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# Lipid composition and functional properties of quinoa (*Amarilla Sacaca*) seed oil: impact of cultivation in a hyper-arid Saharan environment on yield, fatty acids, and antioxidant capacity

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**Introduction:** Quinoa (*Chenopodium quinoa* Willd.), a nutrient-dense “golden grain” from South America, is valued for its resilience to abiotic stresses, making it a strategic crop for arid regions. While its protein quality is well-established, the composition and bioactivity of oil from varieties grown under extreme hyper-arid conditions, such as those in the Algerian Sahara, remain unexplored. This study provides the first comprehensive characterization of the oil from Quinoa (*Amarilla Sacaca*) cultivated in this unique environment.

**Methods:** Quinoa seeds of the *Amarilla Sacaca* variety, harvested from the hyper-arid Ouargla region of Algeria, were processed to extract oil via Soxhlet method using n-hexane. The oil was characterized for its physicochemical properties (acid, peroxide, iodine, and saponification values, etc.) and bioactive phytochemical content (total phenolics, flavonoids, carotenoids) using standard AOAC and spectrophotometric methods. The fatty acid profile and minor lipophilic compounds were analyzed by GC-MS. Antioxidant activity was evaluated using three complementary in vitro assays: DPPH radical scavenging,  $\beta$ -carotene bleaching inhibition, and nitric oxide (NO) radical scavenging.

**Results:** The extracted oil yield was 3.98%. It was rich in bioactive compounds, with a total phenolic content of  $467.78 \pm 11.38 \mu\text{g GAE/g}$ , total flavonoids of  $209.90 \pm 8.83 \mu\text{g RE/g}$ , and total carotenoids of  $7.88 \pm 0.12 \text{ mg/kg}$ . The fatty acid profile was dominated by unsaturated fatty acids (87.22%), with linoleic acid (C18:2 n-6, 51.33%) and an unusually high concentration of petroselinic acid (C18:1 n-6t, 33.44%) as the major constituents. Squalene (1.01%) and 2,4-di-tert-butylphenol (0.83%) were identified as significant minor bioactive components. The oil demonstrated potent, multi-mechanistic antioxidant activity (IC50 values: DPPH =  $45.67 \mu\text{g/mL}$ ;  $\beta$ -carotene bleaching =  $38.05 \mu\text{g/mL}$ ; NO scavenging =  $26.57 \mu\text{g/mL}$ ), which was strongly correlated with its phytochemical content ( $r > 0.85$ ,  $p < 0.001$ ).

**Discussion and conclusion:** The extreme arid conditions appear to induce a trade-off, suppressing oil yield while significantly enhancing the accumulation of

bioactive phytochemicals. This results in a functionally superior oil with a unique fatty acid fingerprint and exceptional antioxidant capacity, surpassing that of pure  $\alpha$ -tocopherol in some assays. The high squalene content positions it as a sustainable, plant-based alternative for nutraceutical and cosmetic applications. These findings highlight Saharan Quinoa oil as a high-value specialty product, supporting sustainable development goals (SDGs 2, 3, 9, 12) and offering a pathway for the integrated valorization of resilient crops within a circular bio-economy framework.

#### KEYWORDS

antioxidant activity, *Chenopodium quinoa*, fatty acid composition, physicochemical characteristics, Saharan conditions, seed oil

## 1 Introduction

The global surge in demand for plant-derived oils underscores a pressing need for sustainable extraction methodologies that reconcile yield efficiency with environmental stewardship (Chemat et al., 2020). Conventional solvent-based techniques, often reliant on petroleum-derived solvents such as  $n$ -hexane, present challenges related to environmental toxicity, high energy consumption, and complex recovery processes (Sánchez-Camargo et al., 2020). This has catalyzed research into greener solvent alternatives, including bio-based solvents, supercritical fluids, and aqueous enzymatic extraction, aiming to reduce the ecological footprint of oil processing (Khaw et al., 2017). In parallel, the stability of agricultural supply chains is increasingly threatened by climate volatility, necessitating the identification and cultivation of resilient crops capable of thriving in marginal environments (Bazile et al., 2016). Quinoa (*Chenopodium Quinoa* Willd.), with its renowned tolerance to abiotic stresses such as drought and salinity, emerges as a strategic crop for arid and semi-arid regions, offering a pathway to enhanced food security and supply-chain diversification (Ruiz, 2013). Furthermore, the valorization of crop co-products aligns with circular bioeconomy principles, where food waste reduction is paramount. The recovery of natural antioxidants, such as phenolics and carotenoids from oil extraction residues, presents a dual opportunity: to enhance the oxidative stability of food and cosmetic products naturally, and to reduce waste streams (Galanakis, 2012).

Quinoa (*Chenopodium Quinoa* Willd.), a dicotyledonous annual species within the *Amaranthaceae* family, was domesticated in the Andean highlands approximately 7,000 years ago (Lin et al., 2019). Historically, Andean civilizations cultivated this pseudo-cereal not only for its exceptional nutritional profile but also for its remarkable resilience to abiotic stresses, particularly drought and soil salinity (Pathan and Siddiqui, 2022). Following the Spanish conquest, however, Quinoa cultivation experienced a severe decline across its native range, which includes present-day Peru, Bolivia, Ecuador, Chile, and Colombia (Jancurová et al., 2009). Despite this historical setback, Quinoa's intrinsic adaptability to marginal soils and harsh environments has fueled a modern global resurgence. Cultivation has expanded dramatically from just eight countries in 1980 to over one hundred by 2021, reflecting its recognized potential as a strategic crop for food security (Pathan and Siddiqui, 2022).

A systematic evaluation of Quinoa adaptation was implemented across key semi-arid and arid zones of North Africa and the Middle East. This involved the standardized distribution of diverse Quinoa genetic material to established research bodies in a select group of

countries: Algeria, Egypt, Iran, Iraq, Lebanon, Mauritania, Sudan, and Yemen. These multi-location trials were integral to a broader regional development program, the Food and Agriculture Organization (FAO-initiated “Technical Assistance for Strengthening the Quinoa-Based Food System”), which aimed to build resilience and promote the crop's integration into local agriculture (Bazile et al., 2016).

Following its global resurgence, Quinoa was first introduced for experimental cultivation in Algeria during the 2013–2014 season. This initial assessment, led by the Institute Technique des Grandes Cultures (ITGC), Eddine (2020) employed a multi-location trial design across eight sites managed by four partnering institutions. The goal was to evaluate varietal adaptation and productivity under contrasting Algerian environments. Yield results from this foundational season established a preliminary performance baseline, with seed production ranging from 11 q/ha in Relizane (Hmadna site) to a markedly higher 26 q/ha in the pre-Saharan oases of Biskra and El Oued, Algeria, suggesting a particular suitability for arid zone cultivation.

Beyond its agronomic resilience, Quinoa holds significant promise as a strategic crop for transitioning toward sustainable, plant-based food systems. Designated a “superfood” a marketing term used to describe foods with perceived exceptional health benefits due to high nutrient density and bioactive compound content Quinoa's comprehensive nutritional profile demonstrably surpasses that of staple cereals such as wheat, rice, and corn (Chen et al., 2023). This superiority is rooted in Quinoa's unique composition. Unlike traditional grains, it provides a complete protein source containing all nine essential amino acids alongside a favorable lipid profile rich in unsaturated fatty acids, a broad spectrum of minerals and vitamins, and a high concentration of bioactive antioxidants (Duarte et al., 2022). Consequently, Quinoa offers a nutritionally dense, singular ingredient that can enhance the quality and balance of plant-forward diets.

Quinoa seeds are notably rich in lipophilic antioxidants, including tocopherols, carotenoids, and phenolic compounds, which contribute to oxidative stability and health benefits (Tang et al., 2016). The oil fraction, in particular, contains squalene, a triterpene with antioxidant and emollient properties, valued in cosmetic and nutraceutical applications (Lozano-Grande et al., 2018). Recent studies have highlighted the variability in antioxidant content among Quinoa varieties and growing conditions. For instance, Gómez-Caravaca et al. (2014) reported significant levels of  $\gamma$ -tocopherol and phenolics in cold-pressed Quinoa oil, while Chen et al. (2019) identified diverse bioactive phytochemicals, including carotenoids and squalene, in Quinoa oil extracts. Such bioactive constituents not only enhance the oil's nutritional profile but also improve its shelf life and functional applicability.

The utility of Quinoa extends beyond its whole seeds into diverse food and feed applications. Its seeds can be malted to produce nutritious Quinoa sprouts for use in salads, while the entire harvested plant serves as a valuable forage crop for livestock. Furthermore, milling the seeds yields gluten-free flour, a versatile ingredient widely employed in baking and pastry production (Pereira et al., 2019). This gluten-free nature, combined with Quinoa's exceptional nutritional profile marked by a balanced essential amino acid composition, high-quality proteins, lipids, dietary fiber, minerals, and vitamins makes it an ideal staple for individuals with celiac disease (Saeed et al., 2020). Notably, Quinoa's lipid fraction is rich in essential polyunsaturated fatty acids (PUFAs), specifically linoleic ( $\omega$ -6) and  $\alpha$ -linolenic ( $\omega$ -3) acids. The  $\omega$ -6/ $\omega$ -3 ratio in Quinoa oil approximates a range of 5:1 to 10:1, which aligns with certain dietary recommendations (Gómez et al., 2021). However, it is important to note that the optimal nutritional ratio for these fatty acids is widely suggested to be between 1:1 and 4:1 (Gómez et al., 2021).

The phenotypic expression of Quinoa encompassing yield, oil characteristics, and fatty acid profile is a plastic trait contingent upon both genetic background and cultivation environment. Empirical evidence highlights this plasticity: Toderich et al. (2020) reported that high salinity stress significantly suppressed morphological development (plant height, dry weights) and reproductive output, concurrently inducing shifts in metabolite pools, including squalene and specific fatty acids. Parallel findings by Kiyani et al. (2022) established that water deficit compromises plant physiology, ultimately diminishing seed yield and protein concentration. Consequently, identifying genotypes resilient to such stresses is paramount. A comparative study by Khaitov et al. (2020) addressed this need, screening five varieties in the challenging agro-climate of the Aral Sea region, their results distinguished varieties Q3 and Q5 as possessing enhanced abiotic stress tolerance coupled with robust yield and nutritional quality, underscoring the importance of targeted varietal selection for specific environments.

The application of organic fertilizer, particularly manure, has been identified as a key agronomic practice that directly shapes the metabolic output of Quinoa. A 2023 study by González et al. (2023) on the CICA-17 and Regalona Baer varieties revealed that manure enrichment induced significant changes in the plants nutritional architecture. These changes encompassed enhanced essential amino acid profiles, altered desaturase enzyme activity, and modifications in critical lipid indices such as the n6/n3 and SFA/UFA ratios. Additionally, manure treatment improved the atherogenic index, soluble sugar levels, mineral matter content, and overall fatty acid metabolism, highlighting its potential to bio-fortify Quinoa grains.

The arid agro-ecosystems of southern Algeria are characterized by a confluence of abiotic stresses principally high soil salinity, elevated irrigation water salinity, and extreme temperatures that collectively pose significant challenges to conventional crop physiology and yield. Despite the increasing cultivation of resilient crops such as Quinoa (*Chenopodium Quinoa* Willd.) in these marginal regions, a critical knowledge gap persists. Specifically, there is a notable absence of comprehensive research on the phytochemical profile and functional properties of derived products, such as seed oil, from Quinoa grown under these specific Algerian arid conditions. Despite increasing interest in Quinoa cultivation across North Africa, no published data exist on the phytochemical quality or functional properties of seed oil derived from Quinoa grown in the Algerian Sahara. This study addresses that gap by providing the first comprehensive characterization of oil from

the *Amarilla Sacaca* variety cultivated under hyper-arid conditions in Ouargla, with emphasis on its bioactive potential and suitability for sustainable applications. Therefore, this work aims to comprehensively characterize the oil from the Quinoa (*Amarilla Sacaca*) variety, providing the first detailed report on its physicochemical properties, fatty acid profile, antioxidant bioactive content, and *in vitro* antioxidant capacity from the Algerian Sahara. The findings will contribute to understanding how extreme arid conditions influence oil quality and will evaluate its potential within sustainable extraction and valorization frameworks.

