ± 0.06 ^{d}	10.39 ± 0.34 ^{a}	5.13 ± 0.07 ^{bc}	5.50 ± 0.08 ^{b}	5.10 ± 0.07 ^{bc}	5.15 ± 0.08 ^{bc}	4.96 ± 0.07 ^{cd}
PUFA/SFA	1.91 ± 0.03 ^{bc}	0.70 ± 0.01 ^{d}	8.30 ± 0.30 ^{a}	1.78 ± 0.02 ^{bc}	2.15 ± 0.03 ^{b}	1.94 ± 0.02 ^{bc}	1.94 ± 0.03 ^{bc}	1.65 ± 0.02 ^{c}
IV (g (I_2) /100 g of oil)	105.24 ± 0.31 ^{c}	85.96 ± 0.31 ^{f}	161.01 ± 0.31 ^{a}	103.36 ± 0.31 ^{d}	108.37 ± 0.31 ^{b}	105.78 ± 0.31 ^{c}	104.96 ± 0.31 ^{cd}	101.06 ± 0.31 ^{e}
SV (mg KOH/g of oil)	192.22 ± 0.81 ^{a}	192.75 ± 0.81 ^{a}	191.96 ± 0.81 ^{a}	192.56 ± 0.81 ^{a}	192.53 ± 0.81 ^{a}	192.51 ± 0.81 ^{a}	192.44 ± 0.81 ^{a}	192.47 ± 0.81 ^{a}

Values are presented as mean ± SD (n = 3). Different lowercase letters (a, b, c…) within the same row indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$). Treatments sharing at least one letter are not significantly different.

difference between the blended oils and argan oil ($p < 0.05$). UFA/SFA of OO is similar to 'Koroneiki' Virgin Olive Oil (4.54) (Hassanein et al., 2022).

3.4. Iodine value and saponification value

The iodine value (IV) is one of the measures applied to calculate the number of double bonds present in VOs (Asbbane, Hallouch, et al., 2024). Results for IV are shown in Table 1, which ranged from 85.96 to 161.01 g I_2/100 g. A low iodine value indicates a low level of unsaturation in the oils (Adejumo, Popoola, Bamiro, Daodu, and James, 2021). WO had the highest IV, which contains the major UFA. The IV of blended oils is very close to that of AO, since the percentage of this oil is the highest in all mixtures. The IV value of OO is in line with that of Moroccan Olive Picholine (85.74 g I_2/100 g) (Gagour, Ibourki, Antari, et al., 2024).

The saponification value (SV) is an index of the mean molecular weight of the FAs contained. A higher SV means the presence of shorter FAs on the glycerol structure (Ait Bouzid et al., 2024). The SV varied between 191.96 "WO" and 192.75 mg KOH/g "OO" (Table 1). Additionally, no significant differences between the SV of the pure and blended oils. High SV indicates that the oils are suitable for soap production (Ait Bouzid et al., 2024).

3.5. Nutritional indices

A number of indices (AI, TI, HH, ALA/LA, DFA, OFA, ODR, DR, S/P and OL/(LA + ALA)) can be calculated based on the fatty acid profiles of the studied oils and their blends. These parameters are frequently used to predict the potential nutritional and health impacts of dietary fats (Table 2). Health-related lipid indices, especially AI and TI, are among the most reliable and widely used markers for determine the effect of fatty acids on cardiovascular disease risk. For oils intended for human consumption, AI <1.0 and TI < 0.5 are considered desirable, along with a high HH (Siol et al., 2025). All tested oils satisfied these requirements, with AI ranging from 0.075 to 0.196 and TI from 0.02 to 0.27. These findings suggest a very low potential for atherogenicity and thrombogenesis. The h/H ratios of the tested oils were consistently high (5.10–13.66), further supporting their health-promoting potential. In addition to these indices, the ratio of omega-6 to omega-3 fatty acids ratio (ALA/LA) was also determined, as it is a crucial determinant of dietary fat quality and plays an essential role in maintaining metabolic

Table 2
Nutritional quality, phenolic compounds (TPC and TFC) and antioxidants capacity (FRAP and DPPH) of pure and blended oils.

	AO	OO	WO	AOW1	AOW2	AOW3	AOW4	AOW5
ALA/LA	0.001 ± 0.000 ^{e}	0.045 ± 0.001 ^{c}	0.226 ± 0.002 ^{a}	0.053 ± 0.005 ^{c}	0.065 ± 0.004 ^{b}	0.047 ± 0.004 ^{c}	0.024 ± 0.000 ^{d}	0.032 ± 0.000 ^{d}
DFA	86.15 ± 0.44 ^{bc}	83.74 ± 0.58 ^{c}	93.21 ± 0.57 ^{a}	86.46 ± 0.71 ^{b}	87.44 ± 0.71 ^{b}	86.85 ± 0.71 ^{b}	86.98 ± 0.58 ^{b}	86.38 ± 0.58 ^{b}
OFA	13.20 ± 0.16 ^{b}	15.62 ± 0.16 ^{a}	6.68 ± 0.16 ^{d}	13.16 ± 0.16 ^{b}	12.40 ± 0.16 ^{c}	12.83 ± 0.16 ^{bc}	12.63 ± 0.16 ^{bc}	13.11 ± 0.16 ^{b}
HH	6.20 ± 0.05 ^{c}	5.10 ± 0.03 ^{d}	13.66 ± 0.25 ^{a}	6.23 ± 0.04 ^{c}	6.70 ± 0.05 ^{b}	6.41 ± 0.04 ^{bc}	6.51 ± 0.06 ^{bc}	6.22 ± 0.05 ^{c}
AI	0.169 ± 0.002 ^{b}	0.196 ± 0.002 ^{a}	0.075 ± 0.002 ^{f}	0.161 ± 0.001 ^{cd}	0.151 ± 0.002 ^{e}	0.158 ± 0.001 ^{cd}	0.156 ± 0.002 ^{de}	0.163 ± 0.002 ^{bc}
TI	0.02 ± 0.01 ^{f}	0.27 ± 0.00 ^{a}	0.10 ± 0.00 ^{e}	0.25 ± 0.01 ^{ab}	0.24 ± 0.01 ^{b}	0.24 ± 0.01 ^{b}	0.19 ± 0.00 ^{d}	0.22 ± 0.00 ^{c}
ODR	0.422 ± 0.000 ^{b}	0.160 ± 0.001 ^{g}	0.798 ± 0.001 ^{a}	0.355 ± 0.002 ^{e}	0.398 ± 0.001^{c}	0.388 ± 0.001 ^{d}	0.384 ± 0.001 ^{d}	0.339 ± 0.001 ^{f}
LDR	0.001 ± 0.000 ^{e}	0.043 ± 0.001 ^{c}	0.185 ± 0.001 ^{a}	0.051 ± 0.004 ^{c}	0.061 ± 0.004 ^{b}	0.045 ± 0.004 ^{c}	0.023 ± 0.000 ^{d}	0.031 ± 0.000 ^{d}
S/P	0.214 ± 0.003 ^{a}	0.214 ± 0.002 ^{a}	0.095 ± 0.003 ^{d}	0.191 ± 0.002 ^{b}	0.180 ± 0.002 ^{c}	0.192 ± 0.002 ^{b}	0.190 ± 0.003 ^{bc}	0.196 ± 0.003 ^{b}
OL/(LA + ALA)	1.37 ± 0.00 ^{f}	5.26 ± 0.05 ^{a}	0.25 ± 0.00 ^{g}	1.82 ± 0.01 ^{c}	1.51 ± 0.01 ^{e}	1.58 ± 0.01 ^{de}	1.61 ± 0.00 ^{d}	1.95 ± 0.01 ^{b}
TPC (mg GAE/g)	0.12 ± 0.04 ^{d}	0.74 ± 0.07 ^{a}	0.40 ± 0.04 ^{bc}	0.27 ± 0.04 ^{cd}	0.14 ± 0.00 ^{d}	0.13 ± 0.00 ^{d}	0.59 ± 0.02 ^{ab}	0.43 ± 0.08 ^{bc}
TFC (mg QE/g)	1.33 ± 0.06 ^{ab}	1.18 ± 0.05 ^{b}	1.99 ± 0.11 ^{ab}	1.36 ± 0.13 ^{ab}	2.92 ± 0.02 ^{a}	2.95 ± 0.50 ^{a}	1.83 ± 0.02 ^{ab}	2.51 ± 0.64 ^{ab}
FRAP ((mg TE/g)	0.31 ± 0.01 ^{bc}	0.21 ± 0.04 ^{cd}	0.53 ± 0.02 ^{a}	0.11 ± 0.01 ^{d}	0.40 ± 0.02 ^{b}	0.20 ± 0.00 ^{cd}	0.31 ± 0.02 ^{bc}	0.24 ± 0.03 ^{c}
DPPH (%)	25.74 ± 1.42 ^{ab}	8.42 ± 2.11 ^{de}	17.82 ± 1.40 ^{bc}	2.48 ± 0.71 ^{e}	16.34 ± 2.13 ^{cd}	28.22 ± 0.70 ^{a}	2.97 ± 1.41 ^{e}	1.49 ± 0.71 ^{e}

