Grasas y Aceites 76 (2)
April-June 2025, 2325
ISSN-L: 0017-3495, eISSN: 1988-4214
https://doi.org/10.3989/gya.0540251.2325

Physicochemical and spectroscopic characterization, and evaluation of the antioxidant and anti-inflammatory potential of oils extracted from *Thunnus thynnus* and *Sardina pilchardus* coproducts

H. Belkhodja[a,✉], A. Remil[b], F.Z. Labbaci[c], F. Belkhadem[d], D. Bouhadi[a] and Z. Benattouche[a]

[a]Laboratory of Bioconversion, Microbiology Engineering and Health Safety, University of Mustapha Stambouli, Mascara, Algeria
[b]Laboratory of Organic, Macromolecular chemistry and Materials, University of Mustapha Stambouli, Mascara, Algeria
[c]Laboratory of physical chemistry of macromolecules and biological interface, University of Mustapha Stambouli, Mascara, 29000, Algeria
[d]Laboratory of Bioactive Organic Synthesis, Department of Industrial Organic Chemistry, University of Science and Technology of Oran, Oran, Algeria
✉Corresponding autor: hamzabelkhodja@yahoo.fr

Submitted: 04 May 2025; Accepted: 01 August 2025; Published: 03 February 2026

SUMMARY: This work aims to valorize the coproducts of two pelagic species, bluefin tuna (*Thunnus thynnus*) and sardines (*Sardina pilchardus*), by the extraction and characterization of the oil coproducts through physicochemical and FTIR-ATR analysis and the in vitro evaluation of their antioxidant and anti-inflammatory potential. Determining the physicochemical parameters revealed that both oils tested are of good quality. The UV-visible absorption spectra presented a strong absorbance band at 310 nm. Therefore, oil from *S. pilchardus* and *T. thynnus* may predominate ω-3 and 9 in its spectrum. The FTIR-ATR spectrum showed bands and peaks corresponding to functional groups of the substances tested. Evaluation of the antioxidant and anti-inflammatory potential showed that the oil from *S. pilchardus* coproducts showed the highest reduction percentage and even the highest anti-inflammatory potential compared to *T. thynnus*. Coproduct oil offers significant therapeutic value as a substitute substance or therapeutic support for reducing oxidative stress and inflammation.

KEY-WORDS: *Coproducts; FTIR-ATR; Oil;* Sardina pilchardus*;* Thunnus thynnus*.*

RESUMEN: ***Caracterización mediante FTIR-ATR y evaluación del potencial antioxidante y antiinflamatorio del aceite extraído de coproductos de* Thunnus thynnus *y* Sardina pilchardus.** Este trabajo tiene como objetivo poner en valor los coproductos de dos especies pelágicas, atún rojo (*Thunnus thynnus*) y sardinas (*Sardina pilchardus*), mediante la extracción y caracterización de los coproductos de los aceites mediante análisis fisicoquímicos y FTIR-ATR y la evaluación in vitro de su potencial antioxidante y antiinflamatorio. La determinación de los parámetros fisicoquímicos mostró que ambos aceites ensayados son de buena calidad. Los espectros de absorción UV-visible presentaron una fuerte banda de absorbancia a 310 nm, por lo que, en los aceites de *S. pilchardus* y *T. thynnus* predominan ω-3 y 9 en su espectro. El espectro FTIR-ATR mostró bandas y picos correspondientes a grupos funcionales de las sustancias ensayadas. La evaluación del potencial antioxidante y antiinflamatorio mostró que el aceite de coproductos de *S. pilchardus* tiene el mayor porcentaje de reducción e incluso el mayor potencial antiinflamatorio en comparación con *T. thynnus*. El aceite de coproducto ofrece un valor terapéutico significativo como sustancia sustitutiva o apoyo terapéutico para reducir el estrés oxidativo y la inflamación.

PALABRAS CLAVE: *Aceite; Coproductos; FTIR-ATR;* Sardina pilchardus*;* Thunnus thynnus*.*

Citation/Cómo citar este artículo: Belkhodja H, Remil A, Labbaci FZ, Belkhadem F, Bouhadi D, Benattouche Z. 2025. Physicochemical and spectroscopic characterization, and evaluation of the antioxidant and anti-inflammatory potential of oils extracted from *Thunnus thynnus* and *Sardina pilchardus* coproducts. *Grasas Aceites* **76** (2), 2325. https://doi.org/10.3989/gya.0540251.2325

1. INTRODUCTION

The amount of waste and coproducts produced by fish transformation is believed to be 50% of the weight of the fish. Without proper treatment, these pollutants are frequently dumped into the environment directly, leading to serious environmental issues (Balasa *et al.,* 2020). The coproducts contain potentially valuable ingredients (antioxidants, anti-stress, antihypertensives, collagens, pigments, etc.) and are primarily made up of heads, viscera, skins, bones, tails, fins, and filleting residues (Coppola *et al.,* 2021).