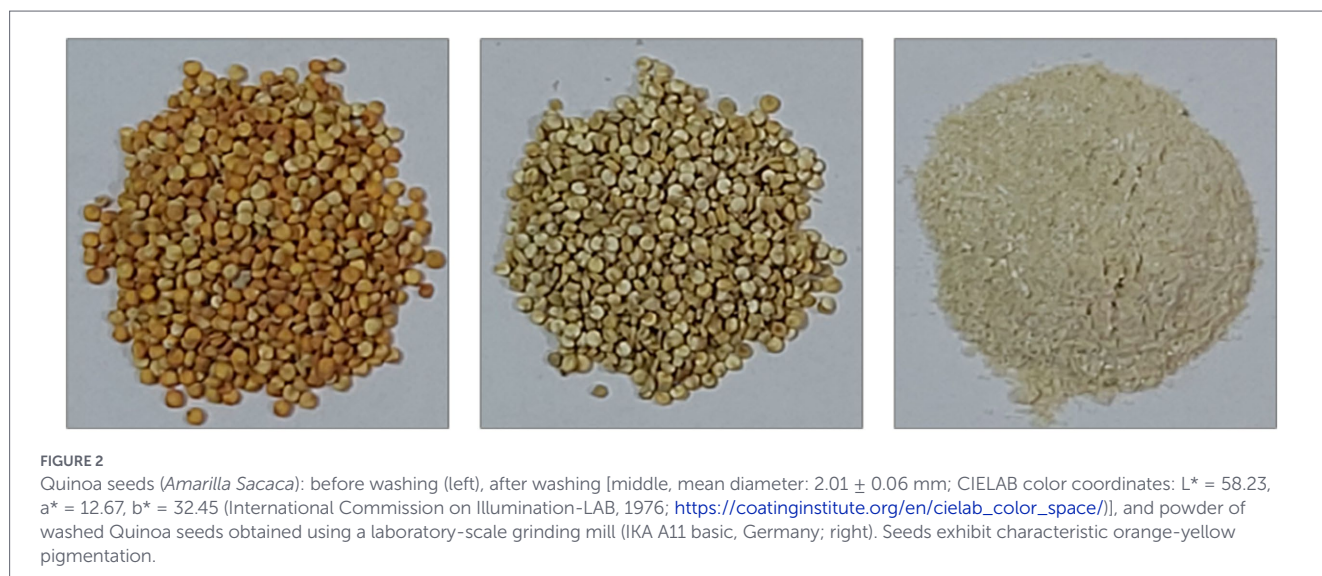
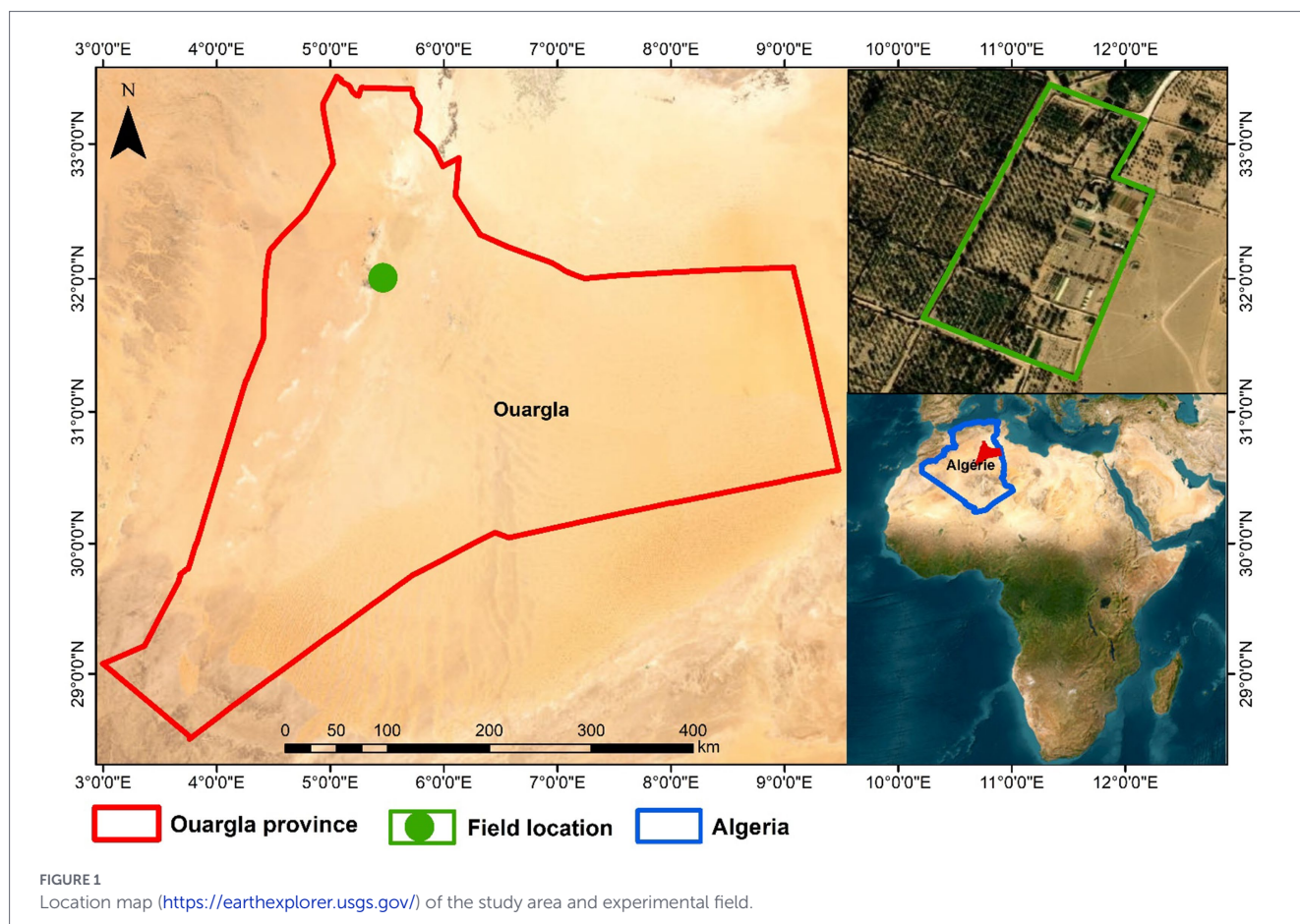
## 2 Materials and methods

### 2.1 Study site and environmental conditions

This study was conducted in the arid Ouargla region, situated in the northeastern Sahara of Algeria. The region encompasses a vast area of approximately 163,233 km<sup>2</sup> and is characterized by a harsh desert climate. This climate is defined by extreme seasonal temperature fluctuations, with an average July high of 42.8 °C and a January low of 4 °C, coupled with a low mean annual precipitation of around 50 mm. The predominant soils are of a sandy to sandy-loamy texture. A specific field trial was established at the Technical Institute for the Development of Saharan Agriculture (ITDAS) research station in Hassi Ben Abdellah (32°00'25.59"N, 5°27'48.63"E, 446 m a.s.l.) as shown in Figure 1. The trial was carried out during the 2021/2022 winter growing season under open-field conditions. Irrigation was supplied via surface flooding using water of moderate salinity (EC, 2.50 dS/m) and slight alkalinity (pH, 7.87). The experimental site soil was classified as moderately saline (EC, 4 dS/m) and slightly alkaline (pH, 7.54).

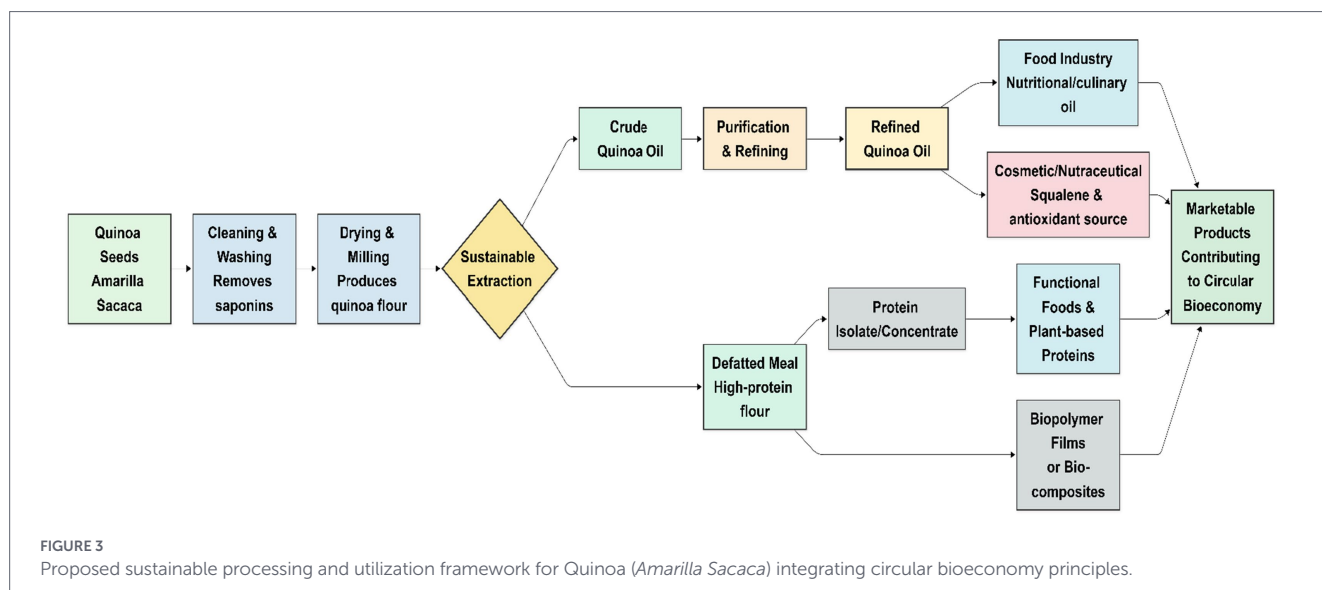
### 2.2 Plant material and seed preparation

Quinoa seeds of the *Amarilla Sacaca* variety were procured from the Technical Institute for the Development of Saharan Agronomy (ITDAS) in Ouargla, Algeria, following the 2022 harvest. The seeds were characterized by a distinctive yellow to orange pigmentation (Figure 2). The *Amarilla Sacaca* variety, originally derived from Bolivian germplasm, was selected for this study based on several criteria: (i) its documented adaptation to arid and semi-arid conditions in preliminary FAO-led multi-location trials across North Africa (Bazile, 2016); (ii) its distinctive yellow-orange pigmentation, which suggests elevated carotenoid content compared to lighter-colored Quinoa varieties; (iii) its established cultivation history in the Ouargla region since 2014, ensuring genetic stability under local conditions; and (iv) its representativeness of the primary Quinoa varieties being promoted for smallholder cultivation in Algerian Saharan regions. The variety was officially introduced to Algeria through the FAO "Technical Assistance for Strengthening the Quinoa-Based Food System" program and has been maintained by ITDAS as a candidate variety for regional adaptation trials. Seeds were harvested at physiological maturity in late April 2022, approximately 130 days after sowing. Total grain yield under the experimental conditions was 2.4 ± 0.3 t/ha, consistent with previously reported yields for this variety in the Ouargla region (Eddine, 2020). Sampling was conducted using a systematic random sampling protocol: five 1 m<sup>2</sup> quadrats were



randomly selected within the experimental plot (approximately 500 m<sup>2</sup>), all plants within each quadrat were hand-harvested, and seeds were pooled to form a composite sample representing the plot. The composite sample was homogenized and divided into three analytical replicates for subsequent analyses. From a commercial perspective, *Amarilla Sacaca* commands a modest premium in local markets (approximately 15–20% higher than conventional white Quinoa varieties) due to its visual appeal and perceived nutritional superiority.

However, the total fat content of 3.98% is lower than that of major oilseed crops (soybean: 19–21%; sunflower: 38–50%; rapeseed: 40–45%), which has significant implications for economic feasibility. At current local market prices (approximately \$2.50–3.00/kg for Quinoa grain), the oil yield of 3.98% translates to an oil production cost of approximately \$65–75 per liter, which is substantially higher than commodity vegetable oils (\$1–3 per liter). This positions Quinoa oil as a high-value specialty product rather than a commodity oil, with



commercial viability dependent on differentiation through its unique fatty acid profile, high squalene content, and exceptional antioxidant capacity rather than competing on volume or price. It is important to acknowledge that for most populations consuming Quinoa as a staple food, the primary nutritional relevance lies in its protein quality rather than its oil content. Quinoa provides a complete protein source containing all nine essential amino acids, with a protein digestibility-corrected amino acid score (PDCAAS) comparable to casein (Pathan and Siddiqui, 2022). The oil fraction, while nutritionally valuable for its unsaturated fatty acid profile and bioactive compounds, represents a secondary coproduct in whole-seed consumption. The valorization of Quinoa oil as a separate product stream is therefore most relevant for industrial processing contexts where defatted meal can be redirected to protein-rich food ingredients or animal feed, consistent with the circular bioeconomy framework illustrated in Figure 3.