Values are presented as mean ± SD (n = 3). Different lowercase letters (a, b, c…) within the same row indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$). Treatments sharing at least one letter are not significantly different.

balance and preventing the development of chronic diseases. WO exhibited a well-balanced ALA/LA ratio of 0.226. Moreover, WO exhibited high values for other nutritional indices, including DFA, ODR, and LDR, whereas OO showed elevated values for OFA and OL/(LA + ALA). Among the blended oils, AOW2 reflected higher values in indices in which WO predominated, while AOW1 and AOW5 showed increased values for indices characteristic of OO. These results indicate that oil blending modulated nutritional indices in a composition-dependent manner, allowing selective enhancement of specific health-related parameters.

3.6. Phytochemical analysis

The phenolic compound content is a very important quality indicator in VOs, due to its role in oxidative stability, nutritional and sensory qualities (Hashempour-Baltork et al., 2017). The TPC of the studied oils varied between 0.02 "WO" and 0.74 mg GAE/g "OO" oil. The highest value was obtained for OO. AOW5 had the highest TPC, which depended on the higher percentage of OO in the formulated oil. The highest TFC values were recorded by AOW2 and AOW3 blended oils (2.92 and 2.95 mg QE/g, respectively). In terms of pure oils, WO has a higher TFC value. Regarding antioxidant activities (FRAP and DPPH), there is a remarkable difference between the studied oils (Table 2).

3.7. Initial oxidative stability

The initial oxidative stability of the studied oils was evaluated using the calculated oxidizability value (COX), oxidative susceptibility (OS) and induction period (IP).

Oil stability increases as the COX value decreases (Al-Amrousi, 2024). The COX values ranged from 2.06 ± 0.02 "OO" to 9.20 ± 0.05 "WO" (Table 3). The results show that WO was the most susceptible to oxidation. Based on COX values, blend oils are stable than other VOs such as cactus (6.45, (Harkaoui et al., 2023)); black cumin (6.6, (Rudzińska et al., 2016)); sunflower (5.69,(Nid Ahmed et al., 2024)); sesame (4.47, (Ghosh et al., 2019)); linseed (12.03,(Symoniuk et al., 2017)); peanut (4.63, (Xu et al., 2015)); soybean (7.53, (Szpunar-Krok & Wondołowska-Grabowska, 2022)). The COX value of OO is in line with that of Moroccan Olive Picholine (2.12) (Gagour, Hallouch, Asbbane, et al., 2024).

Oxidative susceptibility (OS) also provides an indication of oil stability. As shown in Table 3, OS evolves in the same way as COX. The highest value was found in WO and the lowest in OO. Except AOW1, other blended oils have lower values than AO and WO. ANOVA test data showed that the OS of pure and blended oils were significantly different ($p < 0.05$).

COX and OS results indicate that the oil richest in UFAs content, and with the highest UFA/SFA and PUFA/SFA, is the one with the lowest oxidative stability.

The induction period (IP) is a parameter used to assess the stability of oil using the Rancimat test (Aissa et al., 2023). IP of VOs is very important for understanding their oxidative stability and potential applications in food products. The oxidative stability of the studied samples was determined based on the Rancimat test; the results are summarized in Table 3. IP values were done isothermally at four different temperatures (383–413 K). Results show that IP values increase with decreasing temperature. Oxidative stability results indicated that the IP of blended oils were lower than that of AO at all temperatures. WO always has the lowest value, while AO has the highest. The IP values of OO at all temperatures are similar to those published by Gharby, Guillaume, et al. (2021). Oxidative stability indices (COX and OS) show good agreement with Rancimat test results at different temperatures. The AOW5 blended oil shows the best stability (IP = 18.23 h), characterized by low COX and OS values (3.50 and 1347.43 respectively), while the AOW2 blended oil stands out for its reduced stability (IP = 12.29 h), linked to its high COX and OS values (4.15 and 1651.68 respectively). These results confirm the relevance of COX and OS values as reliable indicators of oxidative stability.

The reaction rate (k) values for all studied oils oxidation at each temperature are shown in Table 3. k depends on many factors (FAC and triacylglycerol structure, catalysts, inhibitors etc.) (Symoniuk et al., 2016). A higher k value indicates greater oxidation degradation and therefore lower oxidative stability (Upadhyay & Mishra, 2015). WO was presented the highest reaction rate at 413 K (217.49×10^{-2} h^{-1}). All blended oils showed better oxidative stability than the WO.