One potential solution to this problem is to implement a waste management strategy that incorporates converting these leftovers into products that may be sold. Studies have indicated that consistent consumption of supplements derived from fish can promote the synthesis of substances with a variety of health benefits, such as antihypertensive, antihyperlipidemic, and immunomodulatory effects (Mutalipassi *et al.,* 2021). Coproducts and their metabolites are at the heart of global efforts to discover novel physiologically active substances that produce secondary metabolites and macromolecules with anti-inflammatory and antioxidant properties (El-shafei *et al.,* 2021).

Polyunsaturated fatty acids (PUFAs), especially docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), are abundant in fish oil. These fatty acids can be utilized as a component of functional meals in the food industry or as a nutraceutical element in the pharmaceutical sector due to their numerous health benefits and necessity (Strobel *et al.,* 2020).

The purpose of the study is to value the coproducts of two pelagic species: sardines (*Sardina pilchardus*) and bluefin tuna (*Thunnus thynnus*). Thus, the goal is predicated based on the extraction, physicochemical, and FTIR-ATR characterization of the oil coproducts as well as the in vitro assessment of their anti-inflammatory and antioxidant potential.

2. MATERIALS AND METHODS

2.1. Samples

The experimental study was carried out on coproducts from two species of pelagic fish: sardines (*Sardina pilchardus*) and tuna (*Thunnus thynnus*). Sampling was carried out during February 2024 in the region of Salamandre (Mostaganem, Algeria) (35° 56′ 00″ north, 0° 05′ 00″ east) for the sardine species and in the region of Beni Saf (Ain Temouchent, Algeria) (35° 18′ 8″ North, 1° 23′ 1″ West) for the tuna species.

2.2. Extraction of oils from coproducts

The extraction was carried out according to the protocol described by Rubio-Rodriguez *et al.* (2010). Homogenized solid waste was added to water at a ratio of 1:1. The sample was heated to 75 °C for 15 minutes. After boiling, the homogenized sample was pressed to obtain the liquid fraction and stored in the refrigerator until centrifugation. Centrifugation was performed at 11180 g in 15 min to separate the water from the oil. Petroleum ether was then used to separate the oil from the water thoroughly. Then, the oil fraction was stored at 4 °C after the determination of extraction yield.

2.3. Physicochemical analysis of the oil from coproducts

Determinations of the physicochemical indexes (acidity, peroxide, saponification, iodine, and relative density) to characterize the oil from the coproducts were made according to Nascimento *et al*. (2015).

2.4. UV-Vis spectrophotometric analysis of oil

The analysis was conducted on a SPECORD® 210 PLUS UV/Visible spectrophotometer (Analytik Jena GmbH, Jena, Germany), which is a double-beam spectrophotometer designed for precise quantitative and qualitative analysis in the ultraviolet and visible spectral range (190–1200 nm). It features a Tempered Detector System that enhances measurement stability and accuracy. The instrument is operated using

WinASPECT® UV basic software, which allows for comprehensive spectral acquisition, data processing, and evaluation. 1 ml of the tuna or sardine coproduct oil was put into the spectrophotometer tank. Then, the absorbance and λmax were determined.

2.5. Spectroscopic analysis (FTIR-ATR)

The analysis was carried out on a BRUKER ALPHA spectrometer equipped with an ATR stage with a diamond crystal triglycine sulfate detector and controlled by the Opus v 7.0 122 software. 1 g of the oil was directly deposited onto the reflection crystal of the Platinium-ATR accessory. The acquisitions were performed by taking 200 scans between 4000 and 500 cm^{-1} with a resolution of 1 cm^{-1}.

2.6. DPPH free radical scavenging assay

The DPPH (2,2-diphenyl-1-picrylhydrazyl) scavenging properties of the products were evaluated using the method of Wei *et al.* (2017). Samples at 125, 250, 500, and 1000 µg/ml were combined with 2 mL of a methanolic DPPH solution (180 µmol/L) and incubated for 30 minutes at room temperature. The residual DPPH radical's absorbance was then measured at 517 nm in relation to a blank. Each sample was evaluated with three duplicates, and the antiradical effect was determined using the following equation:

$$\text{Percentage inhibition (\%)} = (\text{Abs}_{\text{Control}} - \text{Abs}_{\text{Sample}}) / \text{Abs}_{\text{Control}} \times 100$$