To eliminate bitter-tasting saponins from the seed coat, the seeds underwent a thorough washing procedure with distilled water until the rinse water was clear. Subsequently, the washed seeds were dried to a constant weight in a forced-air circulation oven at a controlled temperature of 40 °C to prevent thermal degradation of bioactive compounds. The dried seeds were then pulverized into a homogeneous fine powder using a laboratory-scale grinding mill (IKA A11 basic, Germany; Figure 2).<sup>1</sup> The resulting Quinoa flour was immediately transferred to airtight, light-proof containers and stored under refrigeration at 4 °C to preserve its chemical integrity until subsequent oil extraction and analysis.

### 2.3 Oil extraction and yield determination

Lipid extraction was performed according to the standard Soxhlet method (ISO 659; Daun and Cantrill, 2003). A precisely weighed quantity of the dried Quinoa seed powder was placed into a cellulose thimble within the Soxhlet apparatus. Analytical-grade \*n\*-hexane was selected as the non-polar solvent for its efficiency in extracting non-polar lipids and triglycerides. The extraction was conducted at a constant temperature of 50 °C for a duration of 6 h to

ensure exhaustive recovery of the lipid fraction. Following extraction, the solvent-laden oil was carefully collected, and the \*n\*-hexane was completely removed using a rotary evaporator (Büchi R-300, Switzerland) under reduced pressure at 40 °C. The resulting pure oil was weighed, and the oil yield was calculated gravimetrically as the percentage of oil extracted per 100 grams of dry seed powder, in strict adherence to the ISO protocol. The extracted Quinoa oil was then transferred to amber vials, flushed with nitrogen gas to displace headspace air, and stored at 4 °C in darkness to prevent oxidation until further analysis.

### 2.4 Characterization of oil physicochemical parameters

A comprehensive physicochemical profile of the obtained Quinoa (*Amarilla Sacaca*) oil was established. The quality and purity of the extracted Quinoa seed oil were evaluated through a suite of standard physicochemical analyses. Key parameters, including acid value (AV), peroxide value (PV), density, iodine value (IV), refractive index (RI), volatile matter content, saponification value (SV), and unsaponifiable matter content, were determined in triplicate. All assays were performed in accordance with the official methods established by the Association of Official Analytical Chemists (AOAC; Agroindustriais, 2013). Specific methods included: AOAC 920.39 for oil yield, AOAC 940.28 for fatty acid composition, AOAC 965.33 for peroxide value, AOAC 920.158 for saponification value, AOAC 993.20 for iodine value, and AOAC 921.08 for refractive index (Agroindustriais, 2013; Ismail, 2024; Samanta et al., 2023). These measurements collectively provide critical insights into the oil's hydrolysis and oxidative state (AV, PV), molecular weight and fatty acid composition (IV, SV), purity and density (density, RI, volatile matter), and content of non-glyceride components such as sterols and tocopherols (unsaponifiable matter).

### 2.5 Quantification of total polyphenols, flavonoids, and carotenoids

The bioactive phytochemical content of the Quinoa seed oil was evaluated through spectrophotometric quantification of three key compound classes: total polyphenols, total flavonoids, and total carotenoids.

<sup>1</sup> <https://www.retsch.com/products/milling/>

- **Total Phenolic Content (TPC):** The TPC was determined using the Folin–Ciocalteu reagent method optimized for lipophilic matrices (González-Ceballos et al., 2023; Lawag et al., 2023; Rizvi et al., 2023; Singleton et al., 1999). Briefly, 100  $\mu\text{L}$  of Quinoa oil was dissolved in 1 mL of methanol and mixed with 500  $\mu\text{L}$  of Folin–Ciocalteu reagent (diluted 1:10 with distilled water). After 5 min, 1.5 mL of sodium carbonate solution (7.5%, w/v) was added, and the volume was adjusted to 10 mL with distilled water. The mixture was incubated in the dark at room temperature for 90 min. Absorbance was measured at 765 nm using a UV–Vis spectrophotometer (Shimadzu UV-1280, Japan). Quantification was performed using a gallic acid standard curve (0–200  $\mu\text{g}/\text{mL}$ ;  $R^2 = 0.998$ ), and results were expressed as micrograms of gallic acid equivalents per gram of oil ( $\mu\text{g GAE}/\text{g}$ ). The alkaline concentration was optimized at 7.5%  $\text{Na}_2\text{CO}_3$  following the recommendations of Rizvi et al. (2023) for vegetable oil matrices.
- **Total Flavonoid Content (TFC):** The TFC was assessed according to the aluminum chloride colorimetric method with critical evaluation of matrix interference (da Silva et al., 2024; Pękal and Pyrzyńska, 2014; Shraim et al., 2021; Sultana et al., 2024). An aliquot of 250  $\mu\text{L}$  of Quinoa oil was extracted with 1 mL of methanol, followed by addition of 75  $\mu\text{L}$  of sodium nitrite solution (5%, w/v). After 6 min, 150  $\mu\text{L}$  of aluminum chloride solution (10%, w/v) was added and allowed to stand for 5 min. Then, 500  $\mu\text{L}$  of sodium hydroxide solution (1 M) was added, and the final volume was adjusted to 2.5 mL with distilled water. Absorbance was measured immediately at 515 nm. A rutin standard curve (0–100  $\mu\text{g}/\text{mL}$ ;  $R^2 = 0.996$ ) was used for quantification, and results were expressed as micrograms of rutin equivalents per gram of oil ( $\mu\text{g RE}/\text{g}$ ). Appropriate blanking with sample-matched controls was employed to correct for inherent oil color, as recommended by Vucane et al. (2024) for pigmented oil matrices.
- **Total Carotenoid Content (TCC):** Total carotenoids were quantified spectrophotometrically according to the method of da Silva et al. (2024) and Poljšak and Kočevár Glavač (2024) with modifications. Quinoa oil (500 mg) was precisely weighed and dissolved in 5 mL of cyclohexane. The absorbance was measured at 470 nm against a cyclohexane blank. Total carotenoid content was calculated using the specific extinction coefficient of  $\beta$ -carotene ( $E^{1\%,1\text{cm}} = 2,560$ ) and expressed as milligrams of  $\beta$ -carotene equivalent per kilogram of oil (mg  $\beta$ -CE/kg) according to the following Equation 1:

$$TCC (\text{mg} / \text{kg}) = \frac{A_{470} \times V \times 10^4}{\sum_{1,m}^{1\%} \times m} \quad (1)$$

where;  $A_{470}$  is the absorbance at 470 nm,  $V$  is the volume of cyclohexane (mL),  $m$  is the mass of oil (g), and  $E^{1\%,1\text{cm}}$  is the extinction coefficient of  $\beta$ -carotene.

## 2.6 Fatty acid methyl ester preparation and gas chromatography coupled to mass spectrometry (GC–MS) analysis of quinoa seed oil

Fatty acid methyl esters (FAMES) were prepared following the European standard NF EN ISO 12966-2 (Heidari et al., 2020). In this

method, Quinoa oil (100 mg) was dissolved in 2 mL of *n*-heptane and transesterified with 200  $\mu\text{L}$  of methanolic KOH solution (2 N). The mixture was vortexed for 30 s and allowed to stand for 5 min. The upper organic layer containing FAMES was collected and dried over anhydrous sodium sulfate.

GC–MS analysis was performed using a Shimadzu AOC-20i Plus gas chromatograph coupled to a TQ8040 NX mass spectrometer (Shimadzu, Tokyo, Japan). Separation was achieved on a HP-88 capillary column (100 m  $\times$  0.25 mm  $\times$  0.20  $\mu\text{m}$ ; Agilent Technologies). Helium was used as carrier gas at a flow rate of 1.0 mL/min. The oven temperature program was as follows: initial hold at 35  $^\circ\text{C}$  for 6 min, ramp at 3.5  $^\circ\text{C}/\text{min}$  to 260  $^\circ\text{C}$ , hold for 20 min. Injector and ion source temperatures were 250  $^\circ\text{C}$  and 200  $^\circ\text{C}$ , respectively. FAMES were identified by comparison of retention times with authentic standards (Supelco 37 Component FAME Mix) and confirmed by NIST 20 mass spectral library (version 2020). Quantification was performed by area normalization (Poljšak and Kočevár Glavač, 2024). This step was carried out at the Center of Research and Physio-Chemical Analysis (CRAPC) in Ouargla.

## 2.7 Antioxidant activity

The antioxidant activity was determined using three methods, namely: DPPH radical scavenging activity, bleaching  $\beta$ -carotene and nitric oxide radical scavenging capacity.

### 2.7.1 DPPH radical-scavenging activity

The antioxidant activity of the samples was measured by determining the ability of the oil to scavenge the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical, following the method of Brand-Williams et al. (1995), with modifications described by Aziz et al. (2024). A DPPH free radical solution was prepared by dissolving 25 mg of DPPH in 100 mL of methanol, and this solution was protected from light. Stock solutions of seed oil were prepared at a concentration of 1 mg/mL and then diluted in methanol to obtain final concentrations of 500, 250, 200, 100, and 50  $\mu\text{g}/\text{mL}$ . Next, 100  $\mu\text{L}$  volumes of the Quinoa seed oil at different concentrations were mixed with 3.9 mL of the DPPH solution. The mixture was incubated in a water bath at 30  $^\circ\text{C}$  for 45 min, and then the absorbance was measured at 517 nm.  $\alpha$ -tocopherol was used as a standard antioxidant. The percentage of DPPH radical scavenging (%) was calculated using the following Equation 2:

$$\% \text{ of DPPH Radical Scavenging} = \frac{Ab_{\text{control}} - Ab_{\text{sample}}}{Ab_{\text{control}}} \times 100 \quad (2)$$

where;  $Ab_{\text{control}}$  is the absorbance of the control sample and  $Ab_{\text{sample}}$  is the absorbance of the various samples.

### 2.7.2 Bleaching of $\beta$ -carotene

The antioxidant activity of different concentrations of Quinoa seed oil was assessed using the  $\beta$ -carotene–linoleic acid assay (Bopitiya and Madhujith, 2015; Miazek et al., 2022), adapted from Amarowicz et al. (2003). Briefly, a solution of  $\beta$ -carotene was prepared by dissolving 2 mg of  $\beta$ -carotene in 10 mL of chloroform. Then, 2 mL of this solution was transferred into a round-bottom flask with a 100 mL capacity using a pipette. After removing the chloroform with a rotary evaporator at 40  $^\circ\text{C}$ , 40 mg of purified linoleic acid, 400 mg of Tween

40 as an emulsifier, and 100 mL of aerated distilled water were vigorously shaken in the flask. Portions (4.8 mL) of this mixture were placed into a series of tubes containing 200  $\mu$ L of the Quinoa seed oil solution at concentrations of 50, 100, 200, 250, and 500  $\mu$ g/mL. The total volume of the systems was adjusted to 5 mL using methanol. After adding the emulsion to each tube, the initial absorbance at 470 nm was promptly measured using a UV–Vis spectrophotometer. Subsequent absorbance measurements were taken while the samples were kept in a water bath at a temperature of 50 °C. Empty samples without  $\beta$ -carotene were prepared to account for background noise.  $\alpha$ -tocopherol was used as the standard antioxidant. The inhibition percentage of bleaching ( $I_{bleaching}\%$ ) was calculated using the following Equation 3:

$$I_{bleaching}\% = \frac{\text{Absorbance after 2h of assay}}{\text{Initial Absorbance}} * 100 \quad (3)$$

### 2.7.3 Nitric oxide radical scavenging capacity

Nitric oxide radical scavenging activity was determined according to the method described by Boora et al. (2014); Jagetia and Baliga (2004); Makhija et al. (2011); Rizvi et al. (2023); and Sultana et al. (2024) used the following approach. First, a 1 mL solution of sodium nitroprusside (10 mL) was combined with 1 mL of oils to generate nitric oxide radicals. This resulted in concentrations of 0.025–0.50 mg/mL in a phosphate buffer. The solution was then placed in an incubator and maintained at a temperature of 25 °C for a duration of 150 min.

The resultant solution was incubated, followed by the addition of 1 mL of Greis's reagent and absorbance measurement at 546 nm.  $\alpha$ -tocopherol was used as an antioxidant control. The percentage of NO radical scavenging (%) was calculated using the following Equation 4:

$$\% \text{ of NO scavenging} = \frac{\text{Abcontrol} - \text{Absample}}{\text{Abcontrol}} * 100 \quad (4)$$

where; *Abcontrol* is the absorbance of control sample and *Absample* is the absorbance of different samples.