3.8. Kinetic analysis

This study aimed to determine and evaluate the kinetics of the studied oils. The Rancimat test was applied as a reflection of the expected shelf-life as well as determining the kinetic behavior of pure and blended oils. The results of kinetic data are shown in Table 4. Activation energy (Ea) is the minimum energy needed to initiate the oxidation reaction (Fatouh Hamed et al., 2023). The results show that AOW2 had the lowest Ea value (78.15 ± 4.08 kJ/mol), indicating that the low MUFA concentration in AOW2 significantly affected of Ea. Notably, high

Table 3
Calculated oxidizability value (COX), oxidative susceptibility (OS), induction period (IP) and reaction rate (k) of pure and blended oils at 383–413 K determined using the Rancimat method.

Samples	IP (h)				k ($10^{-2}h^{-1}$)				COX	OS
	383 K	393 K	403 K	413 K	383 K	393 K	403 K	413 K		
AO	26.76 ± 0.37 [a]	14.13 ± 1.74 [a]	7.04 ± 0.05 [a]	3.22 ± 0.03 [a]	3.74 ± 0.05 [f]	7.13 ± 0.88 [c]	14.21 ± 0.10 [c]	31.06 ± 0.27 [d]	4.04 ± 0.02 [bc]	1603.94 ± 5.61 [c]
OO	20.09 ± 0.06 [b]	9.46 ± 0.31 [b]	4.11 ± 0.16 [bc]	1.93 ± 0.04 [cd]	4.98 ± 0.01 [e]	10.58 ± 0.35 [bc]	24.35 ± 0.92 [b]	51.83 ± 1.14 [bc]	2.06 ± 0.02 [g]	672.22 ± 5.61 [h]
WO	4.13 ± 0.04 [f]	2.00 ± 0.09 [d]	0.94 ± 0.06 [d]	0.46 ± 0.01 [e]	24.24 ± 0.21 [a]	50.18 ± 2.31 [a]	106.58 ± 6.41 [a]	217.49 ± 0.67 [a]	9.20 ± 0.05 [a]	4032.63 ± 5.61 [a]
AOW1	15.43 ± 0.09 [d]	7.79 ± 0.13 [bc]	4.19 ± 0.23 [bc]	1.84 ± 0.06 [d]	6.48 ± 0.04 [cd]	12.85 ± 0.22 [bc]	23.90 ± 1.29 [bc]	54.37 ± 1.67 [b]	3.71 ± 0.05 [e]	1444.48 ± 5.61 [f]
AOW2	12.29 ± 1.23 [e]	6.38 ± 0.25 [c]	3.84 ± 0.30 [c]	2.01 ± 0.13 [cd]	8.18 ± 0.82 [b]	15.98 ± 0.61 [b]	26.12 ± 2.02 [b]	49.99 ± 3.35 [bc]	4.15 ± 0.05 [b]	1651.68 ± 5.61 [b]
AOW3	14.74 ± 0.05 [d]	7.65 ± 0.62 [bc]	3.78 ± 0.11 [c]	1.84 ± 0.06 [d]	6.79 ± 0.02 [cd]	13.12 ± 1.07 [bc]	26.47 ± 0.79 [b]	54.37 ± 1.67 [b]	3.96 ± 0.05 [cd]	1564.85 ± 5.61 [d]
AOW4	15.91 ± 0.08 [d]	9.54 ± 0.78 [b]	4.23 ± 0.22 [bc]	2.34 ± 0.04 [b]	6.29 ± 0.03 [cd]	10.52 ± 0.87 [cd]	23.70 ± 1.23 [bc]	42.65 ± 0.64 [c]	3.85 ± 0.02 [d]	1511.75 ± 5.61 [e]
AOW5	18.23 ± 0.16 [c]	9.54 ± 0.54 [b]	4.72 ± 0.11 [b]	2.14 ± 0.06 [bc]	5.49 ± 0.05 [e]	10.50 ± 0.59 [cd]	21.19 ± 0.51 [bc]	46.75 ± 1.24 [bc]	3.50 ± 0.02 [f]	1347.43 ± 5.61 [g]

Values are presented as mean ± SD (n = 3). Different lowercase letters (a, b, c…) within the same column indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$). Treatments sharing at least one letter are not significantly different.

Table 4
Kinetics data of the pure and blended oils' oxidation reactions.

Oils	AO	OO	WO	AOW1	AOW2	AOW3	AOW4	AOW5
Eq. (7)	**ln (k) = a (T) + b**							
a	0.0705 ± 0.0022	0.0786 ± 0.0011	0.0734 ± 0.0005	0.07 ± 0.0029	0.0594 ± 0.002	0.0694 ± 0.001	0.0656 ± 0.0039	0.0713 ± 0.0023
b	−23.3944 ± 0.8806	−26.2043 ± 0.4506	−22.6021 ± 0.2005	−22.6515 ± 1.147	−18.3486 ± 0.8117	−22.3909 ± 0.4049	−21.0213 ± 1.5509	−23.3332 ± 0.905
R^2	0.998	0.9996	0.9999	0.9966	0.9977	0.9996	0.993	0.998
T_{coeff} x 10^{-2} (K^{-1})	7.05 ± 0.22	7.86 ± 0.11	7.34 ± 0.05	7.00 ± 0.29	5.94 ± 0.20	6.94 ± 0.10	6.56 ± 0.39	7.13 ± 0.23
Eq. (8)	**ln (k) = ln (A) – (Ea/R) × (1/T)**							
a	−11.1285 ± 0.5258	−12.4279 ± 0.2725	−11.599 ± 0.1697	−11.0544 ± 0.5984	−9.3992 ± 0.3467	−10.9732 ± 0.3339	−10.3631 ± 0.6874	−11.261 ± 0.5378
b	32.6278 ± 1.3227	36.3291 ± 0.6854	35.7576 ± 0.4269	32.9972 ± 1.5053	28.9434 ± 0.8721	32.8348 ± 0.8399	31.138 ± 1.7293	33.3565 ± 1.3528
R^2	0.9956	0.999	0.9996	0.9942	0.9973	0.9982	0.9913	0.9955
A x 10^{12} (h^{-1})	147.94	5991.15	3383.07	214.05	3.71	181.97	33.35	306.57
Ea (KJ/mol)	92.53 ± 6.18	103.33 ± 3.2	96.44 ± 2	91.91 ± 7.04	78.15 ± 4.08	91.23 ± 3.93	86.16 ± 8.08	93.63 ± 6.32
Q_{10}	2.02 ± 0.04	2.19 ± 0.02	2.08 ± 0.01	2.01 ± 0.06	1.81 ± 0.04	2.00 ± 0.02	1.93 ± 0.08	2.04 ± 0.05
Eq. (9)	**ln (k/T) = ln (k$_B$/h) + (ΔS/R) – (ΔH/R) × (1/T)**							
a	−10.7327 ± 0.5232	−12.0342 ± 0.2693	−11.2003 ± 0.1668	−10.6589 ± 0.5969	−9.0003 ± 0.3462	−10.58 ± 0.3303	−9.9627 ± 0.6845	−10.8654 ± 0.5338
b	18.739 ± 1.3161	22.4452 ± 0.6774	21.8607 ± 0.4195	19.1089 ± 1.5015	15.0464 ± 0.871	18.9523 ± 0.8309	17.2376 ± 1.7218	19.4681 ± 1.3427
R^2	0.9953	0.999	0.9996	0.9938	0.997	0.9981	0.9906	0.9952
ΔH^{++} [KJ/mol]	89.24 ± 4.35	100.06 ± 2.24	93.12 ± 1.39	88.62 ± 4.96	74.83 ± 2.88	87.97 ± 2.75	82.83 ± 5.69	90.34 ± 4.44
ΔS^{++} [J/ K.mol]	−41.75	−10.93	−15.79	−38.67	−72.45	−39.97	−54.23	−35.68

MUFA and SFA levels increased the Ea value, while high PUFA level decreased the Ea value for the lipid oxidation process.

