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# Phytochemical Characterization and Evaluation of Contaminants in the Processed Products of Organically Produced *Moringa oleifera* from the Niger Sahel

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## Abstract

In the Nigerien Sahel, *Moringa oleifera* processing presents a valuable economic opportunity for local communities; however, product quality and safety are closely linked to the processing methods employed. This study investigated the phytochemical composition and contamination markers of Moringa leaf extracts (MLE) and Moringa seed oil (MSO) using GC–MS analysis. The results demonstrated a significant influence of processing on chemical profiles. Fatty acids dominated the compositions (32.93%). Room-dried MLE was enriched in esters (39.9%) and terpenes (18.84%), while solar-dried samples showed elevated aldehyde content (25.3%), reflecting lipid oxidation. Sun-dried extracts uniquely contained N,N-dimethyltryptamine and phenylquinonine, indicating the presence of photochemically induced metabolites. In MSO, fatty acids were predominant (72.76%), and extraction conditions affected the stability of bioactive compounds. Cold extraction preserved thermolabile molecules such as squalene (0.29%), which were absent from heat-treated samples. Contamination markers were also identified, including di-n-octyl phthalate (1.68%) in room-dried MLE and 2-dimethylaminoethyl methacrylate (2%) in Solar dryer-dried extracts. Industrial contaminants, such as 10-undecenoyl chloride (3.68%) and 13-oxabicyclo[10.1.0]tridecane (5.85%), were detected in the control MSO. Overall, GC–MS profiling revealed that each processing method yields a distinct phytochemical fingerprint with specific nutritional, pharmacological, and safety implications. These findings highlight the need for optimized processing and packaging strategies to enhance the quality and market value of Moringa-based products in the Sahel.

**Keywords**: Chromatography, Infestation, Processing, Sahel


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## Introduction

*Moringa oleifera* is a multipurpose plant native to subtropical regions, now widely cultivated across tropical and arid zones, particularly in Africa, Asia, and South America (El Bilali *et al.*, 2024). In the Nigerien Sahel, where food insecurity and chronic malnutrition remain significant challenges, its cultivation offers a promising alternative within agroforestry systems. The species is valued primarily for its leaves, which are rich in essential nutrients and widely used in human diets, and for its seeds, which yield a high-quality edible oil (Uzair, 2021; Latla, 2020). Moringa leaves, often regarded as the most nutritious part of the plant, provide key vitamins (B, C, K, and beta-carotene/provitamin A), minerals, and proteins, making them an essential dietary resource (Ndong, Wade, Dossou, Guiro, & Gning, 2007; Luoh, Sheu, Wu, & Yang, 2015; Tamilselvi & Arumugam, 2019). Beyond its nutritional value, Moringa cultivation and marketing generate substantial income and play an increasingly important role in local economies (Hassoumi, 2017; Outani, Adamou, Mahamadou, & Delmas, 2023; Mahamane, Amadou, & Moussa, 2025).

However, conventional farming systems often rely heavily on agrochemicals, raising concerns regarding the safety and quality of Moringa-derived products. Valorizing locally cultivated *M. oleifera*—whether for nutritional or pharmacological applications could therefore enhance community resilience and reduce dependence on humanitarian aid (Djeneba, Dembélé, Touré, & Iknane, 2023). Yet, the composition and quality of bioactive compounds in Moringa products are influenced by multiple factors, including cultivation practices, post-harvest processing, and storage conditions. Such variability has important implications for their nutritional efficacy and pharmacological safety (Djeneba *et al.*, 2023). Notably, a recent study reported that 68% of Moringa samples exceeded the maximum permissible limits for pesticide residues (Adeyeye *et al*., 2020).

In this context, profiling the chemical composition of processed Moringa leaves and seed oils is essential. Particular attention must be paid to assessing the effects of agricultural practices, particularly organic production systems, to ensure both product quality and consumer safety. Accordingly, this study aims to characterize the chemical profile of extracts from organically produced dried leaves and seed oil of *M. oleifera* in the Nigerien Sahel. Using gas chromatography coupled with mass spectrometry (GC-MS), the study evaluates both nutritional constituents and contaminant marker compounds to ensure the safety and quality of Moringa products.

## Materials and methods

### Materials

#### Dried Moringa Leaves

Fresh leaves of *M. oleifera* were collected from mature Moringa plants at the Kanambakache Maradi organic Moringa production site and subjected to a washing and cleaning protocol (Mahamane *et al*., 2025; Mahamane, Laminou, Amadou, & Hamadou, 2024). The methods for processing fresh Moringa leaves included room drying (away from sunlight) for 48 hours, sun-drying for 8 hours, and drying in a solar dryer at 55±5°C for at least 46 hours. The control sample of dried Moringa leaves was purchased from the local market in Maradi.

#### Moringa Leaf Extract (MLE)

*Moringa oleifera* leaf powder was extracted using distilled water and methanol. A 5% (w/v) solution was prepared at a solid-to-solvent ratio of 1:10 (1 g of powder per 10 mL of solvent). The suspension was maintained under continuous stirring at 45 °C for 8 h. The resulting mixture was filtered through Whatman No. 1 filter paper, and the filtrate was collected as the crude extract containing phytochemicals.

#### Moringa Seed Oil Extraction

The transformation of Moringa seeds into oil was undertaken using two distinct physical

extraction methods, in line with the principles outlined by Moneim (2024): cold-press and hot-press techniques. Following the methodology described by Al-Maqtari, Bahadi, Al-Maydama, & Barfed, (2024), cold-press extraction was performed by pressing thoroughly cleaned Moringa seeds at controlled temperatures not exceeding 50 °C for 90 minutes, thereby preserving the integrity of thermolabile compounds. In contrast, hot-press extraction was performed by subjecting the seeds to temperatures above 80 °C for a continuous 2 hours, a process intended to enhance oil yield but with potential implications for the stability of bioactive components.