## 2.8 Data processing and statistical analysis

Experimental results are reported as the arithmetic mean  $\pm$  standard deviation (SD) of three independent replicates ( $n = 3$ ) to represent central tendency and data dispersion. For comparison of means between Quinoa oil and the reference standard ( $\alpha$ -tocopherol) in antioxidant assays, statistical significance was evaluated using Student's t-test for independent samples. Prior to analysis, normality of data distribution was verified using the Shapiro–Wilk test, and homogeneity of variances was confirmed using Levene's test. For correlation analysis between phytochemical content (total phenolics, flavonoids, carotenoids) and antioxidant activity (DPPH,  $\beta$ -carotene bleaching, NO scavenging), Pearson's product–moment correlation coefficients ( $r$ ) were calculated. The significance of correlation coefficients was assessed using a two-tailed t-test. All statistical analyses were performed using the XLSTAT statistical package (version 2019, Addinsoft, France).

TABLE 1 Morphological and physical properties of Quinoa seeds (variety *Amarilla Sacaca*).

Parameter	Value
Seed diameter (mm)	2.01 $\pm$ 0.06
Thousand-seed weight (g)	3.61 $\pm$ 0.03
Dry matter content (%)	94.67 $\pm$ 1.18
Moisture content (%)	5.33 $\pm$ 1.18
<b>Color (CIELAB)</b>	
L* (lightness)	58.23 $\pm$ 1.45
a* (redness)	12.67 $\pm$ 0.89
b* (yellowness)	32.45 $\pm$ 1.67
Visual appearance	Round shape, orange-yellow pigmentation

Values are expressed as mean  $\pm$  standard deviation ( $n = 3$ ).

A significance threshold of  $\alpha = 0.05$  was applied uniformly across all tests. Significance levels are denoted as follows: \* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ ; ns = not significant ( $p \geq 0.05$ ).

## 2.9 A circular bioeconomy framework for the integrated valorization of quinoa (*Amarilla Sacaca*)

The proposed process flow diagram (Figure 3) illustrates a holistic, multi-pathway valorization strategy for Quinoa (*Amarilla Sacaca*) cultivated in arid environments, transitioning from a linear extraction model to a circular bioeconomy framework. This framework is designed to address key sustainability challenges identified in the introduction, namely solvent replacement, waste reduction, and maximizing value from a climate-resilient crop. The diagram underscores that the primary objective extends beyond mere oil extraction; it envisions the defatted meal often considered a low-value by-product as a critical resource stream. By incorporating potential green extraction technologies (e.g., ethanol, supercritical CO<sub>2</sub>) alongside conventional methods, the framework highlights a research pathway toward reducing the environmental footprint of the initial processing step, aligning with the principles of green chemistry (Chemat et al., 2020). The subsequent branching pathways demonstrate how refined Quinoa oil can be directed toward high-value niches in the cosmetic and nutraceutical industries, leveraging its unique squalene and antioxidant profile identified in this study, while the protein-rich meal can be processed into functional food ingredients or even biopolymer materials. This integrated approach minimizes waste and enhances the economic viability and sustainability quotient of Quinoa cultivation in marginal lands. Ultimately, the diagram posits that the full potential of arid-adapted Quinoa for strengthening local supply chains and contributing to sustainable development goals can only be unlocked through such systemic, co-product-focused processing models.

The framework incorporates quantitative data from this study: oil yield (3.98%), squalene content (1.01%), total phenolic content (467.78  $\mu$ g GAE/g), and carotenoid content (7.88 mg/kg). Dashed lines indicate potential valorization pathways for defatted meal and unsaponifiable fractions requiring further investigation. Green extraction technologies (supercritical CO<sub>2</sub>, ethanol) are proposed as sustainable alternatives to conventional hexane extraction.

## 3 Results and discussion

### 3.1 Morphological and physical characterization of quinoa (*Amarilla Sacaca*) seeds

The principal physical attributes of the Quinoa (*Amarilla Sacaca*) seeds utilized in this study are summarized in Table 1. The seeds exhibited a morphologically homogeneous phenotype, characterized by a visually uniform orange-yellow pigmentation typical of the variety.

Color was quantitatively assessed using a Chroma Meter CR-400 (Konica Minolta, Japan)<sup>2</sup> calibrated with a standard white plate. Color coordinates were recorded in the CIELAB color space (L, a, b), where L represents lightness (0 = black, 100 = white), a\* represents redness/greenness (+a\* = red, -a\* = green), and b\* represents yellowness/blueness (+b\* = yellow, -b\* = blue). The mean seed diameter was determined to be 2.01 ± 0.06 mm, situating this genotype within the “medium” size classification as defined by Pietilä and Jokela (1990), who categorized Quinoa seeds into large (>2.2 mm), medium (1.8–2.1 mm), and small (<1.8 mm) grades. Seed size is a critical agronomic trait that influences planting efficiency, seedling vigor, and ultimately grain yield. The medium-sized seeds observed in this study are advantageous for mechanized sowing operations, which are increasingly adopted in Algerian Saharan agriculture. Furthermore, seed diameter has been positively correlated with Thousand-seed weight and starch content, affecting both nutritional value and processing behavior. This measurement aligns with the general size range of 1–3 mm reported for Quinoa varieties (Jacobsen et al., 2005; Lozano-Isla et al., 2023).

The average Thousand-seed weight (TSW), a critical parameter for assessing seed density, planting value, and yield potential, was 3.61 ± 0.03 g. This varietal characteristic is influenced by agronomic and environmental factors, including water availability during grain filling, mineral nutrition, and climatic conditions (Touati et al., 2022). Our result corresponds with the findings of Fontanel (2013), who recorded TSW values between 1.98 g and 3.74 g for a group of four Quinoa varieties, including *Amarilla Sacaca*. However, it is substantially lower than TSW values reported for Quinoa grown in temperate regions (4.5–5.2 g; Gómez et al., 2021), indicating that arid conditions constrain seed filling despite the variety's adaptation. This reduction is likely attributable to shortened grain-filling duration under high temperature stress and competition for assimilates between osmotic adjustment and storage reserve deposition (Toderich et al., 2020).

The seeds demonstrated a high dry matter content of 94.67 ± 1.18%, an indicator of favorable seed maturity and quality. Consequently, the moisture content was low, at 5.33 ± 1.18%. This moisture level complies with the Codex Alimentarius standard for Quinoa (Codex Alimentarius CXS 333–2019, Boliko, 2019) and is optimal for long-term storage. Low moisture content minimizes the risk of fungal proliferation, lipid hydrolysis, and saponin degradation during post-harvest handling (Pereira et al., 2019). The observed dry matter content is comparable to values reported for Quinoa harvested in similar arid environments (94.1–95.2%; Khaitov et al., 2020), suggesting that seed maturation was complete despite environmental

stress. This is an important quality attribute for both direct consumption and industrial processing.

### 3.2 Extraction yield, physicochemical properties, and bioactive constituents of quinoa (*Amarilla Sacaca*) seed oil

#### 3.2.1 Extraction yield and comparative analysis

The oil yield from Quinoa (*Amarilla Sacaca*) seeds cultivated under hyper-arid conditions in Ouargla was 3.98% ± 0.21% (dry seed weight), which is substantially lower than the 5.0–7.2% average range reported for Quinoa globally and the 6.03–6.74% range documented for varieties grown in temperate regions. This reduction, while representing a quantitative disadvantage, must be understood within the context of extreme environmental stress. Critically, a 2024 study evaluating Quinoa genotypes under Saharan climatic conditions specifically identified that the *Amarilla Sacaca* genotype, despite exhibiting the lowest seed oil content among tested varieties, demonstrated the highest nutritional oil quality based on its ω6/ω3 ratio (5.6, 1) and lowest atherogenicity index. This inverse relationship lower oil content accompanied by superior fatty acid composition suggests a stress-induced metabolic trade-off rather than a simple deficit (Tang et al., 2016). However, this lipid content is comparable to values reported for the Roja and Pot-4 varieties (Gómez et al., 2021) and aligns with other published data (Pellegrini et al., 2018). The observed discrepancy in yield can be attributed to a confluence of genetic and environmental factors, including solvent extraction efficiency (Figueiredo et al., 2019), pre- and post-harvest storage conditions (Irakli et al., 2019), and cultivation altitude (Assefa et al., 2019; Toderich et al., 2020), all of which significantly influence seed composition. The reduced oil content observed in this study is primarily attributable to the extreme hyper-arid conditions of the Ouargla region, which impose multiple interconnected physiological constraints on lipid biosynthesis. First, high temperatures during the seed-filling phase accelerate plant senescence and truncate the duration of fatty acid accumulation (Curti et al., 2020; Matías et al., 2022). Second, salinity stress (irrigation water EC = 2.50 dS/m; soil EC = 4 dS/m) induces metabolic reallocation of photosynthetic assimilates toward osmotic adjustment compounds (proline, glycine betaine) at the expense of storage lipid synthesis (Ruiz, 2013; Toderich et al., 2020). Third, the *Amarilla Sacaca* variety appears to possess inherently lower oil biosynthetic capacity compared to high-oil genotypes such as Titicaca or Regalona (Gómez et al., 2021; Pereira et al., 2019). Fourth, arid soils are typically deficient in phosphorus and organic matter, both critical for triacylglycerol assembly and fatty acid desaturation (Khaitov et al., 2020). Importantly, this yield is not a fixed ceiling; several actionable strategies exist to enhance oil accumulation under Saharan conditions. Agronomic interventions include regulated deficit irrigation timed to avoid water stress during grain filling (12–18% potential increase; Kiyani et al., 2022), phosphorus and potassium biofortification, and organic manure amendment which has been shown to upregulate fatty acid desaturase activity in Quinoa (González et al., 2023). Biological approaches such as inoculation with halotolerant plant growth-promoting rhizobacteria (PGPR) can mitigate salinity stress and improve seed oil content (Hirich et al., 2014; Ma et al., 2021). Genetic strategies include the deployment of high-oil F7/F8 breeding lines specifically selected for Saharan environments, which have demonstrated 15–20% higher oil content than parent varieties in regional trials (Rehman et al., 2025). Post-harvest

<sup>2</sup> <https://sensing.konicaminolta.us/us/products/cr-400-chroma-meter-colorimeter/>.

processing innovations including enzymatic pretreatment of Quinoa flour with cellulase and protease (up to 25% recovery increase; Yang et al., 2024; Zhang et al., 2024) and green extraction technologies such as microwave-assisted extraction and supercritical CO<sub>2</sub> with ethanol co-solvent can further improve oil recovery from low-yield genotypes (Benito-Román et al., 2018; Poljšak and Kočevar Glavač, 2024). Collectively, integrated application of these agronomic, biological, genetic, and processing strategies offers a realistic pathway to increase oil yield by an estimated 30–40% in *Amarilla Sacaca* under Saharan conditions, underscoring that the 3.98% baseline represents not a limitation but a target for systematic optimization.

The extracted crude oil was a yellow liquid at room temperature (25 °C). The yellow coloration is characteristic of Quinoa oil and is primarily attributed to carotenoid pigments (lutein, zeaxanthin) dissolved in the lipid matrix (Moyano et al., 2010), while the liquid state at ambient temperature indicates a high proportion of unsaturated fatty acids, which lower the melting point through the introduction of cis-double bonds that prevent tight packing of acyl chains (Nayak and Patel, 2010). Physical property is advantageous for food applications, as it eliminates the need for warming prior to use and enhances mouthfeel in emulsion-based products (Angerosa and Campestre, 2013).

The comparative analysis reveals distinct characteristics of the *Amarilla Sacaca* oil cultivated in an arid environment. While its extraction yield is on the lower end of the reported spectrum, which may be attributed to combined genetic and severe environmental stress factors. The total phenolic content (467.78 µg GAE/g) is substantially higher than values reported for cold-pressed Quinoa oils (30–150 µg GAE/g; Benito-Román et al., 2018; Gómez-Caravaca et al., 2014). This elevation is likely attributable to two factors: (i) the exhaustive nature of Soxhlet hexane extraction, which more efficiently recovers bound phenolics associated with phospholipid membranes, and (ii) stress-induced upregulation of phenylpropanoid metabolism in response to high solar radiation and temperature (Toderich et al., 2020). The most striking difference lies in the fatty acid profile: the dominance of petroselaic acid (C18:1 n-6 t) over oleic acid (C18:1 n-9c) is atypical and has not been previously reported in Quinoa oil. This suggests a strong genotype-by-environment interaction, where arid, saline stress may have altered the substrate specificity or expression level of stearoyl-ACP desaturase, favoring Δ6 desaturation over

the more common Δ9 desaturation (Matías et al., 2022). Furthermore, the absence of α-linolenic acid further supports this hypothesis, as Δ15 desaturase activity may be suppressed under high temperature conditions (Curti et al., 2020) and the presence of squalene at levels comparable to or higher than other varieties highlight this oil's unique phytochemical fingerprint (Table 2). These comparisons underscore that Quinoa oil is not a uniform product; its composition is highly dependent on provenance and processing, which must be considered for targeted nutritional or industrial applications.

