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Nutritional Profile and Physicochemical Properties of the White *Hibiscus sabdariffa* L. Seeds and Oil

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Abstract

The present study focuses on the phytochemical composition and nutritional profile of various parts of a little-known white-flowered variety of *Hibiscus sabdariffa* native to Senegal. Rich in bioactive compounds, these seeds exhibit maximum polyphenol levels of 7.72 ± 0.544 mg GAE/g dry matter (ultrasound) versus 5.065 ± 0.105 mg GAE/g dry matter (maceration), and flavonoid levels of 39.567 ± 0.354 mg QE/g dry matter (ultrasound) versus 40.77 ± 0.007 mg QE/g dry matter (maceration). These bioactive compounds exhibited antioxidant activity of 16.629 ± 0.155 mg AAE/g dry matter (ultrasound) versus 12.597 ± 0.525 mg AAE/g dry matter (maceration) according to the FRAP assay, and 71.305% ± 0.417% (ultrasound) versus 67.305% ± 1.633% (maceration) according to the DPPH assay. These seeds also constitute a good source of minerals; potassium is the most abundant (14754.3011 ± 224.5819 mg/100 g), followed by magnesium (4171.393 ± 12.2863 mg/100 g) and calcium (3116.3201 ± 4.6873 mg/100 g). The iron content is 76.1828 ± 0.7240 mg/100 g, while copper is present in low quantities (4.4785 ± 0.0488 mg/100 g). With maximum oil yields of 6.03 ± 0.327% (mechanical pressing) and 19.12% ± 0.564% (Soxhlet extraction), the oils are characterized by a predominance of unsaturated fatty acids C18:2 (41.76% ± 0.020% vs. 40.495% ± 0.455%) and C18:1 (27.380% ± 0.060% vs. 26.685% ± 0.275%), respectively. Regarding saturated fatty acids, the major compounds were C16:0 (22.990% ± 0.010% vs. 23.145% ± 0.275%) and C18:0 (5.630% ± 0.030% vs. 7.135% ± 1.155%). These characteristics offer promising prospects for this species in various industrial sectors notably the food, pharmaceutical, and cosmetic industries as well as for biofuel production. The enhanced oxidative stability of the oil at 100˚C (12.64 h for mechanical pressing vs. 11.48 h for Soxhlet ex-

traction) allows for more efficient utilization.

Keywords

Senegal, White *Hibiscus sabdariffa,* Phytochemicals, Fatty Acids, Oxidative Stability

1. Introduction

Hibiscus sabdariffa L., commonly known as Bissap in Senegal, has gained global recognition as a multifunctional crop, yet research has predominantly focused on its calyces, leaving the nutritional and bioactive potential of the white-variety seeds largely underutilized. Comprehensive evaluation of these seeds is essential, as their composition of unsaturated fatty acids, essential minerals, and antioxidant compounds offers significant promise for both functional food development and the mitigation of nutritional deficiencies [1] [2]. Accordingly, the present study aims to provide a rigorous characterization of the chemical composition, antioxidant capacity, lipid profile, and mineral content of white-variety *Hibiscus sabdariffa* seeds cultivated in Senegal, thereby facilitating their prospective integration into the pharmaceutical and nutraceutical sectors [3] [4]. This analysis further explores the viability of these seeds as an affordable, unconventional nutritional resource capable of enhancing dietary quality in resource-limited populations [5] [6]. By establishing these baseline data, this research addresses the critical knowledge gap concerning the specific nutritional profile of this under-researched variety within the Senegalese agricultural landscape [4] [7]. Furthermore, the investigation seeks to assess the radical-scavenging efficacy and bioactive potential inherent in these seeds, which may serve as a sustainable source of high-value natural antioxidants [8] [9]. By identifying the specific nutritional and phytochemical constituents of these seeds, the study provides evidence for their potential role in dietary interventions designed to combat oxidative stress and chronic metabolic conditions [10]. Ultimately, this research aims to validate the inclusion of these seeds as a nutrient-dense agricultural byproduct, thereby promoting the sustainable valorization of the white *Hibiscus sabdariffa* cultivar [11] [12]. These findings will elucidate the specific nutritional advantages of this variety, providing a scientific foundation for maximizing its utility as a functional ingredient or protein supplement [13] [14]. Through systematic analysis of these constituents, this research intends to substantiate the viability of utilizing such agricultural byproducts as value-added resources for the food industry [15].