## Methods

### GC-MS Analysis of Dried Moringa Leaf Extracts and Moringa Seed Oil Extracts

Phytochemical analyses of dried moringa leaf extracts (MLE) and moringa seed oil (MSO) were performed using a gas chromatograph equipped with a SHIMADZU GCMS-QP2010 Plus mass selective detector. A comparative analysis of the phytochemical profiles of MLE and MSO was conducted according to the protocol established by Bhalla, Ingle, Patri, & Haranath, (2021). The chromatographic parameters were characterized by an initial column oven temperature of 80.0 °C at 0 min, which was increased to 280.0 °C and maintained for 5 min. The injection was conducted at 250 °C with a 20:1 split ratio and a linear-velocity flow-control mode of 46.3 cm/s. The DB-5MS GC column (30 m × 0.25 mm, 0.25 µm) was used, with helium (99.99% purity) as the carrier gas. Extracts were injected using a multi-mode autosampler in solvent vent injection mode.

The injector operating conditions were as follows: injection volume, 13 µL. The injector temperature was maintained at 80 °C (held for 1 minute) during the solvent evaporation step, to 280 °C at a rate of 10 °C/min for 5 minutes. The total analysis time was 24 minutes. The triple quadrupole mass spectrometer was operated in electron impact (EI) ionization at 70 eV.

The relative amounts of each component were calculated and compared with the average peak area relative to the total area. The peaks of the phytochemical compounds in the chromatogram were identified by comparison with the elemental mass spectra in the National Institute of Standards and Technology (NIST) database (Halket *et al.*, 2004).

### Detection and Identification of Phytochemicals

The spectrometer offers several detection modes. This detection mode allows for compound identification using mass spectral libraries. Phytochemical identification is based on retention times (RT), characteristic fragment ions (m/z), and relative peak intensities. The relative concentration of the Total Ion Chromatogram (% TIC area) of the peaks is determined by dividing the peak area of the identified compound by the total area of all the peaks in the extract. However, accurate peak detection has often been challenging due to interference from the complex matrix of compounds (fatty acids, esters, alcohols, phenols, aldehydes and ketones, terpenes, sterols, heterocyclic and aromatic compounds, glycosides, hydrocarbons, etc.) present in plant extracts (Kind & Fiehn, 2007; Halket *et al.*, 2004).

### Statistical Analysis

A statistical analysis was conducted to evaluate the impact of extract types (MLE and MSO) on the phytochemical composition. The relative concentrations of compounds, expressed as a percentage of the chromatographic peak TIC, were summarized using descriptive statistics (mean and standard deviation). Principal component analysis (PCA) was performed to identify interrelationships among phytochemical compounds and to assess their similarity or

dissimilarity in discriminating compounds, based on chromatographic variables. An ascending hierarchical classification (HAC) of the contamination marker compounds was performed, enabling analysis of interclass (Between-class) and intraclass (Within-class) variances to assess dissimilarity or similarity between clusters of chemical compounds. This statistical analysis attests to the robustness of the classification of chemical compound groups. These statistical analyses were conducted using XLSTAT 5.3.

## Results and Discussion

### Results

**GC-MS Analysis of Moringa Leaf Extracts (MLE)**

The MLE extracts (Fig. 1), analyzed by GC-MS, exhibit distinct chromatographic peaks, each corresponding to a compound identified by its retention time. The number of peaks indicates the presence and diversity of phytochemical constituents (PICs) in each extract. Among the samples, the room-dried leaves (Fig. 1C) showed the highest number of peaks (35), followed by the solar-dried leaves (Fig. 1B) with 26 peaks. The sun-dried leaves (Fig. 1A) and the control sample (Fig. 1D) recorded the lowest counts, each with 19 peaks. The retention times (R.T.) of the detected compounds ranged as follows: 5.735–29.372 min for sun-dried leaves (Fig. 1A), 4.391–27.465 min for solar-dried leaves (Fig. 1B), 4.811–27.171 min for room-dried leaves (Fig. 1C), and 6.117–27.856 min for the control sample (Fig. 1D).

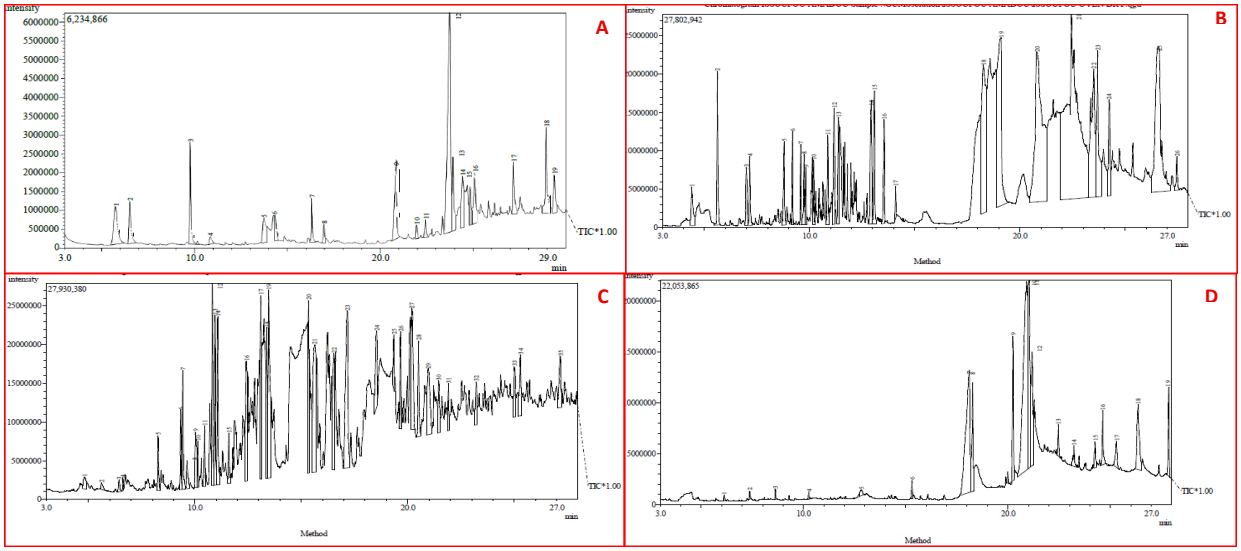


**Fig. 1. Chromatogram profile of analysis of dried leaves of *M. oleifera*; (A): Sun-dried leaves; (B): Solar dryer-dried leaves; (C): room-dried leaves; (D): Control sample**

**Phytochemical Profiles of Dried Moringa Leaf Extracts**

A comparative assessment of the chemical profiles (Table 1) from four Moringa leaf drying methods revealed a pronounced impact of processing on the composition of the resulting extracts. The chemical constituents varied significantly across techniques, with high standard deviations observed in most compound groups.