2.7. Inhibition of protein denaturation assay

The inhibitory activity of bovine serum albumin denaturation was exploited in the study by Hu *et al*. (2020). 50 µL of coproduct oil (125, 250, 500, and 1000 µg/ml) and 950 µL of a bovine serum albumin solution (dissolved in 0.01 M PBS, pH 7.4, 1%, w/v) were used to create the reaction solution. In order to induce protein denaturation, all reaction solutions were stabilized at 37 °C for 15 minutes and then heated to 90 °C for 20 minutes. At room temperature (25 °C), 660 nm was used to measure turbidity. As a control, distilled water was used rather than the sample. The rate of denaturation inhibition was determined using the following formula:

$$\text{Percentage inhibition (\%)} = (\text{Abs}_{\text{Control}} - \text{Abs}_{\text{Sample}}) / \text{Abs}_{\text{Control}} \times 100$$

2.8. Statistical analysis

Values were reported as mean ± SD (Standard Deviation) and each assay was performed in triplicate. Data were investigated with ANOVA analysis. The differences were recognized as significant at $P < 0.05$. The application of ANOVA was performed using the ANOVA function in R (R Core Team, 2024). The HSD.test function, under the Agricolae package was used to apply the Tukey test.

3. RESULTS AND DISCUSSION

3.1. Physicochemical analysis of oil from coproducts

The extraction yield recorded a value of 26.06 ± 0.13% for *S. pilchardus* oil and 28.01 ± 0.34% for *T. thynnus* oil. Table 1 presents the results obtained from the physicochemical analysis of *S. pilchardus* and *T. thynnus* coproduct oil. The results showed an acid number value equal to 1.8 ± 0.15 and 2.46 ± 0.18 for the coproduct oil from *S. pilchardus* and *T. thynnus*, respectively. Both values appeared lower than those of Nascimento *et al.* (2015) (5.4 ± 0.1). Table 1 shows a value for the saponification index equal to 187.18 ± 1.59 and 182.87 ± 1.13 for the coproduct oil from *S. pilchardus* and *T. thynnus,* respectively. Purnamayati *et al.* (2019) recorded a value of 189.10 ± 1.61 for the saponification index of sardine oil. The ratio of long-chain fatty acids to short-chain fatty acids affected the level of saponification value. A quantity of long-chain fatty acids in the oil can decrease saponification.

TABLE 1. Physicochemical indexes of oil from coproducts

	Acid index (mg KOH/g)	Saponification index (mg KOH/g)	Peroxyde index (meqO_2/Kg)	Iodine index (g iodine/ 100 g of oil)	Relative density
Sardine	1.8 ± 0.15 [a]	187.18 ± 1.59 [a]	3.8 ± 0.25 [a]	121 ± 2 [a]	0.94 ± 0.008 [a]
Tuna	2.46 ± 0.18 [b]	182.87 ± 1.13 [b]	2.93 ± 0.08 [b]	119.83 ± 4.91 [b]	0.87 ± 0.011 [b]

Values are presented as mean ± SD of three measurements. Statistical significance was assessed by one-way analysis of variance ANOVA coupled with Tukey's post hoc test. According to Tukey's post hoc test, different letters (a, b, c, d, and e) in a column indicate a significant difference ($p < 0.05$) between groups.

Among the oil quality parameters is the peroxide index. This parameter makes it possible to evaluate the oil's rancidity by monitoring hydroperoxide formation. International fish oil standards require a peroxide value of 3.75 meq O_2/kg. The peroxide index obtained for *T. thynnus* oil was 2.93 ± 0.08 meq O_2/kg, which was comparable to the values obtained by Messina *et al.* (2022) in oil obtained from tuna coproducts. They showed a value of 2.96 ± 0.55 meq O_2/kg. Tuna oil may be suitable for human consumption if it has a peroxide value below 5 meq O_2/kg. A high peroxide value indicates that the oil has been oxidized by forming new peroxides through degradation to other compounds (Suseno *et al.,* 2015). Fish oil contains a large amount of unsaturated fatty acids. It, therefore, oxidizes quickly and becomes rancid. Prolonged rancidity forms peroxide and decreases fish quality by forming aldehydes or ketones as hydroperoxide coproducts (Pravinkumar *et al.,* 2015).

The iodine value expresses the degree of unsaturation in the oil associated with unsaturated fatty acids in oil or fat. The iodine value for fish oil was approximately 119–129 g I_2/100 g (Nascimento *et al.,* 2015). According to Table 1, the iodine value obtained was 121 ± 2 and 119.83 ± 4.91 g I2/100 g for the coproduct oil from *S. pilchardus* and *T. thynnus*. Purnamayati *et al.* (2019) recorded a value of 123.52 ± 0.43 g I_2/100 g for the iodine value of sardine oil. For relative density, the coproduct oil from *S. pilchardus* and *T. thynnus* revealed a value of 0.94 ± 0.008 and 0.87 ± 0.011, respectively. The value obtained was almost equal to that of Purnamayati *et al.* (2019), where they recorded a value of 0.93.