The ΔH and ΔS were calculated using the activated complex approach, and the corresponding regression indicators are presented in Table 4. The high regression coefficient ($R^2 > 0.99$) indicated adequate fit and characterization of the temperature dependence of lipid oxidation. The studied oils presented positive ΔH^{++} values ranging from 74.83 "AOW2" to 100.06 kJ/mol "OO", which indicates that the formation of the activated complex is of the endothermic type. ΔS^{++} values ranged from −72.45 "AOW2" to −10.93 J/ mol K "OO". The entropy results for blended oils are lower than those for olive and walnut oils. Negative ΔS values mean that the activated complexes are more ordered than the reactant molecules, and the higher these negative values are, the fewer species there are in the activated complex state, which reduces the probability that the activated complex will cause lipid oxidation and therefore slows down the process (Asbbane, Bousaid, et al., 2024). The values of T_{coeff} varied from 5.94 × 10^{-2} "AOW2" to 7.86× 10^{-2} K^{-1} "OO" **(**Table 4**).** The Q_{10} numbers show the impact of temperature on the oxidation rate of VO. In general, a lower Q_{10} number means that a higher temperature is necessary to induce some change in k. As shown in Table 4, the Q_{10} number do not differ significantly among the pure oils. The Q_{10} of OO is in line with that established by Gharby, Hajib, et al. (2021).

Sample AOW5 showed the highest kinetic parameters, indicating its lipid oxidation is less sensitive to temperature. This stability is linked to its lower UFAs concentration and higher pigment levels, which together reduce oxidation susceptibility and suggest a longer shelf-life than the other blends.

3.9. Shelf-life prediction

The shelf life of the studied oils was assessed using the Rancimat accelerated test. This test is simple to perform and allows the stability of vegetable oils (VOs) to be quickly assessed. Under ambient conditions, determining shelf life is often tedious and time-consuming. However, in high temperatures tests, the shelf life of VOs can be estimated in hours or days. It decreases logarithmically as the temperature rises (Upadhyay & Mishra, 2015). In this work, the relationship between ln (IP) and T values in pure and blended oils presented a linear dependence with high regression coefficients. The shelf lives predicted as induction times for all studied oils at 20 °C (IP_{20}), 25 °C (IP_{25}),30 °C (IP_{30}) and 35 °C (IP_{35}) (by extrapolation, **Fig. S1**). The shelf life of pure oils at 25 °C was 11,249.04, 16228.76 and 2118.49 h for AW, OO and WO, respectively. While, shelf life of blended oils ranged from 1910.29 "AOW2" to 8207.85 h "AOW5" at 25 °C. The results of the shelf life of all oils presented in Table 5 show that increasing the temperature decreases the shelf life of the oil. The difference in shelf life is related to the quantity of antioxidants and the level of PUFAs. The lower the level of PUFAs, the higher the oxidative stability (Harkaoui et al., 2023).

3.10. Sensory analysis

The blending process plays a crucial role in the sensory quality of the formulated oil (Hashempour-Baltork et al., 2016). Fig. 3 illustrates the sensory profiles of the different oil formulations, showing significant differences among tested samples ($p < 0.05$) for flavor, odor, color, and overall acceptance. Notably, all samples showed no rancidity, with scores remaining at the lowest level of the scale and without significant differences between treatments, indicating that no perceptible oxidative off-flavor developed during the evaluation period. However, variations were observed in flavor, odor, color, and overall acceptance. Among the blended oils, AOW1 achieved the highest overall acceptance, reflecting its balanced sensory profile and harmonious integration of attributes. The statistical grouping confirms that these differences are significant rather than descriptive. Furthermore, the absence of rancid perception is consistent with the relatively low PV and p-AV recorded for all samples,

Table 5
Shelf lives of pure and blended oils at different temperatures (20, 25, 30, 35 °C).

Samples	20 °C		25°C		30°C		35 °C	
	Hours	Months	Hours	Months	Hours	Months	Hours	Months
AO	16,014.30	22.24	11,249.04	15.62	7901.74	10.97	5550.47	7.71
OO	24,047.56	33.40	16,228.76	22.54	10,952.15	15.21	7391.18	10.27
WO	3057.86	4.25	2118.49	2.94	1467.70	2.04	1016.82	1.41
AOW1	8803.48	12.23	6196.33	8.61	4361.28	6.06	3069.69	4.26
AOW2	2572.64	3.57	1910.29	2.65	1418.46	1.97	1053.26	1.46
AOW3	7818.49	10.86	5523.24	7.67	3901.80	5.42	2756.36	3.83
AOW4	6435.03	8.94	4623.91	6.42	3322.53	4.61	2387.42	3.32
AOW5	11,732.28	16.29	8207.85	11.40	5742.18	7.98	4017.20	5.58