**Fatty acids (Essential oils):** Fatty acids emerged as the most abundant chemical family, with the highest proportion (55.85% to 9.92%) and a value across treatments of 32.93%. However, their distribution was uneven across treatments. The control extract exhibited the highest concentration of fatty acids (55.85%), with the most proportional fatty acids being linoleic acid (30.1%) and palmitic acid (18.7%). Sun-dried MLE

followed with 46.7% fatty acids, dominated by oleic acid (37.6%) and stearic acid (7.2%). In contrast, the room-dried extract contained only 9.92% fatty acids and showed a modest level of erucic acid (4.28%).

**Table 1- Profiling of phytochemical compounds of Dried Moringa Leaf Extracts (MLE)**

| N° | Identified compounds/(Chemical) | Area percentage of Dried Moringa Leaf Extracts | | | |
|---|---|---|---|---|---|
| | | Control | Solar drayer drying | Sun drying | Room drying |
| Fatty acids and derivatives | | 55.85 | 19.24 | 46.7 | 9.92 |
| 1 | Palmitic acid | 18.7 | 9 | 0 | 0 |
| 2 | Stearic acid | 7.05 | 0 | 7.2 | 0 |
| 3 | Oleic acid | 0 | 10.24 | 37.6 | 0 |
| 4 | Linoleic acid | 30.1 | 0 | 0 | 0 |
| 5 | Decanoic acid | 0 | 0 | 1.9 | 0 |
| 6 | Erucic acid | 0 | 0 | 0 | 4.28 |
| 7 | Heptadecanoic acid | 0 | 0 | 0 | 5.64 |
| Esters | | 7.6 | 32.74 | 5.1 | 39.9 |
| 8 | Ethyl Palmitate | 5.2 | 7.9 | 0 | 0 |
| 9 | Ethyl Linoleate | 0 | 14.12 | 0 | 0 |
| 10 | Ethyl E-11-Hexadecenoate | 0 | 6.4 | 0 | 0 |
| 11 | Ethyl Stearate | 1.5 | 0 | 0 | 0 |
| 12 | Methyl 11-Octadecenoate | 0 | 0 | 1.2 | 5.05 |
| 13 | Methyl Stearate | 0 | 0 | 0 | 2.29 |
| 14 | Methyl Erucate | 0.9 | 0 | 0 | 0 |
| 15 | Ethyl Icosanoate | 0 | 3.78 | 0 | 0 |
| 16 | Ethyl Docosanoate | 0 | 0.54 | 0 | 0 |
| 17 | Methoxyacetic Acid. 3-Tridecyl Ester | 0 | 0 | 0 | 7.41 |
| 18 | Benzyl Benzoate | 0 | 0 | 0 | 2.49 |
| 19 | Tridecanoic Acid. Methyl Ester | 0 | 0 | 0 | 9.07 |
| 20 | Trans-. Beta. -Terpinyl Benzoate | 0 | 0 | 0 | 2.86 |
| 21 | Bornyl Cinnamate | 0 | 0 | 0 | 1.54 |
| 22 | Benzyl Stearate | 0 | 0 | 0 | 2.5 |
| 23 | 9-Hexadecenoic Acid. Phenylmethyl Ester. (Z)- | 0 | 0 | 0 | 2.16 |
| 24 | Methyl 4.6-Decadienyl Ether | 0 | 0 | 0 | 4.62 |
| 25 | Hexadecyl 3-Methyl-2-Butenoate | 0 | 0 | 3.9 | 0 |
| Phenols | | 5.03 | 6.62 | 17.01 | 14.27 |
| 26 | Phytol | 5.03 | 0 | 0 | 0 |
| 27 | τ-Muurolol | 0 | 2.28 | 0 | 0 |
| 28 | 1-Nonanol | 0 | 0 | 6.81 | 0 |
| 29 | Guaiol | 0 | 0 | 0 | 5.42 |
| 30 | Farnesol | 0 | 0 | 0 | 1.88 |
| 31 | 2-Phenylethylbenzyl alcohol | 0 | 0 | 0 | 0.66 |
| 32 | 2-Tetradecanol | 0 | 0 | 0 | 3.94 |
| 33 | 11-Hexadecen-1-ol. (Z)- | 0 | 0 | 0 | 2.02 |
| 34 | 1.3-Propanediol. 2-ethyl-2-(hydroxymethyl) | 0 | 0 | 0.9 | 0 |
| 35 | 2-Dodecyl-1.3-propanediol | 0 | 0 | 5.9 | 0 |
| 36 | 2-Methyl-3.13-octadecadienol | 0 | 0 | 3.4 | 0 |
| 37 | 2.3-Pinanediol | 0 | 1.15 | 0 | 0 |
| 38 | α-Cadinol | 0 | 1.96 | 0 | 0 |
| 39 | δ-Cadinol | 0 | 1.23 | 0 | 0 |
| 40 | Phenol. 2.6-dimethyl- | 0 | 0 | 0 | 0.35 |
| Aldehydes and ketones | | 16.4 | 26.3 | 6.5 | 12.27 |
| 41 | 9-Hexadecenal | 14.9 | 0 | 6.5 | 0 |
| 42 | 9-Octadecenal (E) | 1.5 | 0 | 0 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| 43 | (Z)-9.17-Octadecadienal | 0 | 26.3 | 0 | 0 |
| 44 | 2-Undecanone | 0 | 0 | 0 | 3.25 |
| 45 | 2-Tetradecanone | 0 | 0 | 0 | 3.44 |
| 46 | 3-Decen-2-one | 0 | 0 | 0 | 1.02 |
| 47 | 8-Pentadaneton | 0 | 0 | 0 | 4.56 |
| Terpenes and sterols | | 3.2 | 11.2 | 0 | 18.84 |
| 48 | α-Phellandrene | 0 | 0.8 | 0 | 0 |
| 49 | Limonene | 0 | 0 | 0 | 0.68 |
| 50 | β-Linalool. α-Terpineol | 0 | 2.9 | 0 | 0 |
| 51 | Sabinol | 0 | 0.8 | 0 | 0 |
| 52 | Squalene | 3.2 | 0 | 0 | 0 |
| 53 | Acetic acid. 1.7.7-trimethyl-bicyclo [2.2.1] hept-2-yl ester | 0 | 0 | 0 | 1.1 |
| 54 | Dihydrocarvyl acetate | 0 | 0 | 0 | 1.44 |
| 55 | p-Menth-1-en-8-yl acetate | 0 | 0 | 0 | 2.39 |
| 56 | Beta-Vatirenene | 0 | 0 | 0 | 0.88 |
| 57 | Vatirenene (isomer) | 0 | 0 | 0 | 1.23 |
| 58 | 2.7.7-Trimethylbicyclo [2.2.1] hept-2-ene | 0 | 0 | 0 | 9.66 |
| 59 | α-Guaiene | 0 | 0 | 0 | 1.46 |
| 60 | α-Cubebene | 0 | 0.8 | 0 | 0 |
| 61 | Copaene | 0 | 0.6 | 0 | 0 |
| 62 | Germacrene D | 0 | 0.7 | 0 | 0 |
| 63 | Cedrene | 0 | 0.6 | 0 | 0 |
| 64 | β-Bisabolene | 0 | 0.6 | 0 | 0 |
| 65 | α-Curcumene | 0 | 1.1 | 0 | 0 |
| 66 | α-Muurolene | 0 | 1.7 | 0 | 0 |
| 67 | γ-Muurolene | 0 | 0.6 | 0 | 0 |
| Heterocyclic and aromatic | | 0.8 | 0 | 3.7 | 2.68 |
| 68 | Benzyl nitrile | 0.2 | 0 | 0 | 0 |
| 69 | 2.3-Benzofuran | 0.3 | 0 | 0 | 0 |
| 70 | 2-Methoxy-4-vinylphenol | 0.3 | 0 | 0 | 0 |
| 71 | 4-[5-Dimethylamino-2-hydroxy-2-pentyl]-2-phenylquinonine | 0 | 0 | 3.7 | 0 |
| 72 | Ethanone. 2-amino-1-phenyl- | 0 | 0 | 0 | 0.29 |
| 73 | 1.4-dimethoxy-2.3.5.6-tetramethylbenzene | 0 | 0 | 0 | 2.29 |
| 74 | p-Benzophenetidide (N-(4-Ethoxyphenyl) benzamide) | 0 | 0 | 0 | 0.1 |
| Glycosides. Amides. Amines | | 10.12 | 3.9 | 16.9 | 0.29 |
| 75 | Methyl 3.6-anhydrohexopyranoside | 0 | 2 | 0 | 0 |
| 76 | octyl-β-D-glucopyranoside | 0 | 0 | 10.2 | 0 |
| 77 | Oleamide | 1.12 | 0 | 0 | 0 |
| 78 | Monopalmitine. Monoolein | 7.5 | 0 | 0 | 0 |
| 79 | Propylhexedrine. Amines | 0 | 2 | 2 | 0.29 |
| 80 | N. N-dimethyl-1-heptadencanamin | 0 | 0 | 2 | 0 |
| 81 | 2-Acetonyl-9-[3-deoxy-β-d-ribouranosyl] hypoxanthine | 0 | 0 | 2.7 | 0 |
| 82 | 2-(Dimethylamino)ethyl methacrylate | 0 | 1.9 | 0 | 0 |
| 83 | L-glutamine | 0.9 | 0 | 0 | 0 |
| 84 | Ethyl-D-glucopyranoside | 0.6 | 0 | 0 | 0 |
| Hydrocarbons | | 0.6 | 0 | 0 | 0 |
| 85 | 1-Octadecyne | 0.6 | 0 | 0 | 0 |
| Phthalate | | 0 | 0 | 0 | 1.68 |
| 86 | Di-n-octyl phthalate | 0 | 0 | 0 | 1.68 |