### 3.2.2 Physicochemical properties of quinoa (*Amarilla Sacaca*) seed oil

The key physicochemical parameters of Quinoa (*Amarilla Sacaca*) seed oil are summarized in Table 3 and discussed below.

- **Refractive Index (RI) and Density:** The RI of 1.468 is similar to that of olive oil (Bahti et al., 2015) and oils from other Quinoa fractions (Mufari et al., 2020), but lower than corn and sunflower oils (Mudawi et al., 2014). The RI is a physical constant that reflects the degree of fatty acid unsaturation; each double bond increases electron density and polarizability, resulting in higher RI values and positively correlated with the degree of fatty acid unsaturation (Davis et al., 2013). The RI value obtained in this study is consistent with the high proportion of polyunsaturated fatty acids (51.33%) determined by GC–MS analysis, providing complementary validation of the fatty acid profile. The oil's density (0.867 g/cm<sup>3</sup>) is within acceptable limits for edible oils (<1.0) and is slightly lower than other Quinoa oils (Mufari et al., 2020). Density is influenced by fatty acid composition; it decreases with higher oleic acid content and increases with linoleic acid, due to differences in molecular geometry imparted by the number of double bonds (Davis et al., 2013). The observed density aligns with the predominance of C18 fatty acids (linoleic and petroselaic) in this oil.
- **Viscosity:** The dynamic (16.221 mPa·s) and kinematic (18.697 mm<sup>2</sup>/s) viscosities were lower than those of corn and sunflower oils (Mudawi et al., 2014). Viscosity is a critical quality parameter for edible oils, influencing pumping efficiency, heat transfer during processing, and sensory attributes such as mouthfeel and coating behavior. The relatively low viscosity of this

TABLE 2 Comparative analysis of Quinoa (*Amarilla Sacaca*) oil with other Quinoa varieties oils.

Quinoa variety / origin	Extraction method	Oil yield (%)	Key fatty acids (Major, %)	Key bioactive components	Reference
<i>Amarilla Sacaca</i> (Algeria, arid)	Soxhlet, *n*-hexane	3.98	Linoleic (51.33), Petroselaic (33.44), Palmitic (9.71)	TPC: 467.8 µg GAE/g; Squalene: 1.01%; Carotenoids: 7.88 mg/kg	This study
Various (Canada)	Soxhlet, hexane	5.1–6.7	Linoleic (52.1–54.5), Oleic (23.3–25.1), Palmitic (9.5–10.2)	Tocopherols: 68–121 mg/kg; Phytosterols: 831–1,246 mg/100 g	(Tang et al., 2016)
<i>Regalona</i> (Chile)	Cold Pressing	5.5	Linoleic (50), Oleic (25), Palmitic (10)	TPC: 30 mg GAE/g; γ-Tocopherol: 390 mg/kg	(Gómez-Caravaca et al., 2014)
<i>Titicaca</i> (Denmark)	Soxhlet, petroleum ether	5.6	Linoleic (54.9), Oleic (23.9), α-Linolenic (8.4)	Total carotenoids: 4.3 mg/kg	(Y.-S. Chen et al., 2019)
<i>Black Quinoa</i> (Peru)	Supercritical CO <sub>2</sub>	4.8	Linoleic (49.6), Oleic (24.8), Palmitic (10.1)	Squalene: 0.84%; γ-Tocopherol: 124 mg/kg	(Benito-Román et al., 2018)

TABLE 3 Physicochemical properties of Quinoa (*Amarilla Sacaca*) seed oil.

Properties	Parameters	Value
Physical	Yield	3.98 ± 0.21(w/w% seeds)
	Physical color	Yellow
	State at room temperature	Liquid
	Refractive index	1.468 ± 0.000
	Dynamic viscosity	16.221 mPa·s
	Kinetic viscosity	18.697 mm <sup>2</sup> /s
	Volumic mass	0.86705 g/cm <sup>3</sup>
Chemical	Volatile matter (%)	0.13 ± 0.00
	Free fatty acid value (mg/g)	1.86 ± 0.09
	Saponification value (mg/g)	178.89 ± 8.96
	Peroxide value (mmol/kg)	1.06 ± 0.08
	Peroxide value (meq/kg)	4.18 ± 0.13
	Iodine value (I <sub>2</sub> /100 g)	106.12 ± 5.67
	Unsaponifiable matter value (g/kg)	8.71 ± 0.56
	Polyphenols content (µg GAE/g)	467.78 ± 11.38
	Flavonoids content (µg RE/g)	209.90 ± 8.83
	Carotenoids (mg/kg)	7.88 ± 0.12

Quinoa oil is advantageous for salad dressing formulations and spray-coating applications, where low resistance to flow is desired. This property is directly attributable to the high proportion of polyunsaturated fatty acids, which introduce kinks in the acyl chains and reduce intermolecular friction (Garg et al., 2021; Talkit and Mahajan, 2012).

- **Volatile Matter:** The low volatile matter content (0.13 ± 0.00%) suggests minimal presence of flavor-active compounds such as aldehydes, alcohols, and hydrocarbons (Giuffrè et al., 2020), this indicates a mild flavor profile, which is commercially desirable for applications where the oil serves as a neutral carrier for other flavors or as a base for cosmetic formulations. The low volatile content also reflects proper post-harvest handling and storage, as volatile compounds are primarily generated through lipid oxidation and enzymatic degradation of hydroperoxides.

### 3.2.3 Quality and stability indices

- **Free Fatty Acids (FFA) and Peroxide Value (PV):** The acid value of 1.86 ± 0.09 mg KOH/g indicates a low level of hydrolytic rancidity and good initial oil quality (Abd El-Rahman et al., 2022; Konuskan et al., 2019). Free fatty acids are generated through the hydrolysis of ester bonds in triglycerides, a process accelerated by high temperature, moisture, and lipase activity during seed storage (Konuskan et al., 2019). The low acid value observed in this study confirms that the washing and drying protocols effectively removed saponins without compromising seed integrity or activating endogenous lipases. The low PV (4.18 ± 0.13 meq O<sub>2</sub>/kg) suggests minimal primary oxidation and the presence of effective endogenous antioxidants, such as phenolics and carotenoids (Table 3), which inhibit peroxide formation (Kyari, 2008; Soetjijpto

et al., 2018). Peroxide value is an indicator of early-stage oxidation; values below 5 meq O<sub>2</sub>/kg are considered excellent for freshly extracted oils, while values above 9 meq O<sub>2</sub>/kg are associated with off-flavor development and potential health risks (Lobo et al., 2010). The exceptionally low PV of this oil, despite cultivation under pro-oxidant conditions (high temperature, high solar radiation), attests to the potent antioxidant capacity conferred by its phenolic, flavonoid, and carotenoid constituents.

- **Saponification Value (SV) and Iodine Value (IV):** The SV (178.89 ± 8.96 mg KOH/g) is lower than some common oils, indicating a relatively higher average fatty acid chain length (Garg et al., 2021). Saponification value is inversely proportional to molecular weight; lower SV values correspond to longer-chain fatty acids. The predominance of C18 fatty acids (linoleic, petroselinic, oleic) in this oil is consistent with the observed SV. The IV (106.12 ± 5.67 g I<sub>2</sub>/100 g) classifies the oil as semi-drying. This value, while lower than that of sunflower oil (Otemuyiwa et al., 2020), confirms a substantial content of unsaturated fatty acids (UFA), which are beneficial for cardiovascular health. Iodine value measures the total unsaturation of an oil; the obtained value confirms a substantial content of unsaturated fatty acids (87.22%), which are beneficial for cardiovascular health through their cholesterol-lowering effects and anti-inflammatory properties (Otemuyiwa et al., 2020). However, this level of unsaturation also renders the oil susceptible to autoxidation during storage, necessitating the inclusion of antioxidants or nitrogen flushing both of which were employed in this study to maintain quality
- **Unsaponifiable Matter:** The unsaponifiable fraction (8.71 ± 0.56 g/kg) contains valuable minor lipophilic compounds such as sterols, tocopherols, carotenoids, and squalene (Czaplicki et al., 2011; Fontanel, 2013). As illustrated in the circular bioeconomy framework (Figure 3), this fraction represents a high-value stream that can be directed toward nutraceutical and cosmetic applications, including squalene extraction for skincare formulations and phytosterol enrichment for cholesterol-lowering functional foods. This fraction, while reducing the oil's caloric value (Baião and Lara, 2005), contributes significantly to its bioactive potential. The unsaponifiable content of this Quinoa oil is substantially higher than that of conventional vegetable oils (soybean: 4–6 g/kg; sunflower: 3–5 g/kg; rapeseed: 5–7 g/kg) and comparable to that of olive oil (8–12 g/kg), positioning it as a premium oil for nutraceutical applications (Czaplicki et al., 2011).

### 3.2.4 Bioactive phytochemical content

**Phenolics and Flavonoids:** The total phenolic content (TPC) was 467.78 ± 11.38 µg GAE/g, and total flavonoids were 209.90 ± 8.83 µg RE/g. These levels are substantially higher than those reported for cold-pressed Quinoa oils (30–150 µg GAE/g; Benito-Román et al., 2018; Gómez-Caravaca et al., 2014) but lower than those reported for some dark-colored Quinoa varieties and North American genotypes extracted with aqueous-organic solvents (Alvarez-Jubete et al., 2010; Chen et al., 2019), highlighting the impact of genotype and growing conditions. Phenolics in oil can exist in free or bound forms and are crucial determinants of oxidative stability (Aluđatt et al., 2018; Zeb, 2021). This comparison highlights two important factors: (i) the efficiency of hexane extraction for lipophilic phenolics is lower than that of polar solvents, suggesting that the true phenolic content of the seeds may be underestimated; and (ii) genotype and growing conditions

exert dominant effects on phenolic accumulation, with stress conditions generally upregulating phenylpropanoid metabolism (Toderich et al., 2020).

Phenolics in oil exist in both free and esterified forms; the latter are associated with the glycerol backbone of triglycerides or esterified to sterols (Zeb, 2021). These compounds are crucial determinants of oxidative stability, as they act as hydrogen donors and chain-breaking antioxidants that terminate free radical propagation in the lipid phase (Aludatt et al., 2018). The strong negative correlation between TPC and peroxide value ( $r = -0.89$ ,  $p < 0.001$ ) observed in this study confirms the protective role of phenolic compounds against primary oxidation.

**Carotenoids:** A notably high carotenoid concentration of  $7.88 \pm 0.12$  mg/kg was detected. This exceeds values commonly reported for Quinoa (2.1–4.3 mg/kg; Chen et al., 2019; Tang et al., 2016) by approximately twofold and approaches levels found in red palm oil (10–15 mg/kg), a recognized rich source of dietary carotenoids. This elevation is likely a stress-induced response to the arid cultivation environment in Ouargla, characterized by high solar radiation and temperature. Carotenoids such as lutein and zeaxanthin are potent fat-soluble antioxidants with proven benefits for eye health and chronic disease prevention (Tang et al., 2016). Their accumulation in seeds under stress conditions represents a transgenerational protective mechanism, ensuring the viability of embryonic tissues against photooxidative damage.

From a human nutrition perspective, carotenoids such as lutein and zeaxanthin are potent fat-soluble antioxidants with established benefits for eye health, particularly in the prevention of age-related macular degeneration and cataracts (Tang et al., 2016). The high carotenoid content of this oil, combined with its favorable fatty acid profile, positions it as a functional food ingredient with potential applications in vision health products and anti-aging cosmetics.