2. Materials and Methods

2.1. Source of Plant Matter

The plant material (*Hibiscus sabdariffa seeds*) used was purchased in the Kaolack region, located in west-central Senegal (14˚30' - 16˚30' W and 13˚30' - 14˚30' N).

This region has a Sudan-Sahelian climate, with annual rainfall of 800 to 900 mm distributed between June and October. It is also characterized by diverse vegetation, including dense shrub savanna in the north and wooded savanna in the south and southeast. The seeds were purchased from a major oilseed supplier who confirmed the variety; this white variety was further verified by farmers active in the field prior to use. A single batch of seeds was sampled, and all analyses were performed on the dehulled seeds. The seeds contained impurities and debris; these were removed through thorough washing followed by sun-drying for three days. The seeds were then winnowed to remove the seed coats. Finally, a portion of the cleaned seeds was ground into powder for Soxhlet extraction and other analyses, while the remainder was used for mechanical extraction (**Figure 1**).

All solvents and reagents used in this study were of analytical grade.



Figure 1. Image of the plant, seeds, and seed powder of the white variety of *Hibiscus sabdariffa* L.

2.2. Determination of Moisture Content

In accordance with the standard [16], approximately 5 g of each sample is weighed to an accuracy of 0.001 g in crucibles that have been previously dried and weighed. The sample is placed in an oven set at 103˚C ± 2˚C for 1 hour. After this heating period, the crucibles are transferred to a desiccator to cool to room temperature. Once cooled, the sample is weighed to an accuracy of 0.001 g. The heating, cooling, and weighing steps are repeated, with successive heating periods of 30 minutes. These cycles are continued until a constant mass is obtained.

The water content is expressed by the following formula:

$$water\ content\left(\mathrm{g}/100\mathrm{g}\right)=\frac{m_1-m_2}{m_1-m_0}$$

where m_0: mass in grams of the empty crucible; m_1: mass in grams of the crucible and the test sample before baking; m_2: mass in grams of the crucible and the test sample after baking.

2.3. Determination of Ash Content

The ash content was determined according to the method [17]. For each sample, 5 g were placed in crucibles and then calcined in a muffle furnace at 550˚C ± 5˚C

for 5 h. After cooling in a desiccator, the crucibles were weighed.

The following formula expresses the ash content:

$$Ash\,content = \frac{m_2 - m_1}{m_0} \times 100$$

where m_2: mass in grams of the crucibles after calcination; m_1: mass in grams of the empty crucibles; m_0: mass in grams of the samples.

2.4. Determination of Mineral Profiling

Mineral analysis was performed according to the method described by [18]. Mineral content was determined using a Perkin Elmer Optima 8000 DV inductively coupled plasma optical emission spectrometer (ICP-OES).

Briefly, 1 g of powder was treated in a muffle furnace at 500˚C for 2 hours; subsequently, 4 mL of 65% HNO_3 and 10 mL of HCl were added to the resulting ash, and the mixture was injected into the instrument [19]. Eight minerals (K, Ca, Mg, Na, Fe, Mn, Cu and Zn) were analyzed according to the parameters and emission lines listed in Table 1.

The wavelengths used for the analysis were as follows: K (766.490 nm), Mg (285.213 nm), Na (589.592 nm), Ca (317.933 nm), Zn (213.857 nm), Cu (324.752 nm), Fe (239.562 nm), and Mn (257.610 nm).

Table 1. ICP-OES operating conditions for mineral determination.

Condition	Description/valeur
Plasma gas flow rate	14 L·min^{-1}
Auxiliary gas flow rate	0.2 L·min^{-1}
Nebulizer gas flow rate	0.8 L·min^{-1}
Plasma gas	Argon
Sample flow rate	1.3 mL·min^{-1}
Rinsing time	7 s
Analysis mode	Axial
RF Power	1300 W

2.5. Extraction Process of Phenolic Compounds

The extraction of bioactive compounds was performed according to the protocol described by [20], with some modifications. Two grams of powder from each matrix were macerated in 20 mL of each solvent (water, methanol, 80% methanol, ethanol, and ethyl acetate) under agitation for 24 hours. For ultrasound-assisted extraction, 2 g of powder were mixed with 20 mL of each solvent. The ultrasonic device used in this study was a Biobase ultrasonic cell disrupter, equipped with a cylindrical sonotrode (6 mm diameter) and operating at a power of 650 W and a frequency of 50 Hz, at a constant temperature of 20˚C ± 1˚C. To maintain this temperature, the beaker containing the mixture was placed in a crystallization dish

through which a flow of cooling water circulated. The extraction duration was 15 minutes.