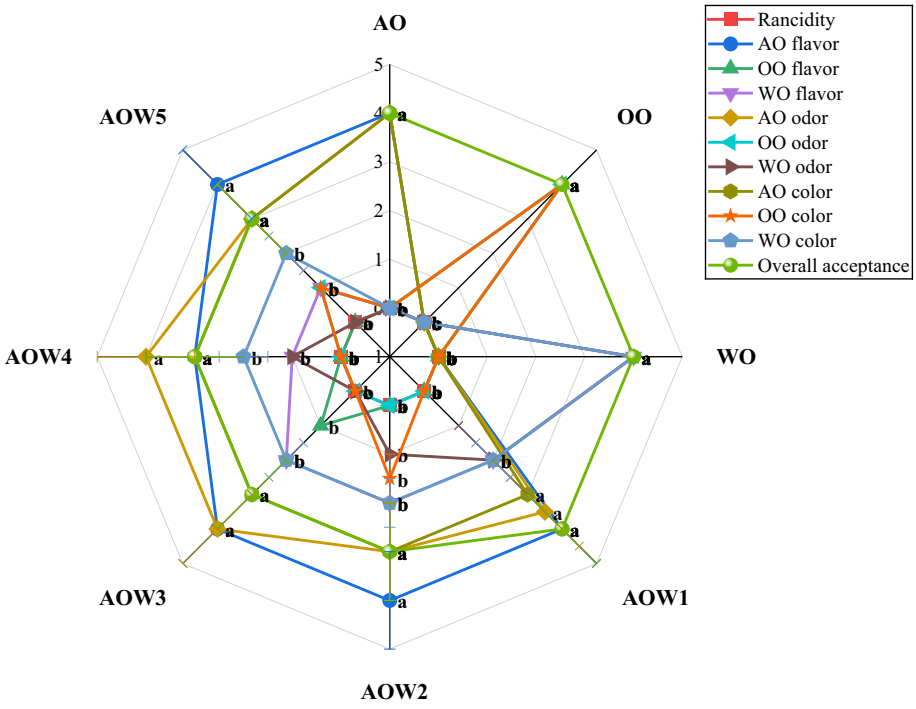

Fig. 3. Results of sensory analysis of pure and blended oils

suggesting that the levels of oxidation products remained below the sensory detection threshold. This concordance between chemical stability parameters and sensory evaluation supports the reliability of the results and indicates that all formulations maintained acceptable oxidative quality under the studied conditions.

3.11. Principal component analysis

Principal component analysis (PCA) was carried out to visualize similarities among quality indices, pigment contents, fatty acids, oxidative stability and phytochemical properties of the studied oil samples (**Fig. S2**). The first two principal components account for 71.74% of the total variance, with PC1 accounting for 39.32% and PC2 explaining 32.42%, indicating that most of the variability in the dataset can be interpreted within this two-dimensional space. All kinetic parameters (T_{coeff}, Ea, Q_{10}, ΔH^{++}, and ΔS^{++}), induction period (IP_{25}), total polyphenol content (TPC), TOTOX and INTOX were positively correlated with the PC1. In contrast, antioxidant activities (DPPH, FRAP), total flavonoid content (TFC) were negatively correlated with PC1, meaning that samples located on the negative side of PC1 exhibit higher antioxidant potential. Additionally, oxidative indices (COX and OS), unsaturated fatty acids and iodine value were positively associated with PC2, whereas pigment contents (chlorophylls, carotenoids) and saturated fatty acids (SFA) were negatively linked with PC2.

The score plot shows a clear distinct clustering of the studied oils. AOW1 and AOW5 are located on the positive side of PC1, indicating stronger correlations with shelf life and saponification value (SV), and exhibit promising potential for industrial exploitation. In contrast, AOW2, AOW3 and AOW4 are positioned on the negative PC1 and are closely linked with TFC and chlorophyll pigment. WO appears separated along PC2, indicating that this oil has a different chemical composition compared with other samples.

Overall, this analysis highlights that the formulations differ specifically in terms of antioxidant activity, fatty acid composition and oxidative stability, which are essential parameters determining oil quality

4. Conclusion

This work was carried out to improve the physicochemical, stability and sensory qualities of AO by blending it with OO and WO. Results showed that blending AO with two oils reduced the formation of oxidation products. Blended oils have lower FFA values than to AO. Balanced oils can be formulated from argan oil and other edible oils to improve physicochemical and sensory quality. Their production in cooperatives should be encouraged in Morocco and made available to the population to enhance their health and nutritional requirements. This work illustrates that using OO and WO in oil blends can yield a good

level of bioactive substances, a balanced ω6:ω3 ratio and suitable stability.

CRediT authorship contribution statement

Abderrahim Asbbane: Writing – original draft, Methodology, Data curation. **Moussa Nid Ahmed:** Writing – original draft, Methodology. **Mohamed Adnan:** Writing – review & editing, Methodology, Investigation. **Wissal Chouacha:** Visualization, Methodology, Investigation, Data curation. **Abdelhakim Bouyahya:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Waleed Al Abdulmonem:** Visualization, Methodology, Investigation, Data curation. **Mohammed Alorini:** Writing – review & editing, Methodology, Investigation. **El Hassan Sakar:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Angelo Maria Giuffrè:** Writing – review & editing, Supervision, Conceptualization. **Said Gharby:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Funding

This work was supported by the Deanship of Graduate Studies and Scientific Research at Qassim University for financial support (QU-APC-2026).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Ibn Zohr University for their interest in this work and technical support. We are also grateful to the CNRST for supporting this work as part of the PASS (PhD-Associate Scholarship) program. The authors also acknowledge the Deanship of Graduate Studies and Scientific Research at Qassim University for financial support (QU-APC-2026).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2026.103878.

Data availability

Data will be made available on request.

References

Adejumo, O., Popoola, E., Bamiro, O., Daodu, J., & James, O. (2021). Physicochemical characteristics and HPLC determination of alpha-tocopherol in eighteen edible vegetable oils marketed in Nigeria. *Dhaka University Journal of Pharmaceutical Sciences, 20*, 49–57. https://doi.org/10.3329/dujps.v20i1.54032

Ahmed, M. N., Abourat, K., Gagour, J., Sakar, E. H., Majourhat, K., Koubachi, J., & Gharby, S. (2024). Valorization of saffron (*crocus sativus* L.) stigma as a potential natural antioxidant for soybean (*glycine max* L.) oil stabilization. *Heliyon, 10*(4). https://doi.org/10.1016/j.heliyon.2024.e25875

Aissa, R., Asbbane, A., Oubannin, S., Bijla, L., Bousaid, Z., Hallouch, O., … Gharby, S. (2023). Oxidative stability of virgin and refined argan [*argania spinosa* L. (Skeels)] oil under accelerated aging conditions and shelf-life prediction at room temperature: A comparative study. *Analytica, 4*(4), 4. https://doi.org/10.3390/analytica4040034

Ait Bouzid, H., Bijla, L., Ibourki, M., Asbbane, A., Sakar, E. H., Koubachi, J., & Gharby, S. (2024). Nutritional potential of ziziphus lotus (l.) lam. Almonds as compared to some oilseeds from Morocco: Evidence from proximate composition, mineral profiling, and oil physicochemical traits. *Journal of Food Quality, 2024*(1), Article 6685429. https://doi.org/10.1155/2024/6685429

Ait Bouzid, H., Oubannin, S., Ibourki, M., Bijla, L., Hamdouch, A., Sakar, E. H., … Gharby, S. (2023). Comparative evaluation of chemical composition, antioxidant capacity, and some contaminants in six Moroccan medicinal and aromatic plants. *Biocatalysis and Agricultural Biotechnology, 47*. https://doi.org/10.1016/j.bcab.2022.102569

Ait Nouisse, A., Belmallam, R., Ait Bouzid, H., Ibourki, M., Giuffrè, A., Devkota, K., … Gharby, S. (2025). Comprehensive evaluation of *lagenaria siceraria* and *cucurbita* species seeds: Proximate composition, antioxidant potential, lipid profiling, and oil properties. *International Agrophysics, 39*, 457–474. https://doi.org/10.31545/intagr/207209