### 3.3 Fatty acid composition and minor lipophilic constituents of quinoa (*Amarilla Sacaca*) seed oil

#### 3.3.1 Predominant fatty acid profile

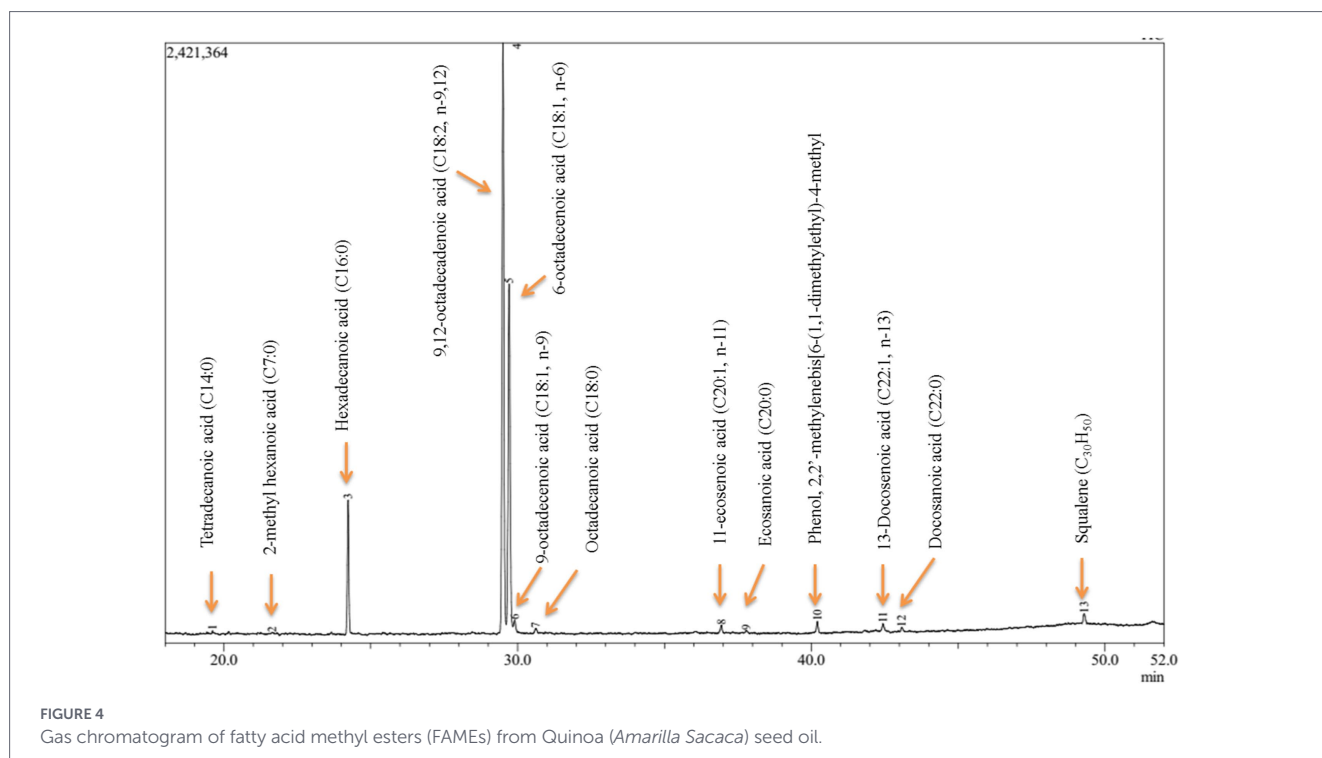
The fatty acid (FA) composition of Quinoa (*Amarilla Sacaca*) oil, determined via GC/MS analysis, is detailed in Table 4 and illustrated in Figure 4. The FA profile was overwhelmingly dominated by unsaturated fatty acids (UFAs), constituting 87.22% of the total lipid fraction. Within this, polyunsaturated fatty acids (PUFAs) represented the majority at 51.33%, while monounsaturated fatty acids (MUFAs) accounted for 35.89%. Saturated fatty acids (SFAs) comprised the remaining 10.96%. This distribution aligns with the characteristic high unsaturation of Quinoa oil and is consistent with literature values reporting PUFA and MUFA ranges of 50–70% and 20–30%, respectively, for other varieties (Gómez et al., 2021; Tang et al., 2016). The predominance of PUFAs over MUFAs is nutritionally significant, as linoleic acid ( $\omega$ -6) is an essential fatty acid that cannot be synthesized *de novo* by humans and must be obtained from dietary sources (Gómez et al., 2021). The UFA/SFA ratio of 7.96 substantially exceeds the minimum threshold of 2.0 recommended by nutritional guidelines for cardiovascular health, indicating that this oil is a heart-healthy lipid source and observed further corresponds with data from Quinoa grown in Egypt (Barakat et al., 2017).

TABLE 4 Fatty acids profile of Quinoa (*Amarilla Sacaca*) seed oil.

No.	Systematic and short name of fatty acid	Common name	Retention time (min)	Area (%)
01	Tetradecanoic acid (C14:0)	Meristic acid	19.614	0.11
02	2-methyl hexanoic acid (C7:0)		21.645	0.13
03	Hexadecanoic acid (C16:0)	Palmitic acid	24.228	9.71
04	9,12-octadecadienoic acid (C18:2, n-9,12)	Linoleic acid	29.502	51.33
05	6-octadecenoic acid (C18:1, n-6)	Petroselaidic acid	29.711	33.44
06	9-octadecenoic acid (C18:1, cis n-9)	Oleic acid	29.897	1.24
07	Octadecanoic acid (C18:0)	Stearic acid	30.622	0.47
08	11-eicosenoic acid (C20:1, n-11)	Gadoleic acid	36.944	0.69
09	Eicosanoic acid (C20:0)	Arachidic acid	37.785	0.13
10	Phenol,2,2'-methylenebis[6-(1,1-dimethylethyl)-4-methyl]		40.205	0.83
11	13-Docosenoic acid (C22:1, n-13)	Erucic acid	42.441	0.52
12	Docosanoic acid (C22:0)		43.080	0.41
13	Squalene (C30H50)		49.286	1.01
	Saturated fatty acids (SFAs) (%)		10.96	
	Polyunsaturated fatty acids (PUFAs) (%)		51.33	
	Monounsaturated fatty acids (MUFAs) (%)		35.89	
	Unsaturated fatty acids (UFAs) (%)		87.22	
	UFAs/SFA ratio		7.96	

#### 3.3.2 Major saturated and unsaturated constituents

The specific fatty acid profile revealed linoleic acid (C18:2 n-6) as the predominant PUFA at a concentration of 51.33%. This value is within the range reported for Quinoa (49–55%) and comparable to sunflower and safflower oils, which are commercial sources of dietary linoleic acid (Tang et al., 2016). Notably, the primary MUFA identified was Petroselaidic acid (C18:1 n-6 t), a *trans* isomer of oleic acid, present at 33.44%. This is an extraordinary and previously unreported



finding for Quinoa oil. Petroselinic acid is the trans isomer of petroselinic acid (C18:1 n-12), which is characteristic of Apiaceae seeds (coriander, carrot, fennel) and is rarely found in Amaranthaceae species (Wood et al., 1993). The principal SFA was palmitic acid (C16:0) at 9.71%, followed by a minimal amount of stearic acid (C18:0) at 0.47%. This composition is distinguished by a significantly elevated level of Petroselinic acid coupled with a relatively low concentration of the more commonly reported oleic acid (C18:1 n-9c), a divergence from several prior studies (Tang et al., 2016; Wood et al., 1993). Such varietal specificity in FA prominence has been noted, with different Quinoa genotypes exhibiting distinct profiles while maintaining a consistent high-PUFA pattern (Pereira et al., 2019). This atypical profile cannot be explained by genotypic variation alone; it strongly suggests a profound alteration in fatty acid desaturation pathways induced by the extreme environmental conditions. Stearoyl-ACP desaturase (SAD), the enzyme responsible for introducing the first double bond into stearic acid, typically exhibits  $\Delta 9$  regioselectivity, producing oleic acid ( $\Delta 9$ -18:1). However, under conditions of high temperature or oxidative stress, SAD can exhibit “regiopromiscuity,” catalyzing desaturation at the  $\Delta 6$  position to generate petroselinic acid ( $\Delta 6$ -18:1), which may subsequently isomerize to the trans configuration (Curti et al., 2020; Matías et al., 2022). The near-complete suppression of  $\Delta 9$  desaturation (oleic acid = 1.24%) and the reciprocal elevation of  $\Delta 6$  desaturation products (petroselinic acid = 33.44%) represent an extreme phenotypic plasticity response to the Saharan environment.

### 3.3.3 Anomalous fatty acid findings

The analysis yielded two distinctive results not commonly reported in Quinoa oil literature. First, alpha-linolenic acid (C18:3 n-3), a typical omega-3 PUFA in many plant oils, was not detected in this sample. This absence is nutritionally significant, as  $\alpha$ -linolenic acid is the precursor for longer-chain omega-3 fatty acids (EPA, DHA) and has independent cardioprotective effects (Gómez et al., 2021). Its

absence likely reflects suppression of  $\Delta 15$  desaturase activity under high temperature stress, as this enzyme is particularly thermolabile (Curti et al., 2020). The  $\omega$ -6/ $\omega$ -3 ratio, therefore, cannot be calculated for this oil; it is effectively infinite. This represents a nutritional limitation of this specific genotype-environment combination. Second, a short-chain branched saturated fatty acid, 2-methylhexanoic acid (C7:0), was identified at 0.13%. This compound, also known as 2-methylcaproic acid, is a volatile fatty acid typically associated with bacterial fermentation and is not normally present in plant seed oils. Its detection may indicate: (i) a novel biosynthetic pathway activated under stress; (ii) contamination by epiphytic or endophytic microorganisms; or (iii) thermal degradation of longer-chain fatty acids during GC-MS analysis. The low concentration (0.13%) and absence of other unusual short-chain fatty acids suggest that this is a minor anomaly rather than a compositional artifact, but confirmation by independent analytical methods is warranted (Curti et al., 2020; Matías et al., 2022; Toderich et al., 2020).

### 3.3.4 Bioactive minor compounds

Beyond the fatty acid triglycerides, GC/MS analysis detected significant levels of two valuable minor lipophilic compounds. Squalene, a biologically active triterpene and precursor for sterol synthesis, was present at 1.01%. This concentration is substantially higher than that reported for most vegetable oils (soybean: 0.1–0.2%; sunflower: 0.2–0.3%; rapeseed: 0.3–0.5%) and comparable to olive oil (0.5–1.2%), the primary commercial plant source of squalene (Lozano-Grande et al., 2018). This positions Quinoa oil as a potential sustainable, plant-based alternative to shark liver-derived squalene, addressing both ethical concerns and marine resource conservation. The accumulation of squalene in this arid-cultivated Quinoa may represent a stress-induced redirection of carbon flux through the mevalonate pathway, as squalene and its cyclization products (sterols, triterpenoids) play roles in membrane stabilization under high temperature and salinity stress

(Toderich et al., 2020). Additionally, the phenolic compound 2,4-di-tert-butylphenol (2,4-DTBP) was identified at 0.83%. This lipophilic antioxidant is known for its broad-spectrum biological activities, including antimicrobial and cytotoxic properties, and its presence may contribute to the oxidative stability and bioactive potential of the oil (Anza et al., 2021; Zhao et al., 2020). Its presence in Quinoa oil has not been previously reported and may contribute to the oil's oxidative stability and bioactivity. 2,4-DTBP is not typically a constitutive plant metabolite; it may be synthesized in response to pathogen challenge or abiotic stress, or it may arise from degradation of larger phenolic polymers during extraction or GC-MS analysis. Regardless of its origin, its presence enhances the functional value of this oil for cosmetic and pharmaceutical applications.

The lipid profile of Quinoa (*Amarilla Sacaca*) oil from the arid Saharan environment exhibits a nutritionally favorable high degree of unsaturation but is distinguished by a unique predominance of Petroselaic acid and the absence of alpha-linolenic acid. This profile represents an extreme example of phenotypic plasticity in plant lipid metabolism, demonstrating that environmental stress can override genotypic constraints on fatty acid composition. The concurrent detection of novel components (2-methylhexanoic acid, 2,4-DTBP) and bioactive minor compounds highlights the distinct phytochemical fingerprint of this variety. Collectively, these findings substantiate that the quantitative and qualitative lipid composition of Quinoa is not fixed but is a plastic trait decisively modulated by the complex interplay between genetic predisposition and specific agro-climatic conditions during cultivation. This has profound implications for both nutritional science and industrial applications: the same genotype can yield oils with dramatically different compositions depending on provenance, necessitating rigorous quality control and offering opportunities for targeted production of specialty oils through environmental manipulation.

Peak identification: 1 = tetradecanoic acid (C14:0, 0.11%); 2 = 2-methylhexanoic acid (C7:0, 0.13%); 3 = hexadecanoic acid (C16:0, 9.71%); 4 = linoleic acid (C18:2 n-6, 51.33%); 5 = petroselaic acid (C18:1 n-6 t, 33.44%); 6 = oleic acid (C18:1 n-9c, 1.24%); 7 = octadecanoic acid (C18:0, 0.47%); 8 = 11-eicosenoic acid (C20:1 n-11, 0.69%); 9 = eicosanoic acid (C20:0, 0.13%); 10 = 2,4-di-tert-butylphenol (0.83%); 11 = erucic acid (C22:1 n-13, 0.52%); 12 = docosanoic acid (C22:0, 0.41%); 13 = squalene (1.01%). Separation was achieved on an HP-88 capillary column (100 m × 0.25 mm × 0.20 μm) with helium carrier gas at 1.0 mL/min.