After extraction, each mixture was centrifuged at 3800 rpm for 15 minutes and then filtered through Whatman filter paper; the resulting liquid was stored at 4˚C until further use. The phenolic compound and flavonoid contents, as well as antioxidant activities, were evaluated for the obtained extracts.

2.6. Determination of Phenolic Content

The total phenolic content was determined using the Folin-Ciocalteu reagent method according to the protocol described by [20]. A 0.5 mL aliquot of the diluted extract solution was mixed with 2.5 mL of Folin-Ciocalteu reagent (1:10 dilution); subsequently, 4 mL of sodium carbonate (Na_2CO_3, 7.5%) was added, and the mixture was incubated at 45˚C for 30 minutes before measuring absorbance at 765 nm.

Results were expressed as milligrams of gallic acid equivalents per gram of dry matter (mg GAE/g DM), based on a calibration curve using gallic acid as the standard.

2.7. Determination of Total Flavonoid Content

The total flavonoid content (TFC) was evaluated by the aluminum chloride colorimetric method according to [21]. Briefly, 1 mL of the diluted extract solution was placed in a 10 mL volumetric flask; 4 mL of distilled water and 0.3 mL of 5% $NaNO_2$ were then added to the mixture. The mixture was allowed to stand for 5 minutes before the addition of 0.3 mL of 10% $AlCl_3$. Subsequently, 1 mL of 2 M NaOH was added to the flask after 6 minutes, and the volume was made up to 10 mL with distilled water. Absorbance was measured at 415 nm after a 30-minute incubation of the mixture. TFC was expressed as milligrams of quercetin equivalent per gram of dry matter (mg QE/g DM), calculated using the equation of the calibration curve established with quercetin as the standard.

2.8. Antioxidant Activity Potential

2.8.1. Reduction Potential by FRAP Method

The reducing power of each extract, reflecting its antioxidant activity, was determined using a modified method for assaying the reduction of Fe^{3+} to Fe^{2+} [22]. Briefly, 1 mL of diluted extract solution was added to 2.5 mL of 0.2 M sodium phosphate buffer (pH 6.6) and 2.5 mL of a 1% (w/v) potassium ferricyanide ($K_3Fe(CN)_6$) solution. The mixture was vortexed and incubated at 50˚C for 20 minutes; subsequently, 2.5 mL of 10% (w/v) trichloroacetic acid was added, followed by centrifugation at 3000 rpm. Finally, 2.5 mL of the supernatant was mixed with 2.5 mL of deionized water and 0.5 mL of 0.1% (w/v) ferric chloride, and the absorbance was measured at a wavelength (λmax) of 700 nm against a blank. The reducing power of the extract was expressed as milligrams of ascorbic acid equivalent per gram of dry matter (mg AAE/g DM).

2.8.2. Reduction Potential by DPPH Method

The DPPH (2,2-diphenyl-1-picrylhydrazyl) radical is used to calculate the percentage inhibition of the extracts. A 0.2 mM methanolic DPPH solution was prepared. A volume of 0.8 mL of this solution was added to 4 mL of diluted extract. After an incubation period of 30 minutes at room temperature and protected from light, the absorbance of the mixture was measured at 517 nm [23]. The percentage inhibition also referred to as radical scavenging activity corresponding to the discoloration of the mixture, was estimated using the following formula:

$$\%inhibition = \frac{A_c - A_s}{A_c} \times 100$$

where "A_c" represents the absorbance of the control (0.2 mM methanolic DPPH solution) and "A_s" represents the absorbance of the sample.