3.2. UV-Vis spectrophotometric analysis of oil

Spectrophotometric (UV-Vis) analysis of *S. pilchardus* and *T. thynnus* oil exhibited absorbances in wavelengths ranging from 200 to 800 nm (figure 1). The UV-visible absorption spectra presented a strong absorbance band at 310 nm. According to Oliveira *et al*. (2020), the spectra of omegas present characteristic absorption bands: λ ≈ 298 nm for ω-3, λ ≈ 278 nm for ω-6, λ equal to 227 and 291 nm for ω-9.

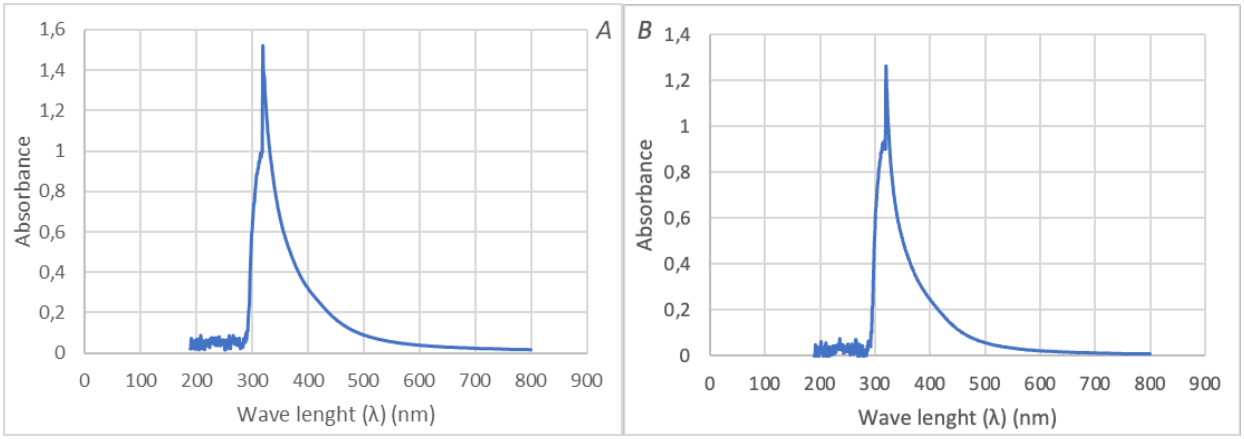
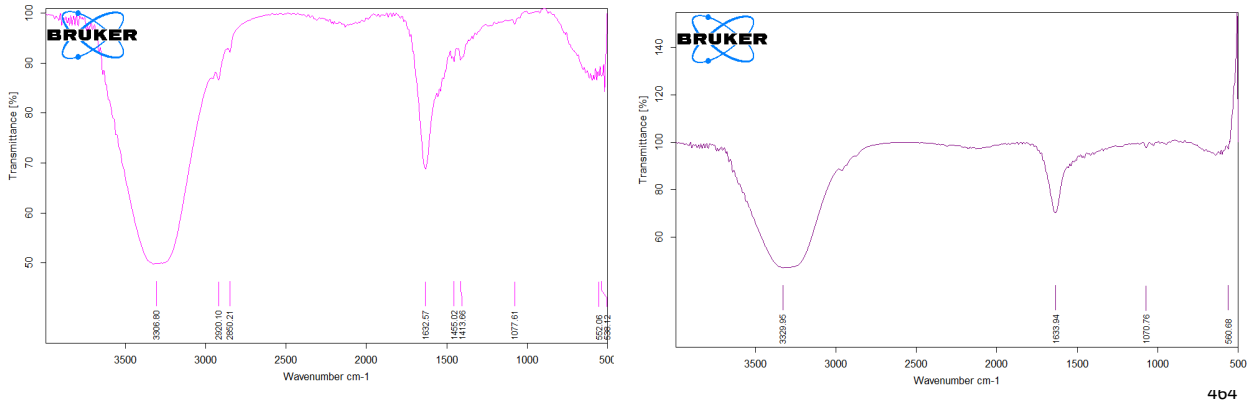


FIGURE 1. UV-Vis absorption spectrum of *S. pilchardus* (A) and *T. thynnus* (B) oil.



A B

FIGURE 2. FTIR spectra of oil extracted from coproducts of *S. pilchardus* (A) and *T. thynnus* (B).