**TIC**: Total Ion Chromatogram (% TIC area)

**Esters:** Ester compounds showed distinct patterns, with high concentrations in room-dried (39.9%) and solar dryer-dried (32.74%) MLE, and much lower levels in sun-dried (7.6%) and control (5.1%) samples. Notably, the room-dried extract contained a diverse array of methyl esters, accounting for 22.03% of its composition.

**Alcohols and phenols:** This group included phytol (5.03%), predominantly found in the control extract. Alcohols and phenols were more prevalent in sun-dried (17.4%) and room-dried (14.27%) MLE, while solar-dried samples contained the least (6.62%).

*Aldehydes and ketones:* These compounds displayed marked variability. Solar-dried MLE had the highest concentration (26.3%), mainly (Z)-9,17-octadecadienal. Room-dried MLE featured several ketones, including 2-undecanone (3.25%), 2-tetradecanone (3.44%), 8-pentadanetone (4.56%), and 3-decan-2-one (1.02%). The control extract contained 16.4% aldehydes, mainly 9-hexadecenal (14.98%) and 9-octadecenal (1.5%).

**Heterocyclic and aromatic compounds:** This group exhibited a mean concentration of 1.80, indicating high variability. The control extract was notable for the presence of benzyl nitrile (0.2%), 2,3-benzofuran (0.3%), and 2-methoxy-4-vinylphenol (0.3%). The sun-dried extract uniquely contained N,N-Dimethyltryptamine (DMT) and 4-[5-Dimethylamino-2-hydroxy-2-pentyl]-2-phenylquinoline, each at 3.7%.

**Miscellaneous compounds (Glycosides, Amides, Amines):** This group had a moderate concentration (12.45) and considerable heterogeneity. The control extract was distinguished by oleamide (1.12%), monopalmitin, and mono-olein (7.55%). Sun-dried MLE was rich in glucopyranoses, notably octyl-β-D-glucopyranoside (10.2%).

*Terpenes and sterols:* These compounds exhibited moderate variability (8.31). Room-dried MLE had the highest content (18.84%), followed by dryer-dried MLE (11.2%). The control extract contained only 3.2%.

**Hydrocarbons and other compounds:** The hydrocarbon group was represented solely by 1-Octadecyne, found exclusively in the control sample. Additionally, phthalate was detected in the room-dried MLE at a low concentration (1.68%).