2.9. Determination of Oil Content

Mechanical extraction and Soxhlet extraction were used to determine the oil content. A seed sample (m_0 = 50 g) was used for mechanical press extraction; following extraction and a 4-hour settling period, the resulting oil was filtered by centrifugation. The recovered crude oil was weighed and stored in opaque vials at 4˚C for later use. For Soxhlet extraction, a quantity (m_0 = 20 g) of finely ground seeds underwent an 8-hour extraction at 69˚C ± 1˚C in a Soxhlet apparatus, using n-hexane (200 mL) as the extraction solvent. The oil was then recovered by evaporating the solvent at 45˚C using a vacuum rotary evaporator (model R-200, Buchi, Zurich, Switzerland). The resulting crude vegetable oil was oven-dried for 20 minutes at 103˚C, cooled in a desiccator for 30 minutes, and then weighed.

Oil contents were calculated gravimetrically using the following formula:

- Soxhlet: oil mass (SEWHS) = 3.8241 g
- Mechanical press: oil mass (MEWHS) = 3.0148 g

$$Oil\ content\left(\%\right) = \frac{oil\ mass}{m_0} \times 100$$

2.10. Determination of Fatty Acid Profile

In accordance with the standard [24], to prepare the sample, 0.1 g of the oil was dissolved in 2 mL of isooctane, 0.1 mL of methanolic KOH was added, and the mixture was vortexed for 1 min, followed by a 2-min stand. Then, 2 mL of saturated water were added and vortexed again. After phase separation, the isooctane phase was dried using anhydrous sodium sulfate, and 1 µL was injected into the gas chromatography (GC) instrument. The GC was equipped with a BPX70 SGE capillary column (60 m × 0.25 µm ID × 320 µm) and operated with a flame ionization detector (FID) maintained at 280˚C. The injector temperature was set at 250˚C, with helium as the carrier gas at 0.7 mL/min. Fractional injection (15:1 ratio) was applied. The oven temperature program was as follows: 175˚C for 10 min, increasing by 3˚C/min to 220˚C for 5 min, then increasing to 280˚C. Fatty

acid identification was performed using GC software by comparing retention times with reference standards. To determine the fatty acid composition, the surface area of each fatty acid was divided by the total surface area of all detected fatty acids, and the result was multiplied by 100.

2.11. Determination of Induction Time

The oxidative stability of the oil sample was evaluated using the Rancimat test (**Figure 2**), in accordance with the standard (ISO 6886, 2016) [25]. This method measures oxidative stability as the oxidative induction time (hours). Briefly, 3 g of the oil sample (*Hibiscus sabdariffa seed oil*) were placed in the reaction vessel of the Rancimat instrument (Metrohm, Herisau, Switzerland). The vessel was then heated to 100℃ with an airflow of 20 L/h. Volatile compounds released during oil degradation were collected in a flask containing 60 mL of distilled water. The conductivity of this solution, which increases with oxidation, was continuously measured and recorded by the Rancimat software. The oxidative stability of the oil sample was determined by analyzing the conductivity curves obtained using the software's extrapolation method. This procedure was repeated at temperatures of 100˚C and 120˚C, and all analyses were performed in duplicate.

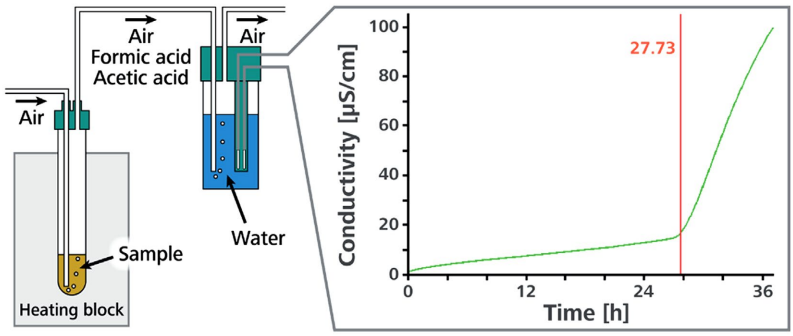


Figure 2. Operating principle of the Rancimat test.

2.12. Statistical Analyses

For the sample, analyses were performed in duplicate (n = 2), and the duplicates correspond to repeated measurements from the same extraction. Standard deviations and mean values were calculated (Mean ± SD). One-way analysis of variance (ANOVA) followed by Tukey's test ($p < 0.05$) was performed using R-4.1.2 software, and graphs were created using OriginPro 2026b software.