Al-Amrousi, E. F. (2024). The effect of roasting process on tiger nut oil properties and enhancing the oxidative stability of sunflower oil by blending with it. *Egyptian Journal of Chemistry, 67*(1), 1–12. https://doi.org/10.21608/ejchem.2023.220294.8195

Arslan, F. N., Şapçı, A. N., Duru, F., & Kara, H. (2017). A study on monitoring of frying performance and oxidative stability of cottonseed and palm oil blends in comparison with original oils. *International Journal of Food Properties, 20*(3), 704–717. https://doi.org/10.1080/10942912.2016.1177544

Asbbane, A., Bousaid, Z., Guillaume, D., El Harkaoui, S., Matthäus, B., Charrouf, Z., … Gharby, S. (2024). Effects of physical refining process on quality and stability of argan oil (argania spinosa (l.) skeels). *Scientific Reports, 14*(1), 23045. https://doi.org/10.1038/s41598-024-74466-6

Asbbane, A., Hallouch, O., Oubannin, S., Gagour, J., Ait Bouzid, H., & Gharby, S. (2024). Lipid oxidation of argan compared to virgin olive, and cactus oils: Rancimat test for kinetic and thermodynamic analysis. *Chemical Papers*. https://doi.org/10.1007/s11696-024-03688-9

Asbbane, A., Ibourki, M., Hallouch, O., Oubannin, S., El Boukhari, A., Bouyahya, A., … Gharby, S. (2025). A comparative evaluation of the physico- and bio-chemical characteristics and antioxidant activities of six argan (*argania spinosa* (L.) Skeels) varieties. *Journal of Agriculture and Food Research, 19*, Article 101582. https://doi.org/10.1016/j.jafr.2024.101582

Asgari, S., Sahari, M. A., & Barzegar, M. (2017). Practical modeling and optimization of ultrasound-assisted bleaching of olive oil using hybrid artificial neural network-genetic algorithm technique. *Computers and Electronics in Agriculture, 140*, 422–432. https://doi.org/10.1016/j.compag.2017.06.025

Bijla, L., Aissa, R., Ait Bouzid, H., Sakar, E. H., Ibourki, M., Laknifli, A., & Gharby, S. (2022). Spent coffee ground oil as a potential alternative for vegetable oil production: Evidence from oil content, lipid profiling, and physicochemical characterization. *Biointerface Research in Applied Chemistry, 12*, 6308–6320. https://doi.org/10.33263/BRIAC125.63086320

Bijla, L., Ait Bouzid, H., Ibourki, M., Ainane, A., Aissa, R., Laknifli, A., Ainane, T., & Gharby, S. (2021). Antioxidant activity, chemical composition and morphological properties of green and roasted coffee beans as affected by the microwave roasting method. *Pharmacologyonline, 2*, 546–555. Scopus https://www.scopus.com/inward/record.uri?eid=2-s2.0-85116380788&partnerID=40&md5=b62849042e374602ea198077b09c9467.

Codex Alimentarius. (2023). In FAO (Ed.), *standard for named vegetable oils CXS 210-1999*. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXS+210-1999%252FCXS_210e.pdf.

Djikeng, F. T., Etta, E. H., Mainsah Ngandung, E., Etake, N. N., Djikeng, F. T., & Tiencheu, B. (2024). Extending African walnut oil (*tetracarpidium conophorum*) shelf-life by blending it with palm, groundnut and avocado oils and study of their oxidative stability during accelerated storage. *Hybrid Advances, 7*, Article 100331. https://doi.org/10.1016/j.hybadv.2024.100331

Fadda, A., Sanna, D., Sakar, E. H., Gharby, S., Mulas, M., Medda, S., … Durazzo, A. (2022). Innovative and sustainable technologies to enhance the oxidative stability of vegetable oils. *Sustainability, 14*(2). https://doi.org/10.3390/su14020849

Fatouh Hamed, S., Hashim, A., & Zaher, F. (2023). Shelf-life prediction of flaxseed oil blended with different antioxidants: Kinetic and thermodynamic study using rancimat methodology. *Egyptian Journal of Chemistry, 0*(0). https://doi.org/10.21608/ejchem.2023.223442.8293

Gagour, J., Ahmed, M. N., Asbbane, A., Belmallam, R., Hallouch, O., El Antari, A., … Gharby, S. (2025). Ultrasonic-assisted enrichment of sunflower oil with leave powder from four mediterranean olive cultivars: Chemical profiling, functional potential and impact on UV induced oxidation. *Journal of Food Composition and Analysis, 144*. https://doi.org/10.1016/j.jfca.2025.107651

Gagour, J., Ahmed, M. N., Bouzid, H. A., Oubannin, S., Bijla, L., Ibourki, M., … Gharby, S. (2022). Proximate composition, physicochemical, and lipids profiling and elemental profiling of rapeseed (*brassica napus l.*) and sunflower (*helianthus annuus l.*) grown in Morocco. *Evidence-Based Complementary and Alternative Medicine, 2022*(1), Article 3505943. https://doi.org/10.1155/2022/3505943

Gagour, J., Hallouch, O., A. Asbbane, Bijla, L., Laknifli, A., Lee, L.-H., … Gharby, S. (2024). A review of recent progresses on olive oil chemical profiling, extraction technology, shelf-life, and quality control. *Chemistry & Biodiversity, 21*(4). https://doi.org/10.1002/cbdv.202301697

Gagour, J., Hallouch, O., Asbbane, A., Laknifli, A., Sakar, E. H., Majourhat, K., & Gharby, S. (2024). Physicochemical characterization of 'moroccan picholine' olive (*olea europaea* L.) oil produced in southern Morocco using multivariate statistical analysis. Analytica, *5*(1), 1. https://doi.org/10.3390/analytica5010008.

Gagour, J., Ibourki, M., Antari, A. E., Sakar, E. H., Aissa, R., Giuffrè, A. M., … Gharby, S. (2024). Leaf mineral profiling and its correlation with oil physicochemical traits from four olive (olea europaea l.) cultivars grown in Morocco as affected by olive ripening stages. *European Food Research and Technology, 250*(5), 1443–1456. https://doi.org/10.1007/s00217-024-04475-2

Gagour, J., Oubannin, S., Ait Bouzid, H., Bijla, L., El Moudden, H., Sakar, E. H., … Gharby, S. (2022). Physicochemical characterization, kinetic parameters, shelf life and its prediction models of virgin olive oil from two cultivars ("arbequina" and

"moroccan picholine") grown in Morocco. *OCL, 29*, 39. https://doi.org/10.1051/ocl/2022033

Gharby, S., Asbbane, A., Ahmed, M. N., Gagour, J., Hallouch, O., Oubannin, S., … Ibourki, M. (2025). Vegetable oil oxidation: Mechanisms, impacts on quality, and approaches to enhance shelf life. *Food Chemistry: X.* , Article 102541. https://doi.org/10.1016/j.fochx.2025.102541

Gharby, S., & Charrouf, Z. (2022). Argan oil: Chemical composition, extraction process, and quality control. *Frontiers in Nutrition, 8*. Doi;10.3389/fnut.2021.804587.