**GC-MS Analysis of Moringa Seed Oil Extracts (MSO)**

Moringa seed oil extracts (Fig. 2) show that the cold extract has the highest number of peaks (18 peaks), followed by the control sample (Fig. 1D) with (14 peaks) and the hot extract (Fig. 2E) with (13 peaks). The chromatogram analysis of Moringa seed oil shows that the RTs of the identified compounds vary from 16.056 to 22.418 min for the hot MSO (Fig. 2E), 15.464 to 23.651 min for the cold extract (Fig. 2F), and 16.024 to 22.122 min for the control sample (Fig. 2G). The retention time was used to characterize the compounds identified in the chromatograms and to determine their polarity, volatility, and mass.

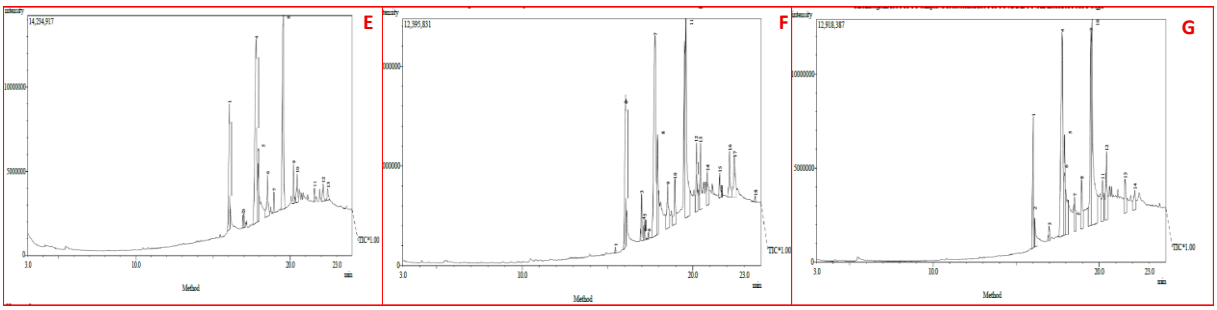


**Fig. 2. Chromatogram profile of *M. oleifera* seed oil analysis; (E) Hot extract; (F): Cold extract; (G): Control sample**

**Phytochemical Compositions of Moringa Seed Oil Extracts**

A comparative analysis of the three oil extraction methods (Table 2) reveals a significant influence of the extraction processes on the chemical profiles of the compounds. Table 2 shows the dominance of

the average relative concentration of the TIC area and also the stability of the fatty acids (72.76%) in the three MSO. Within this chemical family, oleic acid is the predominant compound (28.03%), while stearic acid is the most stable with the lowest variability (6.08). Finally, ricinoleic acid is detected exclusively in the control extract (20.66%) and is absent from the other extraction methods. In contrast, hot extraction is distinguished by its high undecenoic acid content (29.6%). However, the ester composition shows a strong presence of ethyl esters in the control extract, as well as other specific compounds, such as chloride and glyceryl. Conversely, the cold extract produces methyl esters, including linoleate, stearate, and 2-monopalmitin. On the other hand, the hot extract exhibits selectivity for compounds such as lactones and ethers. The aldehyde composition is the most variable in the cold extract, which clearly favors its formation (23.57%) and exhibits specificities, such as (Z)-7-tetradecenal. Thus, other specific compounds, present in low quantities, such as ketones, are found in all the extracts. On the other hand, hydrocarbons containing squalene at a trace level (0.29%) are present only in the cold extract.

**Table 2- Profiling of phytochemical compounds of Moringa Seed Oil Extracts (MSO)**

| N° | Identified compounds / (Chemical families) | Area percentages in MSO | | |
|---|---|---|---|---|
| | | **MSO Control** | **MSO Hot extraction** | **MSO Cold extraction** |
| Fatty Acids | | 73.85 | 80.58 | 63.84 |
| 1 | Palmitic acid | 7.84 | 12.4 | 10.56 |
| 2 | Oleic acid | 24.44 | 32.59 | 27.07 |
| 3 | Stearic acid | 6.04 | 5.99 | 6.22 |
| 4 | Indecenoic acid | 14.87 | 29.6 | 19.99 |
| 5 | Ricinoleic acid | 20.66 | 0 | 0 |
| Esters and Glycerides | | 14.21 | 5.24 | 8.58 |
| 6 | Allyl decanoate | 0 | 0.7 | 0 |
| 7 | Methyl 14-methylpentadecanoate | 0 | 0 | 0.24 |
| 8 | Methyl linoleate | 0 | 0 | 0.78 |
| 9 | Methyl 11-octadecenoate | 0 | 0 | 0.57 |
| 10 | Methyl stearate | 0 | 0 | 0.39 |
| 11 | Methyl 2-methylhexadecanoate | 2.3 | 0 | 0 |
| 12 | Ethyl stearate | 2.44 | 0 | 0 |
| 13 | 2.3-Dihydroxypropyl palmitate | 0 | 1.4 | 0 |
| 14 | 2-Monopalmitin | 0 | 0 | 6.6 |
| 15 | Glyceryl 2-pentadecanoate | 3.62 | 0 | 0 |
| 16 | 13-Oxabicyclo[10.1.0]tridecane | 5.85 | 3.14 | 0 |
| Aldehydes | | 4.87 | 12.22 | 23.57 |
| 17 | 9-Octadecenal | 2.6 | 5.56 | 4.71 |
| 18 | 7.11-Hexadecadienal | 2.27 | 2.95 | 4.82 |
| 19 | 10-Undecenal | 0 | 0 | 5.34 |
| 20 | 9-Tetradecnal (Z) | 0 | 2.28 | 0 |
| 21 | (Z)-9-Tetradecnal | 0 | 1.43 | 0 |
| 22 | (Z)-7-Tetradecnal | 0 | 0 | 4.96 |
| 23 | 13-Octadecenal. (Z)- | 0 | 0 | 3.74 |
| Ketones | | 2.75 | 1.08 | 1.53 |
| 24 | 1-(2.2-Dimethylcyclopentyl) ethanone | 2.75 | 1.08 | 1.53 |
| Hydrocarbon | | 0 | 0 | 0.29% |
| 25 | Squalène | 0 | 0 | 0.29 |
| **Lactones** | | 0.64 | 0.89 | 2.19 |
| 26 | 13-Hexyloxacyclotridec-10-en-2-one | 0.64 | 0.89 | 2.19 |
| **Chlorides** | | 3.68 | 0 | 0 |
| 27 | 10-Undecenoyl chloride | 3.68 | 0 | 0 |