Therefore, the oil from *S. pilchardus* and *T. thynnus* may predominate ω-3 and 9 in its spectrum. The absorption band at λ ≈ 300 nm can be attributed to tocopherols and unsaturated fatty acids (oleic, linoleic, linolenic). Additionally, Saito *et al.* (2023) found that fatty acids (oleic and linoleic acids) contributed significantly to UV absorption above 270 nm. Fully conjugated long-chain unsaturated fatty acids like linolenic acid (C18:3Δ*cis*-9, *cis*-12, *cis*-15) have a strong and broad absorption band at λ ≈ 300 nm (Lechuga and Michaelian, 2023). The primary dietary sources of EPA and DHA are fatty marine fish such as sardines. However, their high content of mono, di, and tri-unsaturated fatty acids was linked to the consumption of marine phytoplankton. Oleic acid (monounsaturated) was then exported to the endoplasmic reticulum and then desaturated by Δ12 and Δ15 desaturases, generating linoleic acid and α-linolenic acid, which served as precursors for ω-6 and ω-3 long chains (Jesionowska *et al.,* 2023).

3.3. Spectroscopic analysis (FTIR-ATR)

For the oil extracted from sardine and tuna coproducts, the FTIR-ATR spectrum presented a broadband at 3306 and 3329 cm^{-1} which was linked to the vibration of C–H and the stretching of the *cis*-alkene -HC = CH - polyunsaturated fatty acids (Dórame-Miranda *et al*., 2021). The high frequency of this band indicated the abundance of polyunsaturated acyl groups. A weak peak at 2920 cm-1 for sardine represented the stretching vibration of –CH, $–CH_2$, and $–CH_3$ from an aliphatic alkane. An average peak appeared at 1632 and 1633 cm^{-1}, indicating elongation vibrations by the *cis* double bond (C=C). A weak peak appeared at 1077 and 1070 cm^{-1}, indicating the C=O of the COOH carboxylic group. A weak peak appeared at 552 and 560 cm^{-1}, representing the -HC=CH *cis* group.

However, no peaks representing secondary products of lipid oxidation (carbonyl group of aldehydes and ketones) were detected by FTIR spectra in the 3800–3400 cm^{-1} range. There is evidence that during more prolonged extraction, the ester bond of triacylglycerols was cleaved by hot water (Pudtikajorn and Benjakul, 2020). In the study by Pudtikajorn and Benjakul (2020), the FTIR spectra of the tuna sample show that the main functional groups responsible for the IR absorption peaks were: C–H stretching vibration of the *cis* double bond at 3015 cm^{-1}; symmetric and asymmetric stretching vibration of CH_2 at 2920 and 2850 cm^{-1}, respectively. The results of the FTIR analysis carried out by Khalihena Groune *et al.* (2024) showed that sardine oil was very rich in polyunsaturated fatty acids (mainly docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA)) and monounsaturated fatty acids (primarily oleic acid).

3.4. DPPH free radical scavenging assay

The antioxidant activity profile showed that the fractions tested have a dose-dependent anti-radical activity; that is to say, the increase in the concentration increased the percentage of inhibition (Table 2). The

anti-radical capacity was determined by comparison with the activity of a reference antioxidant compound (ascorbic acid). From the results obtained, it was noticed that for the concentration of 1000 µg/ml, the oil from *S. pilchardus* coproducts showed the highest percentage reduction (89.96 ± 0.29%) compared to *T. thynnus* (83.72 ± 2.08%). It should be mentioned that ascorbic acid remains more active than the fractions tested, with an inhibition percentage of 96.63 ± 0.98%. The concentration necessary to inhibit 50% of the radical DPPH was calculated by linear regression of the inhibition percentages calculated as a function of different concentrations of the extracts. The IC_{50} values for the coproduct oil from *S. pilchardus* and *T. thynnus* are shown in Table 2.

TABLE 2. Anti-radical activity (%) of oil

	125	250	500	1000	IC_{50} (mg/ml)
Sardine	38.24 ± 0.22 [a]	58.85 ± 0.15 [a]	75.62 ± 0.35 [a]	89.96 ± 0.29 [a]	0.185
Tuna	27.19 ± 0.87 [ab]	52.62 ± 0.86 [ab]	72.03 ± 0.59 [ab]	83.72 ± 2.08 [ab]	0.2
Ascorbic acid	46.11 ± 0.39 [d]	69.90 ± 1.98 [c]	83.21 ± 2.35 [b]	96.63 ± 0.98 [a]	0.125

Values are presented as mean ± SD of three measurements. Statistical significance was assessed by one-way analysis of variance ANOVA coupled with Tukey's post hoc test. According to Tukey's post hoc test, different letters (a, b, c and d) in a column indicate a significant difference ($p < 0.05$) between groups.

The oil from *S. pilchardus* presented the highest antioxidant activity compared to *T. thynnus*, with an IC_{50} value equal to 0.185 mg/ml and 0.2 mg/ml, respectively. However, ascorbic acid showed the lowest IC_{50} value (0.125 mg/ml). Radical scavenging assays demonstrated that *S. pilchardus* lipids effectively neutralize peroxide, hydroxyl, and nitric oxide radicals. In a study by Borges *et al.* (2014), concentrations of 0.5 and 4 mg/ml were tested to evaluate the protective role of sardine oil in situations of induced oxidative stress. The results showed the increased protective effect of sardine oil rich in omega 3 against this oxidative stress.