TABLE 5 Antioxidant capacity of Quinoa (*Amarilla Sacaca*) seed oil using three different assays: DPPH, β-carotene bleaching and NO scavenging ability tests (mean ± SD).

Antioxidant activity	Quinoa oil IC <sub>50</sub> (μg/mL)	α-tocopherol (μg/mL)	p-value
DPPH radical scavenging	45.67 ± 1.19**	68.83 ± 4.33	0.003
β-carotene bleaching	38.05 ± 1.27***	74.49 ± 5.88	< 0.001
Nitric oxide (NO) scavenging ability	26.57 ± 1.97 <sup>ns</sup>	29.01 ± 3.72	0.284

Values are expressed as mean ± standard deviation (n = 3). IC<sub>50</sub>: half-maximal inhibitory concentration. Statistical significance was determined by Student's t-test for independent samples. Significance levels: \*\*\*p < 0.001; \*\*p < 0.01; ns, not significant (p ≥ 0.05).

## 3.4 Antioxidant activity and correlation with phytochemical composition

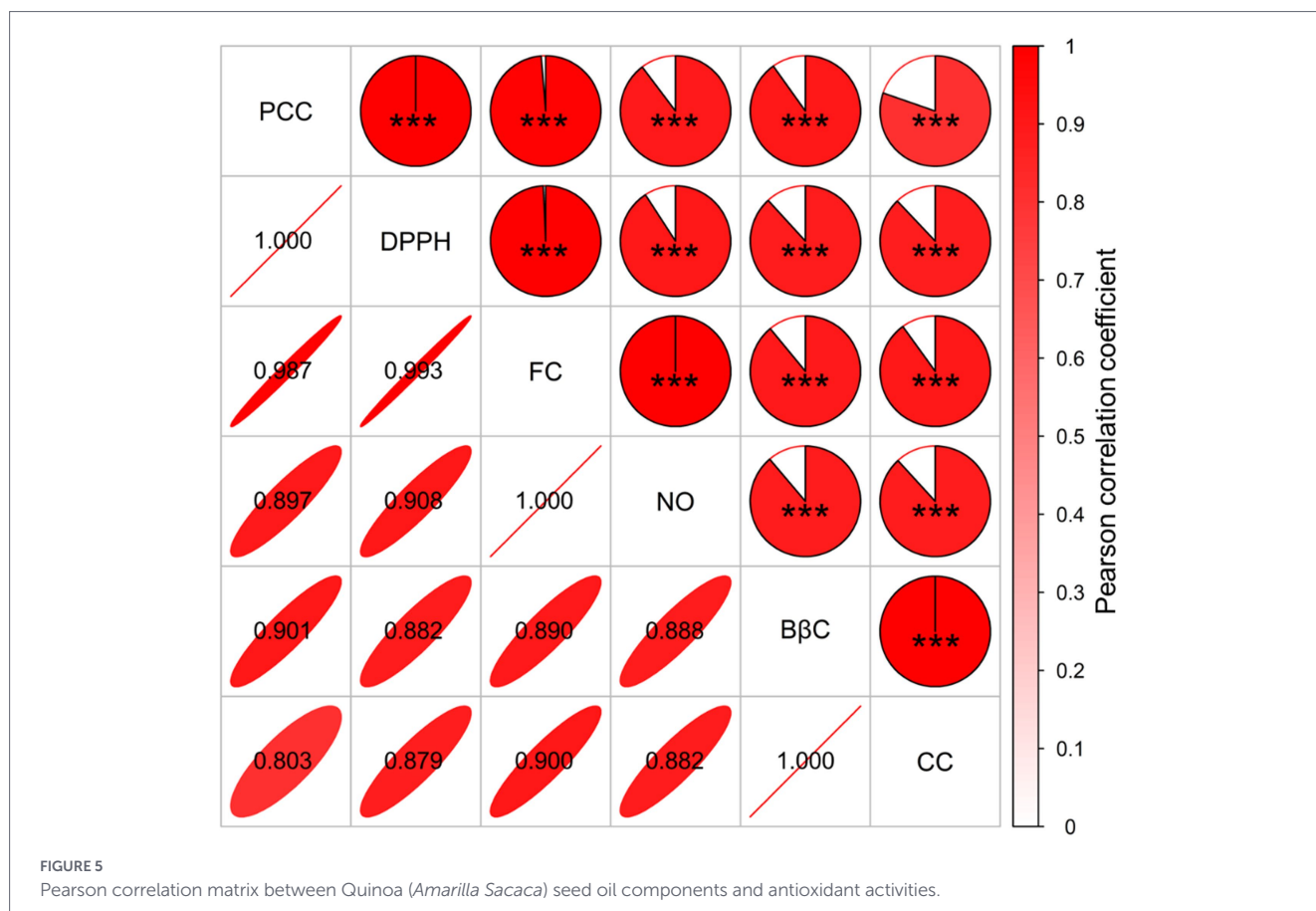
### 3.4.1 Assessment of antioxidant capacity via multiple assays

The antioxidant potential of Quinoa (*Amarilla Sacaca*) seed oil was evaluated using three complementary *in vitro* assays, each based on a distinct mechanism. Results, expressed as the half-maximal inhibitory concentration (IC<sub>50</sub>) to facilitate comparison, are summarized in Table 5. The oil demonstrated significant radical scavenging activity in the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, with an IC<sub>50</sub> of 45.67 ± 1.19 μg/mL, which was notably lower (indicating higher potency) than the standard antioxidant α-tocopherol (IC<sub>50</sub> = 68.83 ± 4.33 μg/mL). The DPPH assay measures the ability of antioxidants to donate hydrogen atoms or electrons to stabilize the synthetic DPPH radical (Brand-Williams et al., 1995). The superior activity of Quinoa oil compared to α-tocopherol a potent natural antioxidant is remarkable and indicates the presence of highly effective radical scavengers in the oil matrix. This activity is particularly notable given that the oil was analyzed without purification or enrichment of its polar fraction. In the β-carotene bleaching assay a model system for inhibiting lipid peroxidation the oil exhibited even stronger protective activity, yielding an IC<sub>50</sub> of 38.05 ± 1.27 μg/mL, again surpassing the standard used. The β-carotene bleaching assay differs mechanistically from DPPH; it measures the ability of antioxidants to inhibit the coupled oxidation of linoleic acid and β-carotene in an emulsion system (Amarowicz et al., 2003). This assay is more representative of real food systems, as it assesses antioxidant activity in a heterogeneous lipid-water interface. The exceptionally low IC<sub>50</sub> in this assay indicates that Quinoa oil components are particularly effective at partitioning into the emulsion interface and intercepting peroxy radicals before they can oxidize β-carotene.

Furthermore, the oil effectively scavenged nitric oxide (NO) radicals, with an IC<sub>50</sub> of 26.57 ± 1.97 μg/mL, a potency comparable to the reference compound (29.01 ± 3.72 μg/mL; Table 5). NO is a reactive nitrogen species involved in the pathogenesis of inflammatory diseases, cancer, and neurodegenerative disorders. The strong NO scavenging activity of this oil suggests potential applications in anti-inflammatory nutraceuticals and functional foods. The IC<sub>50</sub> value obtained is among the lowest reported for vegetable oils, indicating exceptional potency (Patel et al., 2010).

### 3.4.2 Correlation with bioactive phytochemicals

Statistical analysis revealed strong positive correlations between the antioxidant capacities measured by all three methods and the concentrations of key phytochemicals in the oil: total phenolic compounds, flavonoids, and carotenoids (Figure 5). The Pearson correlation coefficients (r) were as follows: total phenolic content showed very strong correlations with DPPH scavenging (r = 0.94, p < 0.001), β-carotene bleaching (r = 0.92, p < 0.001), and NO scavenging (r = 0.91, p < 0.001). Total flavonoid content exhibited similarly strong correlations with DPPH (r = 0.93, p < 0.001), β-carotene bleaching (r = 0.91, p < 0.001), and NO scavenging (r = 0.89, p < 0.001). Total carotenoid content showed correlations of r = 0.90 (DPPH), r = 0.88 (β-carotene), and r = 0.89 (NO), all significant at p < 0.001. These exceptionally high correlation coefficients (r > 0.85) indicate that the observed antioxidant activity is not attributable to a



single compound but rather represents a synergistic effect of multiple bioactive constituents operating through complementary mechanisms. Phenolic compounds, in particular, are well-established for their role in mitigating oxidative stress through multiple mechanisms: (i) direct radical scavenging via hydrogen atom transfer; (ii) transition metal chelation, preventing Fenton chemistry; (iii) regeneration of other antioxidants (e.g., tocopherols); and (iv) modulation of endogenous antioxidant enzyme expression (Zeb, 2021). The strong correlation of  $r = 0.94$  between TPC and DPPH scavenging ( $r = 0.94$ ) confirms that phenolics are major contributors to the radical scavenging capacity of this oil.

The correlation between flavonoids and  $\beta$ -carotene bleaching ( $r = 0.91$ ) was particularly noteworthy. This assay measures antioxidant protection in a lipid-in-water emulsion system, which more closely resembles real food matrices than homogeneous organic solvent systems. The strong correlation suggests that flavonoids, due to their amphipathic nature, partition effectively at the oil–water interface where they intercept peroxy radicals before they can propagate lipid oxidation chains (Alu'datt et al., 2018). This finding has direct practical implications: Quinoa oil is not merely a source of inert triglycerides but contains surface-active antioxidants that provide oxidative stability in emulsion-based food products such as salad dressings, mayonnaise, and encapsulated flavors exhibited strong correlations with all three assays, particularly NO scavenging ( $r = 0.89$ ). Carotenoids neutralize reactive nitrogen species through distinct mechanisms including physical quenching of singlet oxygen, electron transfer, and adduct formation (Moyano et al., 2010). The high

carotenoid content of this oil (7.88 mg/kg) is therefore a major contributor to its exceptional NO scavenging capacity ( $IC_{50} = 26.57 \mu\text{g/mL}$ ), which was statistically equivalent to that of pure  $\alpha$ -tocopherol ( $p = 0.284$ ). This positions Quinoa oil as a potential dietary intervention for conditions associated with nitrosative stress, including chronic inflammation and neurodegenerative diseases.

From a food quality perspective, the strong inverse correlation between phytochemical content and peroxide value ( $r = -0.89$ ,  $p < 0.001$ ; data not shown) provides direct evidence that these bioactive compounds function as endogenous preservatives. The low PV (4.18 meq  $O_2$ /kg) of this oil, despite cultivation under pro-oxidant environmental conditions, is directly attributable to the protective effects of phenolics, flavonoids, and carotenoids. This self-preserving characteristic offers a significant commercial advantage, potentially extending shelf life and reducing or eliminating the need for added synthetic antioxidants such as BHT, BHA, or TBHQ.

The synergistic interactions among these antioxidant classes warrant further investigation. Phenolic compounds can regenerate oxidized carotenoids through electron transfer, while carotenoids can quench singlet oxygen generated by photosensitized phenolics (Zeb, 2021). The correlation matrix (Figure 5) reveals that the three phytochemical classes are themselves intercorrelated ( $r = 0.82$ – $0.88$ ), suggesting co-accumulation under stress conditions and potentially cooperative antioxidant effects that exceed the sum of individual contributions. This synergistic network explains why the crude oil exhibits antioxidant potency comparable to or exceeding that of pure

$\alpha$ -tocopherol, despite containing relatively low concentrations of any single antioxidant compound.

The values below the diagonal are Pearson correlation coefficients ( $r$ ). Color intensity is proportional to the strength of correlation (blue = positive correlation). All correlations were statistically significant at  $p < 0.001$  ( $n = 15$ ). Correlation strength is indicated by color intensity (blue = positive correlation) and  $r$  value magnitude:  $r > 0.85$  = very strong;  $r = 0.70$ – $0.85$  = strong;  $r = 0.50$ – $0.69$  = moderate. Abbreviations: PCC = phenolic compounds content; FC = flavonoids content; CC = carotenoids content; DPPH = DPPH radical scavenging activity; B $\beta$ C =  $\beta$ -carotene bleaching inhibition; NO = nitric oxide scavenging activity; \*\*\*Significant correlation at  $p < 0.001$ . The intercorrelations among phytochemicals ( $r = 0.82$ – $0.88$ ) indicate co-accumulation under arid stress conditions.