TIC: Total Ion Chromatogram (% TIC area)

**Characterization of Contamination Marker Compounds**

Analysis of chemical contamination marker compounds (Table 3) revealed their presence in two Moringa leaf processing methods. The chemical compounds identified in the room-grown MLE were composed of di-n-octyl phthalate (DNOP) products with a TIC abundance of 1.68%, benzyl benzoate (2.49%), and benzyl stearate (2.5%). DNOP, a di-n-octyl phthalate ester, is a synthetic plastic-derived compound that can enter the product from the environment (Li, Liu, Kang, Liu, & Wang, 2022; Waring, Harris, & Mitchell, 2018). Benzyl benzoate is a compound that can be natural or synthetic. Benzyl stearate is a derivative of plant-based and synthetic compounds. However, in the dryer MLE, 2-dimethylaminoethyl methacrylate was identified with a TIC abundance of 2%. In contrast, the control MLE sample, which contained two detected compounds, benzyl nitrile (0.2%) and 2,3-benzofuran (0.3%), had a very low TIC concentration. Benzyl nitrile is widely produced by chemical synthesis from benzyl chloride. Benzofuran can originate from natural or synthetic sources.

**Table 3- Profile of contamination marker compounds**

| Extract Type Method | | Identified Compound | % TIC | TR (min) |
|---|---|---|---|---|
| MLE | Room | Di-n-octyl phthalate | 1.68 | 25 |
| | | Benzyl benzoate | 2.49 | 15 |
| | | Benzyl stearate | 2.5 | 25 |
| | Sun dried | 2-Dimethylaminoethyl methacrylate | 2 | 24.251 |
| | Control | Benzyl nitrile | 0.2 | 6.12 |
| | | 2.3-Benzofuran | 0.3 | 7.36 |
| MSO | Control | 10-Undecenoyl chloride | 3.68 | 20.194 |
| | | 1-(2.2-dimethylcyclopentyl) ethanone | 2.75 | 21.549 |
| | | 13-Oxabicyclo[10.1.0]tridecane | 5.85 | 20.431 |

TIC: Total Ion Chromatogram (% TIC area); MLE: Moringa leaf extract; MSP: Moringa seed oil

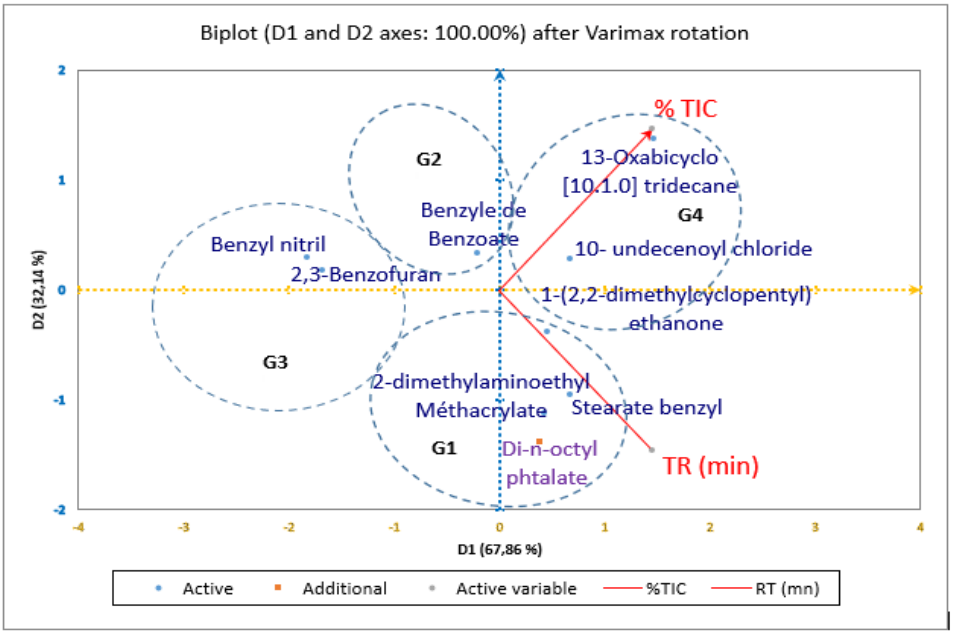


**Fig. 3. Principal component analysis (PCA) of compounds**

In the MSO, only the control sample contained compounds detected as a source of contamination: 10-undecenoyl chloride (3.68%), 1-(2,2-dimethylcyclopentyl) ethanone (2.75%), and 13-oxabicyclo[10.1.0]tridecane (5.85%).

**Comparative Analysis of Contaminants**

Principal component analysis (Fig. 3) facilitated the classification and differentiation of compounds based on key variables extracted from the GC-MS chromatograms (Fig. 4). Specifically, retention time (RT) and relative concentration (expressed as % of the total ion chromatogram, TIC area) enabled the identification of four distinct contaminant groups.