Gharby, S., Guillaume, D., Nounah, I., Harhar, H., Hajib, A., Matthäus, B., & Charrouf, Z. (2021). Shelf-life of moroccan prickly pear (*Opuntia ficus-indica*) and argan (*Argania spinosa*) oils: A comparative study. *Grasas y Aceites, 72*(1), 1, 10.3989/gya.1147192.

Gharby, S., Hajib, A., Ibourki, M., Sakar, E. H., Nounah, I., Moudden, H. E., … Harhar, H. (2021). Induced changes in olive oil subjected to various chemical refining steps: A comparative study of quality indices, fatty acids, bioactive minor components, and oxidation stability kinetic parameters. *Chemical Data Collections, 33*, Article 100702. https://doi.org/10.1016/j.cdc.2021.100702

Gharby, S., Harhar, H., Guillaume, D., Haddad, A., Matthäus, B., & Charrouf, Z. (2011). Oxidative stability of edible argan oil: A two-year study. *LWT - Food Science and Technology, 44*(1), 1–8. https://doi.org/10.1016/j.lwt.2010.07.003

Gharby, S., Harhar, H., Mamouni, R., Matthäus, B., Addi, E. H. A., & Charrouf, Z. (2016). Chemical characterization and kinetic parameter determination under rancimat test conditions of four monovarietal virgin olive oils grown in Morocco. *OCL, 23*(4), 4. https://doi.org/10.1051/ocl/2016014

Ghosh, M., Upadhyay, R., Mahato, D. K., & Mishra, H. N. (2019). Kinetics of lipid oxidation in omega fatty acids rich blends of sunflower and sesame oils using rancimat. *Food Chemistry, 272*, 471–477. https://doi.org/10.1016/j.foodchem.2018.08.072

González, R., González, C. G., & Rincón, M.Á. (2023). Chemical and sensory assessment of extra virgin olive oil blends with omega-3 polyunsaturated fatty acids from plant origin. *Revista Chilena de Nutricion, 50*(2), 213–225. https://doi.org/10.4067/S0717-75182023000200213

Guillaume, D., Pioch, D., & Charrouf, Z. (2019). Argan [Argania spinosa (L.) Skeels] Oil. In M. F. Ramadan (Ed.), *Fruit oils: Chemistry and functionality* (pp. 317–352). Springer International Publishing. https://doi.org/10.1007/978-3-030-12473-1_16.

Hallouch, O., Ibourki, M., Asbbane, A., Devkota, K., Giuffrè, A. M., Majourhat, K., & Gharby, S. (2025). Exploring the bioactive potential of argan oil cake: A comprehensive physicochemical comparison with various seeds cakes. *Current Research in Nutrition and Food Science Journal, 13*(1), 77–100. https://doi.org/10.12944/CRNFSJ.13.1.5

Hallouch, O., Ibourki, M., Bijla, L., Oubannin, S., Asbbane, A., Mazar, A., … Gharby, S. (2025). A review on the utilization of the by-products generated during the production of argan oil. *Journal of Agriculture and Food Research, 20*, Article 101770. https://doi.org/10.1016/j.jafr.2025.101770

Harkaoui, S. E., Gharby, S., Kartah, B., Monfalouti, H. E., El-sayed, M. E., Abdin, M., … Matthäus, B. (2023). Lipid profile, volatile compounds and oxidative stability during the storage of Moroccan *Opuntia ficus-indica* seed oil. *Grasas y Aceites, 74*(1), Article 1. https://doi.org/10.3989/gya.1129212

Hashempour-Baltork, F., Torbati, M., Azadmard-Damirchi, S., & Savage, G. P. (2016). Vegetable oil blending: A review of physicochemical, nutritional and health effects. *Trends in Food Science & Technology, 57*, 52–58. https://doi.org/10.1016/j.tifs.2016.09.007

Hashempour-Baltork, F., Torbati, M., Azadmard-Damirchi, S., & Savage, G. P. (2017). Quality properties of sesame and olive oils incorporated with flaxseed oil. *Advanced Pharmaceutical Bulletin, 7*(1), 97–101. https://doi.org/10.15171/apb.2017.012

Hassanein, M. M. M., Al-Amrousi, E. F., Abo-Elwafa, G. A., & Abdel-Razek, A. G. (2022). Characterization of egyptian monovarietal koroneiki virgin olive oil and its co-products. *Egyptian Journal of Chemistry, 65*(12), 637–645. https://doi.org/10.21608/ejchem.2022.167449.7064

IOC. (2021). *IOC standards, METHODS and GUIDES International Olive Council.* International Olive Council. https://www.internationaloliveoil.org/what-we-do/chemistry-standardisation-unit/standards-and-methods/.

IOC. (2024). *World market of olive oil and table olives—Data from december 2024*. International Olive Council. https://www.internationaloliveoil.org/world-market-of-olive-oil-and-table-olives-data-from-december-2024/.

ISO 12966-2. (2017). Animal and vegetable fats and oils—Gas chromatography of fatty acid methyl esters Part 2: Preparation of methyl esters of fatty acids. https://www.iso.org/standard/72142.html.

ISO 3656. (2011). *Animal and vegetable fats and oils—Determination of ultraviolet absorbance expressed as specific UV extinction.* ISO. https://www.isoorg/standard/51008.html.

ISO 3960. (2017). In ISO (Ed.), *Animal and vegetable fats and oils—Determination of peroxide value—Iodometric (visual) endpoint determination.* https://www.isoorg/standard/71268.html.

ISO 660. (2020). *Animal and vegetable fats and oils—Determination of acid value and acidity* (4 ed.) https://www.iso.org/standard/75594.html.

ISO 6885. (2016). Animal and vegetable fats and oils—Determination of anisidine value, i. https://www.iso.org/cms/render/live/en/sites/isoorg/ contents/data/standard/06/95/69593.html.