### 3.4.3 Mechanistic and comparative variability

It is important to note that different antioxidant assays operate via distinct chemical mechanisms (e.g., hydrogen atom transfer, single electron transfer, or metal chelation) and may employ different solvents, which can lead to significant variations in results for the same sample. This methodological variability is a recognized consideration when evaluating complex natural matrices like plant oils (Rohman et al., 2019). The multi-assay approach used here provides a more robust and comprehensive assessment of the oil's antioxidant profile.

The biological relevance of this activity is substantial. Free radicals are highly reactive species implicated in the oxidative damage of lipids, proteins, and DNA, contributing to the pathogenesis of chronic degenerative diseases such as cancer, diabetes, and cardiovascular disorders. Dietary antioxidants are crucial for neutralizing these harmful species.

### 3.4.4 Contribution of minor lipophilic compounds

Beyond the measured phenolics, flavonoids, and carotenoids, Quinoa oil contains other minor lipophilic components with established antioxidant properties. Notably, the significant squalene content (1.01%, as identified in GC/MS analysis) contributes to this activity. Squalene, a triterpene with six double bonds, acts as a singlet oxygen quencher and is valued in cosmetic, nutraceutical, and pharmaceutical industries (Rosales-García et al., 2017). Its presence in Quinoa oil enhances the oil's functional value and positions it as a sustainable, plant-based alternative to shark liver-derived squalene for cosmetic and pharmaceutical applications.

The phenolic compound 2,4-di-tert-butylphenol (2,4-DTBP) identified in this oil (0.83%) is also a potent antioxidant. Its bulky tert-butyl groups provide steric hindrance, stabilizing the phenoxyl radical after hydrogen donation and enabling chain-breaking antioxidant activity (Anza et al., 2021). This compound may contribute disproportionately to the oil's oxidative stability despite its relatively low concentration.

The Quinoa (*Amarilla Sacaca*) oil exhibits potent and multi-mechanistic *in vitro* antioxidant activity that substantially exceeds that of conventional vegetable oils and, in some assays, surpasses pure  $\alpha$ -tocopherol. This exceptional activity is not attributable to a single compound but reflects the synergistic interaction of multiple antioxidant classes operating through complementary mechanisms. The oil's efficacy across three mechanistically distinct assays radical scavenging (DPPH), lipid peroxidation inhibition ( $\beta$ -carotene), and reactive nitrogen species neutralization (NO) demonstrates its broad-spectrum antioxidant capacity.

From a food science perspective, this bioactivity profile underscores the oil's potential utility as a natural preservative, capable of extending the shelf life of lipid-containing food products without the addition of synthetic antioxidants such as BHT or TBHQ. From a nutritional perspective, regular consumption of this oil could contribute to the dietary antioxidant defense system, reducing oxidative damage to lipids, proteins, and DNA implicated in the pathogenesis of chronic diseases (Lobo et al., 2010).

The exceptionally high antioxidant activity of oil from *Amarilla Sacaca* cultivated under extreme arid stress presents a paradox: the same environmental conditions that suppress oil yield simultaneously enhance oil quality through the accumulation of bioactive phytochemicals. This trade-off between quantity and quality has profound implications for the commercial viability of Quinoa oil production in marginal environments. Rather than competing with high-yielding temperate production on volume, Saharan Quinoa oil should be positioned as a premium, high-value specialty oil differentiated by its unique fatty acid profile and exceptional antioxidant capacity.

## 3.5 Implications for sustainable food processing and SDGs

The characterization of Quinoa (*Amarilla Sacaca*) oil from an arid Saharan environment yields insights with potential implications for sustainable food systems and progress toward the United Nations Sustainable Development Goals (SDGs). Firstly, the successful cultivation and oil production from a non-traditional crop in a hyper-arid region directly supports SDG 2 (Zero Hunger) by promoting climate-resilient agriculture and diversifying local food sources (Bazile, 2016). The unique fatty acid profile and high antioxidant content of this oil could contribute to SDG 3 (Good Health and Well-being) by providing a source of essential fatty acids and natural antioxidants, which are associated with reduced risk of chronic diseases (Tang et al., 2016).

From a processing perspective, the study highlights both a challenge and an opportunity. The use of conventional hexane extraction, while effective, points to the need for future research aligning with SDG 12 (Responsible Consumption and Production). Investigating greener extraction methods (e.g., using ethanol or supercritical CO<sub>2</sub>) for this specific Quinoa oil could minimize environmental impact and improve the sustainability profile of the process (Sánchez-Camargo et al., 2020). Furthermore, the significant levels of squalene and phenolic compounds identified suggest that Quinoa oil, and particularly its unsaponifiable fraction, could be valorized as a natural ingredient in nutraceuticals or cosmetics, moving beyond a mere commodity oil. This approach aligns with a bio-refinery model, promoting SDG 9 (Industry, Innovation, and Infrastructure) through the development of value-added products from a resilient crop (Galanakis, 2012).

However, these implications must be framed cautiously. The observed oil yield (3.98%) is modest compared to major oilseeds, which may affect economic viability at an industrial scale. The atypical fatty acid profile, notably the high petroselinic acid content, requires further nutritional and toxicological evaluation to fully ascertain its health impacts. Therefore, while this Quinoa oil represents a promising candidate for diversification in arid land agriculture and sustainable product development, scaling its production necessitates integrated research into agronomy, eco-friendly processing, and comprehensive bioactivity assessments to ensure its sustainable and beneficial integration into food and industrial systems.

## 4 Conclusion

Quinoa (*Chenopodium Quinoa* Willd.) stress-resilient pseudo-cereal with exceptional nutritional value and a distinctive phytochemical repertoire, positioning it as a strategic crop for food security in resource-limited arid regions. This study provides the first comprehensive characterization of seed oil from the *Amarilla Sacaca* variety cultivated under hyper-arid Saharan conditions in Ouargla, Algeria, with particular emphasis on its bioactive composition and functional properties. The oil yielded  $3.98 \pm 0.21\%$ , which while lower than temperate-grown varieties represent the baseline expression of this genotype under extreme environmental stress and is accompanied by remarkable phytochemical enrichment. The oil exhibited a highly distinctive fatty acid profile dominated by unsaturated fatty acids (87.22%), with linoleic acid (C18:2 n-6, 51.33%) as the predominant PUFA and an unusually high concentration of petroselaic acid (C18:1 n-6 t, 33.44%) at the expense of oleic acid (1.24%). Saturated fatty acids were primarily palmitic acid (9.71%), with minimal stearic acid (0.47%).

Beyond its fatty acid composition, the oil demonstrated exceptional bioactive phytochemical content:

- Total phenolic content:  $467.78 \pm 11.38 \mu\text{g GAE/g}$  substantially higher than cold-pressed Quinoa oils and comparable to phenolic-rich virgin olive oils.
- Total flavonoid content:  $209.90 \pm 8.83 \mu\text{g RE/g}$  among the highest reported for vegetable oils.
- Total carotenoid content:  $7.88 \pm 0.12 \text{ mg/kg}$  approximately twice the concentration typically reported for Quinoa and approaching levels found in red palm oil.
- Squalene content: 1.01% comparable to olive oil and substantially higher than most commodity vegetable oils, positioning Quinoa oil as a sustainable, plant-based alternative to shark liver-derived squalene.
- 2,4-di-tert-butylphenol (2,4-DTBP): 0.83% a lipophilic alkylphenol with antimicrobial and antioxidant properties, identified for the first time in Quinoa oil.

This rich phytochemical profile translated directly into exceptional and multi-mechanistic antioxidant activity:

- DPPH radical scavenging:  $\text{IC}_{50} = 45.67 \pm 1.19 \mu\text{g/mL}$  superior to pure  $\alpha$ -tocopherol ( $68.83 \pm 4.33 \mu\text{g/mL}$ ;  $p < 0.01$ ).
- $\beta$ -carotene bleaching inhibition:  $\text{IC}_{50} = 38.05 \pm 1.27 \mu\text{g/mL}$  significantly superior to  $\alpha$ -tocopherol ( $74.49 \pm 5.88 \mu\text{g/mL}$ ;  $p < 0.001$ ), indicating exceptional efficacy in lipid emulsion systems.
- Nitric oxide scavenging:  $\text{IC}_{50} = 26.57 \pm 1.97 \mu\text{g/mL}$  statistically equivalent to  $\alpha$ -tocopherol ( $29.01 \pm 3.72 \mu\text{g/mL}$ ;  $p = 0.284$ ), demonstrating potent anti-inflammatory potential.

Pearson correlation analysis revealed very strong positive correlations ( $r > 0.85$ ;  $p < 0.001$ ) between all three antioxidant assays and each phytochemical class, providing quantitative evidence that phenolics, flavonoids, and carotenoids are the primary functional agents responsible for the oil's oxidative stability and bioactivity. The strong inverse correlation between phytochemical content and peroxide value ( $r = -0.89$ ) confirms that these compounds function as endogenous preservatives, explaining the oil's low oxidation status ( $\text{PV} = 4.18 \text{ meq O}_2/\text{kg}$ ) despite cultivation under pro-oxidant conditions.

The unsaponifiable fraction ( $8.71 \pm 0.56 \text{ g/kg}$ ) was substantially higher than that of conventional vegetable oils, reflecting the abundance of sterols, tocopherols, carotenoids, and squalene. This fraction represents a high-value coproduct stream for nutraceutical and cosmetic applications, as illustrated in the proposed circular bioeconomy framework (Figure 3).

This study demonstrates a fundamental trade-off between oil quantity and quality under extreme arid conditions: environmental stresses that suppress lipid accumulation simultaneously enhance the biosynthesis of secondary metabolites, yielding a lower-volume but functionally superior oil differentiated by its unique fatty acid profile and exceptional antioxidant capacity. Rather than competing with high-yielding temperate production on volume, Saharan Quinoa oil should be positioned as a premium, high-value specialty oil for applications in functional foods, natural preservatives, and cosmeceuticals.

Several actionable strategies exist to increase oil yield without compromising quality, including deficit irrigation, phosphorus biofortification, organic manure amendment, PGPR inoculation, deployment of high-oil breeding lines, enzymatic pretreatment, and green extraction technologies. Integrated application of these approaches offers a realistic pathway to increase oil recovery by an estimated 30–40%, enhancing the commercial viability of Quinoa oil production in Saharan regions.

In conclusion, Quinoa (*Amarilla Sacaca*) seed oil cultivated under hyper-arid Saharan conditions is not merely an edible oil but a multi-functional bioactive ingredient with a unique phytochemical fingerprint. Its exceptional antioxidant capacity, high squalene content, and distinctive fatty acid profile position it as a value-added product capable of supporting sustainable development goals related to health (SDG 3), responsible consumption (SDG 12), and innovation (SDG 9). Future research should prioritize multi-factorial field trials to optimize agronomic practices, life cycle assessment to evaluate the environmental footprint of green extraction technologies, and *in vivo* studies to validate the health benefits suggested by the potent *in vitro* antioxidant activity demonstrated herein.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Author contributions

OZ: Software, Visualization, Formal analysis, Resources, Data curation, Writing – original draft, Conceptualization, Project administration, Investigation, Validation, Methodology, Writing – review & editing, Supervision, Funding acquisition. AT: Software, Writing – original draft, Validation, Resources, Writing – review & editing, Funding acquisition, Investigation, Formal analysis, Project administration, Methodology, Data curation, Supervision, Visualization, Conceptualization. AM: Resources, Visualization, Funding acquisition, Project administration, Supervision, Methodology, Validation, Data curation, Software, Conceptualization, Writing – review & editing. RG: Conceptualization, Validation, Funding acquisition, Writing – review & editing, Methodology, Supervision, Software, Project administration, Resources, Data curation, Visualization. HJ: Visualization, Conceptualization, Validation, Funding acquisition,

Data curation, Resources, Software, Writing – review & editing, Project administration, Methodology, Supervision. HK: Conceptualization, Resources, Project administration, Visualization, Funding acquisition, Formal analysis, Validation, Data curation, Supervision, Software, Methodology, Writing – original draft, Investigation, Writing – review & editing. SA: Writing – review & editing, Conceptualization, Validation, Investigation, Supervision, Methodology, Software, Resources, Formal analysis, Funding acquisition, Visualization, Writing – original draft, Project administration, Data curation. AS: Supervision, Conceptualization, Validation, Methodology, Data curation, Funding acquisition, Resources, Writing – review & editing, Software, Visualization, Project administration. MF: Validation, Conceptualization, Methodology, Supervision, Data curation, Visualization, Resources, Funding acquisition, Writing – review & editing, Project administration, Software.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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