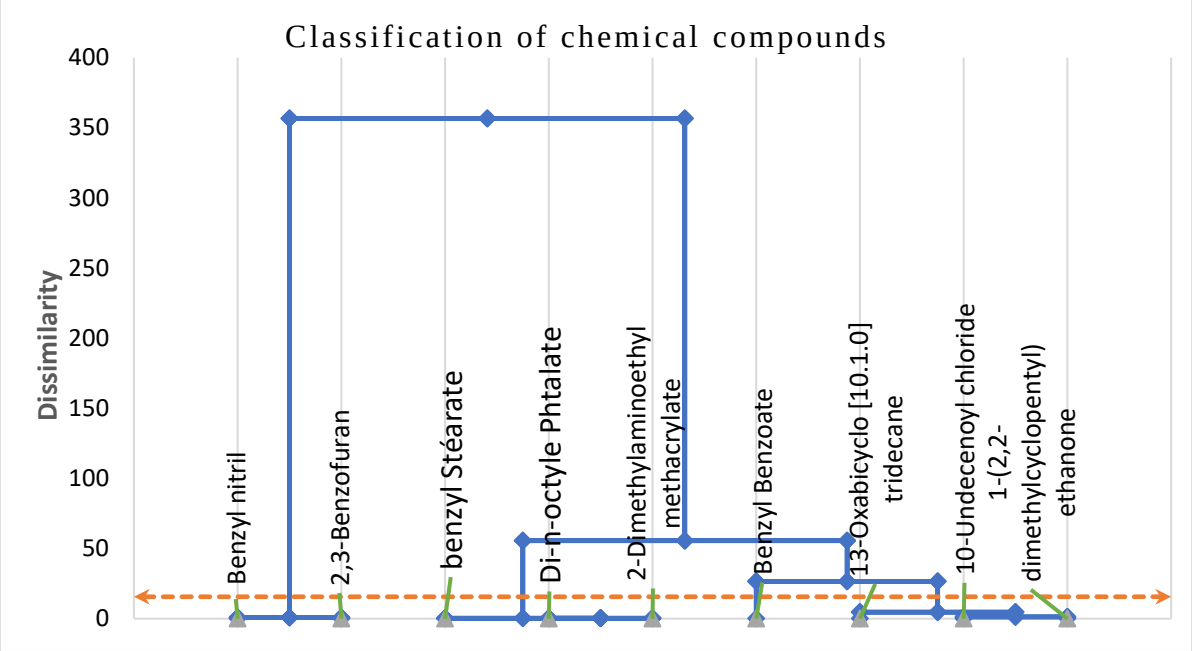


**Fig. 4. Ascending Hierarchical Classification (AHC) of chemical compounds**

**Group 1:** Characterized by RTs ranging from 15 to 25 minutes and relative concentrations between 1.68% and 2.5%. This group includes Benzyl stearate and Di-n-octyl phthalate (both found in room-dried MLE), as well as 2-Dimethylaminoethyl methacrylate (detected in Solar dryer-dried MLE).

**Group 2:** Composed solely of Benzyl benzoate (room dried MLE), with a retention time of 25 minutes and a relative concentration of 2.5%.

**Group 3:** Defined by short retention times (6.12–7.36 min) and low relative concentrations (0.18–3%). This group includes Benzyl nitrite and 2,3-benzofuran, both of which were identified in the control (market sample).

**Group 4:** Exhibits retention times between 20.19 and 21.55 minutes and higher relative concentrations ranging from 2.75% to 5.85%. The compounds in this group include 10-Undecenoyl chloride, 1-(2,2-dimethylcyclopentyl) ethenone, and 13-Oxabicyclo[10.1.0]tridecane.

A Hierarchical Ascending Clustering (HAC) analysis of the contamination marker compounds was performed based on their TIC and TR percentages. Thus, four clusters are well defined, with 97.27% of the total variance in the data explained by inter-cluster distances. The interclass variances (Between-class) are 54.27, and the intraclass variance (within-class) is 1.5. The high interclass variance confirms that the compounds within each

cluster are highly similar to one another and distinctly different from those in other clusters. The compounds are characterized by class. Class 1 consists of late-eluting chemical compounds with the highest retention times and medium abundance. The compounds in this class are: Di-n-octyl phthalate (MLE room drying), 2-dimethylaminoethyl methacrylate (MLE solar dryer), and benzyl stearate (MLE by room drying). Class 2 is composed of benzyl benzoate (MLE by room drying), the only compound in this class with a high mean abundance and a median TR that distinguishes it from other groups of compounds. Early-eluting, low-abundance compounds characterize class 3. The compounds that characterize this class are: benzyl nitrite and 2,3-benzofuran (control sample).

Late-eluting compounds and high abundance characterize class 4. The following compounds constitute this class: 10-undecenoyl chloride, 1-(2,2-dimethylcyclopentyl) ethanone, and 13-oxabicyclo[10.1.0]tridecane.

**Discussion**

A comparative analysis of the chemical profiles of *Moringa oleifera* leaves, based on the processing methods employed, clearly demonstrates that drying techniques exert a decisive influence on extract composition. Consistent with previous findings (Chong, Dibagar, Maulion, & Figiel, 2023; Bamisaye, Olasebikan, Asebioge, & Samson, 2025), this study demonstrates that drying conditions significantly impact the stability and concentration of bioactive compounds (Table 2). The abundance of essential fatty acids such as linoleic, palmitic, and oleic acids in the control, sun, and solar dryer extracts corroborates the results of Nakra, Tripathy, & Srivastav, (2024), who reported that drying is among the most widely used preservation techniques for medicinal plants, significantly shaping their physicochemical and functional properties. Thus, drying is a critical step for retaining bioactive molecules in Moringa leaves, while the variability observed across processing methods underscores the potential to tailor the levels of specific compounds of nutritional and pharmacological interest.

A notable finding is the exclusive detection of N,N-dimethyltryptamine (DMT) and 4-[5-dimethylamino-2-hydroxy-2-pentyl]-2-phenylquinonine in sun-dried extracts. This suggests that sun exposure may trigger photochemical transformations that lead to the synthesis of unique compounds with potential pharmacological applications, including antimalarial and anti-inflammatory effects (Konmy, Olounladé, Doko-Allou, & Azando, 2020). These results underscore the specificity of drying conditions in shaping chemical diversity.

Room-dried extracts were particularly enriched in esters (39.9%) and terpenes (18.8%), confirming earlier findings (Chukwu *et al*., 2024) that documented abundant methyl esters such as methyl palmitate, methyl stearate, and octadecenoic acid methyl ester in dried Moringa leaves. This preservation of esters highlights room-drying as a favorable technique for maintaining volatile lipid derivatives. Moreover, the distinctive terpene profiles obtained by room-drying and solar-drying demonstrate complementary outcomes: room-drying favors more volatile monoterpenes such as limonene, dihydrocarvyl acetate, and menthyl acetate, while solar-drying preserves less volatile sesquiterpenes such as α-cubebene, germacrene D, and β-bisabolene. These compounds are well-documented for their antioxidant, antimicrobial, and anti-inflammatory activities (Peixoto *et al*., 2015; Eddin *et al*., 2021, 2022). Such differentiation highlights the pharmacological significance of processing choices, as each method harnesses distinct therapeutic potentials.