Yates *et al.* (2014) showed that *Sardina pilchardus* oil reduced oxidative stress and neuroinflammation in several ways. Additionally, it was shown that this oil showed a dose-dependent inhibitory effect on DPPH radical scavenging activity. The maximum inhibition exhibited by the oil was 96.87 ± 0.76% at 4 mg/ml, and the IC_{50} was 0.148 mg/ml. Collective evidence suggested that the ratio of ω-3 PUFA is an essential dietary factor in reducing oxidative stress (Maffei *et al.,* 2014).

According to the results of Cardeira *et al.* (2022), the coproducts of *S. pilchardus* exhibited the highest ORAC value (1.94 ± 0.08 µmol TEAC/mg) in the radical absorption capacity test of oxygen. These results were consistent with a previous evaluation of antioxidants by an alternative method (2,2-diphenyl-1-picrylhydrazyl-DPPH), where the coproduct extracts presented the lowest IC_{50} values (Melgosa *et al.,* 2020). According to Trilaksani *et al.* (2023), the antioxidant activity of tuna oil produced IC_{50} values, namely F0 of 184.07 ppm, F1 of 119.63 ppm, and F2 of 130.45 ppm.

3.5. Inhibition of protein denaturation assay

According to the results (Table 3), there was a proportional relationship between the concentration of the sample and the percentage of inhibition of protein denaturation. In addition, it was shown that *S. pilchardus* oil presented a percentage of inhibition of BSA denaturation ranging from 33.23 ± 0.44 to 83.16 ± 0.14% for concentrations varying from 125 to 1000 µg/ml. It was followed by *T. thynnus* oil with a value of 81.09 ± 0.4% for the concentration 1000 µg/ml. The comparison with Ibuprofen showed that the latter presented a higher percentage of inhibition (91.10 ± 2.1%). The study by Yates *et al.* (2014) showed that the anti-inflammatory effect of *S. pilchardus* oil was more marked after 12 hours of incubation. The ability of *S. pilchardus* oil to help reduce inflammation was comparable to that of piroxicam (an anti-inflammatory drug), which was even more effective than the drug after 12 and 24 hours. Evidence suggested that DHA and EPA can be converted into anti-inflammatory eicosanoids and docosanoids called resolvins, protectins, and maresins. Fatty acids can also be directly converted to N-acyl ethanolamines (NAEs), which have anti-inflammatory properties (Balvers *et al.,* 2010).

TABLE 3. The inhibition percentage (%) of BSA by oil

	125	250	500	1000
Sardine	33.23 ± 0.44 ^{d}	61.71 ± 0.48 ^{c}	71.53 ± 0.53 ^{b}	83.16 ± 0.14 ^{ab}
Tuna	30.14 ± 0.21 ^{d}	59.28 ± 0.28 ^{c}	75.24 ± 0.63 ^{b}	81.09 ± 0.4 ^{ab}
Ibuprofen	36.78 ± 0.38 ^{a}	60.98 ± 0.3 ^{a}	78.02 ± 1.11 ^{b}	91.10 ± 2.1 ^{c}

Values are presented as mean ± SD of three measurements. Statistical significance was assessed by one-way analysis of variance ANOVA coupled with Tukey's post hoc test. According to Tukey's post hoc test, different letters (a, b, c and d) in a column indicate a significant difference ($p < 0.05$) between groups.

According to the study by Azeem *et al.* (2010), Thunnus coproduct extract showed significant anti-inflammatory activity, which may be due to the inhibition of inflammatory mediators by the action of steroids. Synergistic effects between hydrophobic and hydrophilic chemicals from different fish sources and anti-inflammatory qualities have been observed by other authors. Rudkowska *et al.* (2010) found that fish proteins and ω3 had a synergistic positive influence. According to Chevrier *et al.* (2015), the combination treatment resulted in a greater reduction of TNF-α expression compared to the treatment with ω3 alone.

4. CONCLUSIONS

All of these results showed that the oil from the coproducts of bluefin tuna (*Thunnus thynnus*) and sardine (*Sardina pilchardus*) have an interesting anti-radical and anti-inflammatory activity and, therefore, present considerable therapeutic interest as an alternative compound or therapeutic support for the prevention of inflammation, oxidative stress and cardiovascular pathologies. Future research should focus on optimizing the oil extraction processes, identifying specific bioactive lipid compounds, analyzing the fatty acid profiles, and evaluating their mechanisms of action in vitro and in vivo to better understand their therapeutic potential.