3. Results and Discussion

3.1. Moisture Content

Seeds of the white variety of *Hibiscus sabdariffa* cultivated in Senegal exhibit a low moisture content of 7.905% ± 0.005%, corresponding to a dry matter content of 92.095%. This low moisture content generally contributes to their high stability and long shelf life, protects against mold growth, and allows for a high dry matter

yield. Research by [26] and [27] indicated that seed moisture content should fall within the 4% - 8% range to allow for prolonged storage and prevent microbial activity. This moisture content is close to that observed in the sample studied in Egypt by [28] which had a moisture content of 6.97% and higher than that recorded in the sample from Benin (3.98%) studied by [29].

These observed differences confirm that origin, drying and storage conditions, seed maturity stage, and handling can significantly influence moisture content. Compared to other oilseeds, these values are lower than the maximum levels accepted for peanuts (9% w/w DM) [29], cottonseed (9.87 ± 0.10%) [30] and sesame (7% w/w DM) [31], indicating superior quality in *Hibiscus sabdariffa* seeds.

3.2. Ash Content

The ash content of seeds from the white variety of *Hibiscus sabdariffa* is 5.0063% ± 0.001%. This value is close to the 5.73% reported by [28] in Egypt and the 5.64% obtained from seeds analyzed in Benin [32]. These high ash contents indicate that *Hibiscus sabdariffa* seeds could be a good source of minerals.

3.3. Mineral Profiling

Simply analyzing food allows for more precise nutritional information to be obtained. Many physiological and metabolic processes within the human body depend on minerals. We analyzed a wide range of essential mineral elements, including four macro-elements (K, Ca, Na, Mg) and four micro-elements (Zn, Fe, Mn, and Cu). Living organisms contain significant amounts of macronutrients such as potassium, calcium, sodium, and magnesium [33]. The mineral profile of the analyzed seeds is presented in **Table 2**. The results indicate that the white variety of *Hibiscus sabdariffa* cultivated in Senegal was rich in minerals; potassium was the most abundant macro-element (14754.3011 ± 224.5819 mg/Kg), followed by magnesium (4171.393 ± 12.2863 mg/Kg), calcium (3116.3201 ± 4.6873 mg/Kg), and sodium (415.3011 ± 2.4332 mg/Kg). Among the trace elements, iron was the most abundant (76.1828 ± 0.7240 mg/Kg), followed by zinc, manganese, and copper, with 50.0285 ± 0.0472 mg/Kg, 32.664 ± 0.2975 mg/Kg, and 4.4785 ± 0.0488 mg/Kg, respectively. These results are consistent with those reported by [11] and with data on seeds from India and Cameroon [34]-[36], while remaining notably high. In their review, they noted levels of 680 mg/100g for calcium and sodium, 420 mg/100g for magnesium, 1350 mg/100g for potassium, 5.9 mg/100g for zinc, and 8.8 mg/100g for iron. Similarly, these values were significantly higher for the sample of seeds grown in Senegal than for the sample studied in Thailand [2]. The macro- and micronutrient contents of *Hibiscus sabdariffa* seeds specifically K, P, Mg, Zn, Fe, Mn, and Cu were determined to be 2092.50 ± 1.89, 891.22 ± 3.71, 366.00 ± 1.34, 7.17 ± 0.13, 6.81 ± 0.20, 5.88 ± 0.14, and 4.22 ± 0.11 mg/100g of sample, respectively.

The differences observed in this study demonstrate that the plants' place of origin even within the same species can lead to variations in their elemental composition, depending on soil characteristics and environmental contamination.

Table 2. Mineral profile of seeds from the white variety of *Hibiscus sabdariffa* L. cultivated in Senegal.

Mineral profile (mg/Kg)	WHS
Ca	3116.3201 ± 4.6873[c]
Na	415.3011 ± 2.4332[d]
K	14754.202 ± 224.5819[a]
Mg	4171.393 ± 12.2863[b]
Mn	32.664 ± 0.2975[e]
Zn	50.0285 ± 0.0472[e]
Fe	76.1828 ± 0.7240[e]
Cu	4.4785 ± 0.0488[f]

3.4. Extraction of Phenolic Compounds

As part of the assessment of nutrient bioavailability, we determined the maximum concentration of phenolic compounds in the seeds of the white variety of *Hibiscus sabdariffa* cultivated in Senegal, using five different extracts (aqueous, methanolic, 80% methanolic, ethanolic, and ethyl acetate) and two extraction techniques (maceration and ultrasound) to identify the method and solvent best suited to our sample.