The analysis of terpene alcohols further illustrates this specificity: sun-dried leaves contained the highest concentrations, while solar-dried extracts showed exclusive compounds, including τ-muurolol, α-cadinol, and δ-cadinol, which are recognized for their antioxidant and anti-inflammatory effects. In

contrast, room-drying favored the production of guaiol and farnesol. Similarly, aldehyde and ketone profiles varied with drying methods, with solar dryer drying yielding elevated levels of unsaturated aldehydes, such as (Z)-9,17-octadecadienal, a product of fatty acid oxidation (Ayseli & Ayseli, 2020; Codex Alimentarius, 2024).

In terms of lipid composition, the extracts revealed a predominance of unsaturated fatty acids, notably oleic acid (28.3%). However, these values differed from those reported for Moringa oil (Vergara-Jimenez, Almatrafi, & Fernandez, 2017), likely due to environmental and genetic variability (Anwar, Latif, Ashraf, & Gilani, 2007). This confirms that both growth conditions and processing protocols strongly modulate lipid composition. Notably, squalene was detected only in the cold extract, highlighting its thermo-sensitivity and confirming previous reports on its degradation under heat treatments (Kelly, 1999; Wiesner-Kiełczewska, Zagrodzki, Gawalska, & Paśko, 2025). The preservation of this valuable antioxidant underscores the importance of cold-extraction methods for maximizing its nutraceutical potential.

Overall, the differential chemical profiles obtained across drying and extraction methods reflect the high biochemical plasticity of Moringa leaves. Room-drying enhances the retention of esters and monoterpene, while solar-drying favors the retention of sesquiterpenes and aldehydes, and sun-drying induces the formation of unique photochemical compounds of pharmacological interest. These findings underscore the importance of carefully selecting processing techniques to optimize the preservation and functionality of bioactive compounds in Moringa leaves, depending on their intended nutritional or therapeutic application.

## Conclusion

This study thoroughly characterized the phytochemical composition and contamination profile of dried leaf and seed oil extracts of Moringa. The results obtained conclusively demonstrate the decisive influence of processing methods on the types of bioactive compounds. GC-MS analysis revealed a diverse array of chemical compounds with distinct profiles, depending on the drying and extraction methods employed. Room and sun-dried extracts better preserve chemical qualities and functional properties. Cold extraction was found to be the most optimal method for preserving thermosensitive compounds. The detection of contaminants, including plastic residues and oxidation products, underscores the importance of selecting suitable packaging materials.

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## Author Contributions

**Mr. Massaoudou Mahamane:** conducted the literature review, sample collection for laboratory analysis, data analysis and interpretation, and drafted the initial version. **Dr. Issoufou Amadou:** conceptualized, supervised, validated, proofread, and edited the manuscript, and provided advice on structuring the data analyses and refining the manuscript. **Dr. Xiang-Rong Cheng**: provided technical support for data analysis and writing, and offered advice on structuring and refining the manuscript.

### Availability of Data and Materials

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

### Declarations

### Ethics Approval and Consent to Participate

Not applicable.

**Consent for Publication**

Not applicable.

**Competing Interests**

The authors declare that they have no competing interests.

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# شناسایی فیتوشیمیایی و ارزیابی آلاینده‌ها در محصولات فرآوری شده *مورینگا اولیفرا* تولید شده به‌صورت ارگانیک از ساحل نیجر

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## چکیده

در ساحل نیجر، فرآوری *مورینگا اولیفرا* یک فرصت اقتصادی ارزشمند برای جوامع محلی ارائه می‌دهد؛ با این حال، کیفیت و ایمنی محصول ارتباط نزدیکی با روش‌های فرآوری مورد استفاده دارد. این مطالعه با استفاده از آنالیز GC-MS، ترکیب فیتوشیمیایی و نشانگرهای آلودگی عصاره‌های برگ مورینگا (MLE) و روغن دانه مورینگا (MSO) را بررسی کرد. نتایج، تأثیر قابل توجه فرآوری بر پروفایل‌های شیمیایی را نشان داد. اسیدهای چرب در ترکیبات غالب بودند. MLE (۳۲/۹۳ ٪) خشک‌شده در اتاق غنی از استرها (۳۹/۹٪) و ترپن‌ها (۱۸/۸۴٪) بود، در حالی‌که نمونه‌های خشک‌شده در آفتاب، محتوای آلدهید بالایی (۲۵/۳٪) نشان دادند که نشان‌دهنده اکسیداسیون لیپید است. عصاره‌های خشک‌شده در آفتاب به‌طور منحصر به فردی حاوی N-، N-دی‌متیل‌تریپتامین و فنیل‌کینونین بودند که نشان‌دهنده وجود متابولیت‌های القا شده فتوشیمیایی است. در MSO، اسیدهای چرب غالب بودند (۷۲/۷۶٪) و شرایط استخراج بر پایداری ترکیبات زیست‌فعال تأثیر گذاشت. استخراج سرد، مولکول‌های حساس به حرارت مانند اسکوالن (۰/۲۹٪) را حفظ کرد که در نمونه‌های تیمار شده با حرارت وجود نداشتند. نشانگرهای آلودگی نیز شناسایی شدند، از جمله دی-ان-اکتیل فتالات (۱/۶۸٪) در MLE خشک شده در اتاق و ۲-دی متیل آمینو اتیل متاکریلات (۲٪) در عصاره‌های خشک شده در خشک‌کن خورشیدی. آلاینده‌های صنعتی، مانند ۱۰-آندسنوئیل کلرید (۳/۶۸٪) و ۱۳-اوکسابی‌سیکلو [۱۰.۱.۰] تری‌دکان (۵/۸۵٪)، در MSO کنترل شناسایی شدند. به‌طور کلی، پروفایل GC-MS نشان داد که هر روش فرایند، اثر انگشت فیتوشیمیایی متمایزی با پیامدهای تغذیه‌ای، دارویی و ایمنی خاص ارائه می‌دهد. این یافته‌ها بر نیاز به بهینه‌سازی فرایندها و بسته‌بندی برای افزایش کیفیت و ارزش بازار محصولات مبتنی بر مورینگا در ساحل تأکید می‌کند.

**واژه‌های کلیدی:** آلودگی، ساحل، فرآوری، کروماتوگرافی

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