RESEARCH DATA POLICY

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

ACKNOWLEDGMENTS

The author expresses their sincere gratitude to the Laboratory of Bioconversion Microbiology Engineering and Health Safety and the faculty of Natural and Life Sciences of the University of Mustapha Stambouli of Mascara (Algeria).

DECLARATION OF COMPETING INTEREST

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

FUNDING SOURCES

The authors of this article declare that they have no funding sources.

AUTHORSHIP CONTRIBUTION STATEMENT

H. Belkhodja, A. Remil, D. Bouhadi.: Conceptualization, Formal analysis, H. Belkhodja, A. Remil, F.Z. Labbaci, F. Belkhadem: Investigation, Methodology, H. Belkhodja, A. Remil, Z. Benattouche: Project administration, Writing – original draft, Writing – review & editing.

Artificial Intelligence Usage

The authors of this article declare that there is no artificial intelligence usage.

REFERENCES

Azeem AK, Dilip C, Prasanth SS, Junise VHS, Sajeev K, Naseera C. 2010. Anti-inflammatory activity of the glandular extracts of *Thunnus alalunga*. *Asian Pac. J. Trop. Med.* **3** (10), 794–796.

Balasa AF, Chircov C, Grumezescu AM. 2020. Marine biocompounds for neuroprotection—A review. *Mar. Drugs* **18**, 290.

Balvers MGJ, Verhoeckx KCM, Plastina P, Wortelboer HM, Meijerink J, Witkamp RF. 2010. Docosahexaenoic acid and eicosapentaenoic acid are converted by 3T3-L1 adipocytes to N-acyl ethanolamines with anti-inflammatory properties. *Biochim. Biophys. Acta* **1801**, 1107–1114.

Borges C, Ribeiro A, Carvalho AC, Sousa F, Oliveira I, Batista I, Bandarra NM, Gomes AC, Cavaco-Paulo A. 2014. Study of sardine oil antioxidant properties for the development of topical therapeutic formulations. *Planta Med*. **80** (S01), P2O67. doi:10.1055/s-0034-1395057.

Cardeira M, Bernardo A, Leonardo IC, Gaspar FB, Marques M, Melgosa R, Paiva A, Simões P, Fernández N, Serra AT. 2022. Cosmeceutical potential of extracts derived from fishery industry residues: Sardine wastes and codfish frames. *Antioxidants* **11** (10), 1925. https://doi.org/10.3390/antiox11101925

Chevrier G, Mitchell PL, Rioux LE, Hasan F, Jin T, Roblet CR, Marette A. 2015. Low-molecular-weight peptides from salmon protein prevent obesity-linked glucose intolerance, inflammation, and dyslipidemia in LDLR−/−/ApoB100/100 mice. *J. Nutr.* **145** (7), 1415–1422. https://doi.org/10.3945/jn.114.208215

Coppola D, Lauritano C, Palma Esposito F, Riccio G, Rizzo C, De Pascale D. 2021. Fish waste: from problem to valuable resource. *Mar. Drugs* **19** (2), 116. https://doi.org/10.3390/md19020116

Dórame-Miranda RF, Gámez-Meza N, Ovando-Martínez M. 2021. Encapsulation of sardine oil by electrospraying with gliadins and pecan nutshell extracts for its stabilization. *Food Bioprocess Technol.* **14**, 457–470. https://doi.org/10.1007/s11947-020-02567-x

El-Shafei R, Hegazy H, Acharya B. 2021. A review of antiviral and antioxidant activity of bioactive metabolites of macroalgae within an optimized extraction method. *Energies* **14**, 3092.

Hu S, Yuan J, Gao J, Wu Y, Meng X, Tong P, Chen H. 2020. Antioxidant and anti-inflammatory potential of peptides derived from in vitro gastrointestinal digestion of germinated and heat-treated foxtail millet (*Setaria italica*) proteins. *J. Agric. Food Chem.* **68**, 9415–9426. https://doi.org/10.1021/acs.jafc.0c03732

Jesionowska M, Ovadia J, Hockemeyer K, Clews AC, Xu Y. 2023. EPA and DHA in microalgae: health benefits, biosynthesis, and metabolic engineering advances. *J. Am. Oil Chem. Soc.* **100** (11), 831–842. https://doi.org/10.1002/aocs.12718

Khalihena Groune AL, ElHamidi A, Halim M. 2024. Comparative investigation of fatty acids in the Mauritania sardinella and Moroccan sardine. *Curr. Nutr. Food Sci.* **20** (1), 85–91. https://doi.org/10.2174/1573401319666221114101642

Lechuga I, Michaelian K. 2023. Fatty acid vesicles as hard UV-C shields for early life. *Foundations* **3** (1), 99–114. https://doi.org/10.3390/foundations3010010

Maffei S, De Felice C, Cannarile P, Leoncini S, Signorini C, Pecorelli A, Montomoli B, Lunghetti S, Ciccoli L, Durand T. 2014. Effects of ω-3 PUFAs supplementation on myocardial function and oxidative stress markers in typical Rett syndrome. *Mediators Inflamm.* **2014**, 1–8.