Lakhlifi El Idrissi, Z., El Guezzane, C., Boujemaa, I., El Bernoussi, S., Sifou, A., El Moudden, H., … Tabyaoui, M. (2024). Blending cold-pressed peanut oil with omega-3 fatty acids from walnut oil: Analytical profiling and prediction of nutritive attributes and oxidative stability. *Food Chemistry, X, 22*, Article 101453. https://doi.org/10.1016/j.fochx.2024.101453

Ma, X., Huang, C., Zheng, C., Wang, W., Ying, H., & Liu, C. (2024). Effect of oil extraction methods on walnut oil quality characteristics and the functional properties of walnut protein isolate. *Food Chemistry, 438*, Article 138052. https://doi.org/10.1016/j.foodchem.2023.138052

Mahesar, S. A., Sherazi, S. T. H., Khaskheli, A. R., Kandhro, A. A., & Uddin, S. (2014). Analytical approaches for the assessment of free fatty acids in oils and fats. *Analytical Methods, 6*(14), 4956–4963. https://doi.org/10.1039/C4AY00344F

Monfreda, M., Gobbi, L., & Grippa, A. (2012). Blends of olive oil and sunflower oil: Characterisation and olive oil quantification using fatty acid composition and chemometric tools. *Food Chemistry, 134*, 2283–2290. https://doi.org/10.1016/j.foodchem.2012.03.122

Nid Ahmed, M., Gagour, J., Asbbane, A., Hallouch, O., Atrach, L., Giuffrè, A. M., … Gharby, S. (2024). Advances in the use of four synthetic antioxidants as food additives for enhancing the oxidative stability of refined sunflower oil (*Helianthus annuus* L.). *Analytica, 5*(2), Article 2. https://doi.org/10.3390/analytica5020018

O'Brien, R. D. (2008). *Fats and oils: Formulating and processing for applications, Third Edition* (3rd ed.). CRC Press https://doi.org/10.1201/9781420061673.

Oubannin, S., Asbbane, A., Goh, K. W., Singh, J., Zafar, I., Bouyahya, A., & Gharby, S. (2024). Green enrichment of argan oil (*argania spinosa* L.) with thyme (*thymus vulgaris* L.) and oregano (*origanum vulgare* L.) leaves: Evaluating quality and stability improvements. *Food Chemistry: X, 24*, Article 101818. https://doi.org/10.1016/j.fochx.2024.101818

Oubannin, S., Asbbane, A., Hallouch, O., Giuffrè, A. M., Sakar, E. H., & Gharby, S. (2024). Synergistic potential of co-millinged edible argan oil (*argania spinosa* L.) and oregano leaves (*origanum vulgare* L.) in food applications. *Future Foods, 10*. https://doi.org/10.1016/j.fufo.2024.100430

Oubannin, S., Bijla, L., Gagour, J., Hajir, J., Aabd, N. A., Sakar, E. H., … Gharby, S. (2022). A comparative evaluation of proximate composition, elemental profiling and oil physicochemical properties of black cumin (*nigella sativa* L.) seeds and argan (*argania spinosa* L. skeels) kernels. *Chemical Data Collections, 41*, Article 100920. https://doi.org/10.1016/j.cdc.2022.100920

Pan, F., Wang, X., Wen, B., Wang, C., Xu, Y., Dang, W., & Zhang, M. (2020). Development of walnut oil and almond oil blends for improvements in nutritional and oxidative stability. *Grasas y Aceites, 71*(4), Article 4. https://doi.org/10.3989/gya.0920192

Roiaini, M., Ardiannie, T., & Norhayati, H. (2015). Physicochemical properties of canola oil, olive oil and palm olein blends. *International Food Research Journal, 22*(3), 1227–1233.

Rudzińska, M., Hassanein, M. M. M., Abdel–Razek, A. G., Ratusz, K., & Siger, A. (2016). Blends of rapeseed oil with black cumin and rice bran oils for increasing the oxidative stability. Journal of Food Science and Technology, 53(2), 1055–1062. https://doi.org/10.1007/s13197-015-2140-5.

Sakar, E. H., Khtira, A., Aalam, Z., Zeroual, A., Gagour, J., & Gharby, S. (2022). Variations in physicochemical characteristics of olive oil (cv 'moroccan picholine') according to extraction technology as revealed by multivariate analysis. *AgriEngineering, 4*(4), Article 4. https://doi.org/10.3390/agriengineering4040059

Siol, M., Mańko-Jurkowska, D., Stanaszek, I., Zieniuk, B., Bryś, A., & Bryś, J. (2025). Toward functional oil blends: Physicochemical and nutritional evaluation of Rapeseed–Hazelnut oil mixtures. *Foods, 14*(23). https://doi.org/10.3390/foods14234008

SNIMA. (2003). Corps gras d'origines animale et végétale – Huiles d'argane – Spécifications. https://www.imanor.gov.ma/Norme/nm-08-5-090/.

Symoniuk, E., Ratusz, K., & Krygier, K. (2016). Comparison of the oxidative stability of linseed (linum usitatissimum l.) oil by pressure differential scanning calorimetry and rancimat measurements. *Journal of Food Science and Technology, 53*(11), 3986–3995. https://doi.org/10.1007/s13197-016-2398-2

Symoniuk, E., Ratusz, K., & Krygier, K. (2017). Oxidative stability and the chemical composition of market cold-pressed linseed oil. *European Journal of Lipid Science and Technology, 119*(11), Article 1700055. https://doi.org/10.1002/ejlt.201700055

Symoniuk, E., Ksibi, N., Wroniak, M., Lefek, M., & Ratusz, K. (2022). Oxidative stability analysis of selected oils from unconventional raw materials using rancimat apparatus. *Applied Sciences, 12*(20), Article 10355. https://doi.org/10.3390/app122010355

Szpunar-Krok, E., & Wondołowska-Grabowska, A. (2022). Quality evaluation indices for soybean oil in relation to cultivar, application of N fertiliser and seed inoculation with *bradyrhizobium japonicum*. *Foods, 11*(5), Article 5. https://doi.org/10.3390/foods11050762

Terpinc, P., Schreiner, M., & Abramovič, H. (2026). Kinetic and thermodynamic evaluation of the oxidative stability of camelina oil and its blends with olive oil using the rancimat test. *Food Chemistry, 501*, Article 147571. https://doi.org/10.1016/j.foodchem.2025.147571

Torres, M., Martínez, M., Pierantozzi, P., Albanese, M., Nasjleti, A., & Maestri, D. (2011). Contribution of compositional parameters to the oxidative stability of olive and walnut oil blends. *Journal of the American Oil Chemists' Society, 88*(6), 755–762. https://doi.org/10.1007/s11746-010-1735-2

Torri, L., Bondioli, P., Folegatti, L., Rovellini, P., Piochi, M., & Morini, G. (2019). Development of perilla seed oil and extra virgin olive oil blends for nutritional, oxidative stability and consumer acceptance improvements. *Food Chemistry, 286*, 584–591. https://doi.org/10.1016/j.foodchem.2019.02.063

Upadhyay, R., & Mishra, H. N. (2015). Multivariate analysis for kinetic modeling of oxidative stability and shelf life estimation of sunflower oil blended with sage (*salvia officinalis*) extract under rancimat conditions. *Food and Bioprocess Technology, 8*(4), 801–810. https://doi.org/10.1007/s11947-014-1446-z

Xu, T., Li, J., Fan, Y.-W., Zheng, T., & Deng, Z.-Y. (2015). Comparison of oxidative stability among edible oils under continuous frying conditions. *International Journal of Food Properties, 18*(7), 1478–1490. https://doi.org/10.1080/10942912.2014.913181