Melgosa R, Trigueros E, Sanz MT, Cardeira M, Rodrigues L, Fernández N, Matias AA, Bronze MR, Marques M, Paiva A. 2020. Supercritical CO_2 and subcritical water technologies for the production of bioactive extracts from sardine (*Sardina pilchardus*) waste. *J. Supercrit. Fluids* **164**, 104943.

Messina CM, Arena R, Manuguerra S, La Barbera L, Curcuraci E, Renda G, Santulli A. 2022. Valorization

of side stream products from sea cage fattened bluefin tuna (*Thunnus thynnus):* Production and in vitro bioactivity evaluation of enriched ω-3 polyunsaturated fatty acids. *Mar. Drugs* **20**, 309. https://doi.org/10.3390/md20050309

Mutalipassi M, Esposito R, Ruocco N, Viel T, Costantini M, Zupo V. 2021. Bioactive compounds of nutraceutical value from fishery and aquaculture discards. *Foods* **10**, 1495.

Nascimento VLV, Bermudez VMS, Oliveira ALL, Kleinberg MN, Ribeiro RTM, Abreu RFA, Carioca JOB. 2015. Characterization of a hydrolyzed oil obtained from fish waste for nutraceutical application. *Food Sci. Technol.* **35** (2), 321–325.

Oliveira CM, dos Santos JG, Costa Sousa RG. 2020. UV spectrophotometry applied to the quantification of omega-3, -6 and -9 in fresh tissues of wild and farmed tambaqui. *Int. J. Innov. Educ. Res.* **8** (12), 183–195.

Pravinkumar M, Eugien LX, Viswanathan C, Raff SM. 2015. Extraction of fish body oil from *Sardinella longiceps* by employing direct steaming method and its quantitative and qualitative assessment. *J. Coast. Life Med.* **3** (12), 962–966.

Pudtikajorn K, Benjakul S. 2020. Simple wet rendering method for extraction of prime quality oil from skipjack tuna eyeballs. *Eur. J. Lipid Sci. Technol.* **122** (8), 1–29. https://doi.org/10.1002/ejlt.202000077

Purnamayati L, Dewi EN. 2019. Physical blending characteristic of fish oil and sesame oil. *IOP Conf. Ser. Earth Environ.* Sci. **246**, 012054.

Rubio-Rodríguez N, Beltrán S, Jaime I, Diego SM, Sanz MT, Rovira CJ. 2010. Production of omega-3 polyunsaturated fatty acid concentrates: A review. *Innov. Food Sci. Emerg. Technol.* **11** (1), 1–12. https://doi.org/10.1016/j.ifset.2009.10.006

Rudkowska I, Marcotte B, Pilon G, Lavigne C, Marette A, Vohl MC. 2010. Fish nutrients decrease expression levels of tumor necrosis factor-alpha in cultured human macrophages. *Physiol. Genomics* **40** (3), 189–194. https://doi.org/10.1152/physiolgenomics.00120.2009

Saito S, Numadate N, Teraoka H, Enami S, Kobayashi H, Hama T. 2023. Impurity contribution to ultraviolet absorption of saturated fatty acids. *Sci. Adv.* **9**, 1–7. https://doi.org/10.1126/sciadv.adj6438

Strobel SA, Hudnall K, Arbaugh B, Cunniffe JC, Scher HB, Jeoh T. 2020. Stability of fish oil in calcium alginate microcapsules cross-linked by in situ internal gelation during spray drying. *Food Bioprocess Technol.* **13** (2), 275–287. https://doi.org/10.1007/s11947-019-02391-y

Suseno HS. 2015. Proximate, fatty acid, and mineral composition of tuna (Thunnus sp.) by-product from West Sumatra Province, Indonesia. *Pak. J. Nutr.* **14** (1), 62–66.

Trilaksani W, Sinulingga F, Setyaningsih I, Indra Aja Nasution M. 2023. Evaluation of fatty acid quality and antioxidant activity of supplement tablets from tuna eyes oil and Spirulina platensis. *Int. J. Chem. Biochem. Sci.* **24** (5), 632–638.

Wei L, Li Q, Tan W, Dong F, Luan F, Guo Z. 2017. Synthesis, characterization, and the antioxidant activity of double quaternized chitosan derivatives. *Molecules* **22**, 501.

Yates CM, Calder PC, Rainger GE. 2014. Pharmacology and therapeutics of omega-3 polyunsaturated fatty acids in chronic inflammatory disease. *Pharmacol. Ther.* **141**, 272–282.