3.5. Total Phenolic Content

Figure 3 shows the phenolic compound content of seeds from the white variety of *Hibiscus sabdariffa* originating from Senegal. Based on the data in the graph, water and ethanol are the best extraction solvents, with respective yields of (maceration: 5.065 ± 0.105 mg GAE/g DM and ultrasound: 7.72 ± 0.544 mg GAE/g DM) and (maceration: 3.68 ± 0.01 mg GAE/g DM and ultrasound: 4.065 ± 0.158 mg GAE/g DM). Next come ethyl acetate, 80% methanol, and finally, methanol. Ultrasound-assisted extraction proved to be the most effective method for extracting phenolic compounds, regardless of the solvent used. This highlights the value of this technique as a "green" method capable of extracting a maximum amount of bioactive compounds in a very short time. The phenolic compound contents measured in *Hibiscus sabdariffa* seeds from Senegal were lower than those observed in the sample analyzed in the state of Andhra Pradesh, India (38.41 ± 1.06 mg GAE/g DM) [37] but higher than those analyzed in the Mono department, Benin (0.203 mg GAE/g DM for water and 0.104 mg GAE/g DM for ethanol) [11].

3.6. Total Flavonoid Content

Flavonoids plant-derived compounds responsible for the aroma and color of flowers are found in various parts of the plant [38]. *Hibiscus sabdariffa* contains the following flavonoid subclasses: quercetin, hibiscitrin, chlorogenic acid, luteolin, gossypitrin, protocatechuic acid, gossytrin, eugenol, pelargonic acid, and sterols [39]. Flavonoids offer numerous human health benefits through various mechanisms, notably the neutralization of free radicals. They act on radical molecules to

stabilize and reduce them via direct and indirect processes. Based on the results presented in Figure 4, ethanol and water remained the most effective solvents for extracting flavonoid compounds, with respective yields of (maceration: 40.77 ± 0.007 mg QE/g DM and ultrasound: 39.567 ± 0.354 mg QE/g DM), compared to (maceration: 24.4 ± 0.017 mg QE/g DM and ultrasound: 33.216 ± 0.253 mg QE/g DM). As previously observed, ethyl acetate, methanol, and 80% methanol followed. Compared to other studies conducted on this same variety of *Hibiscus sabdariffa* originating from Senegal, the flavonoid contents obtained in our study are higher than those reported for samples of the white variety of *Hibiscus sabdariffa* grown in the garden of the Laboratory of Physiology and Experimental Pharmacology at the University of Abomey-Calavi, Benin (12.27 mg QE/g DM) [40].

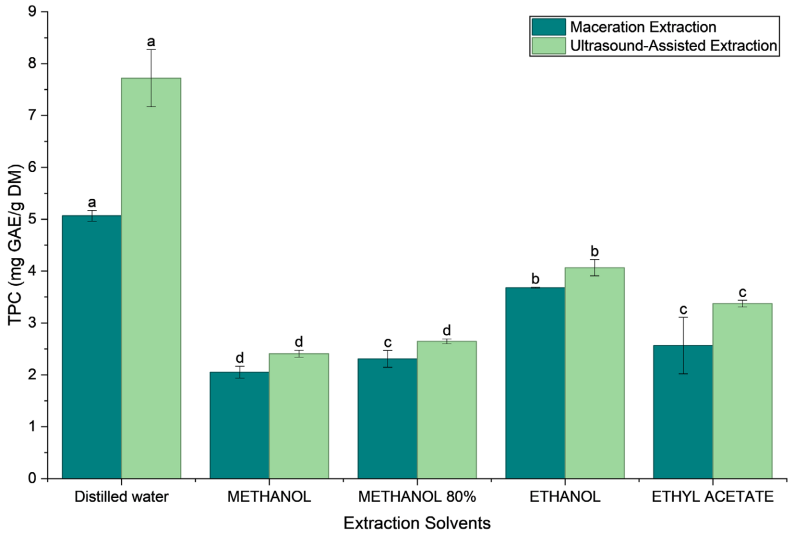


Figure 3. Total polyphenol content in seeds of the white variety of *Hibiscus sabdariffa* L. from Senegal obtained by ultrasound-assisted extraction and maceration extraction.

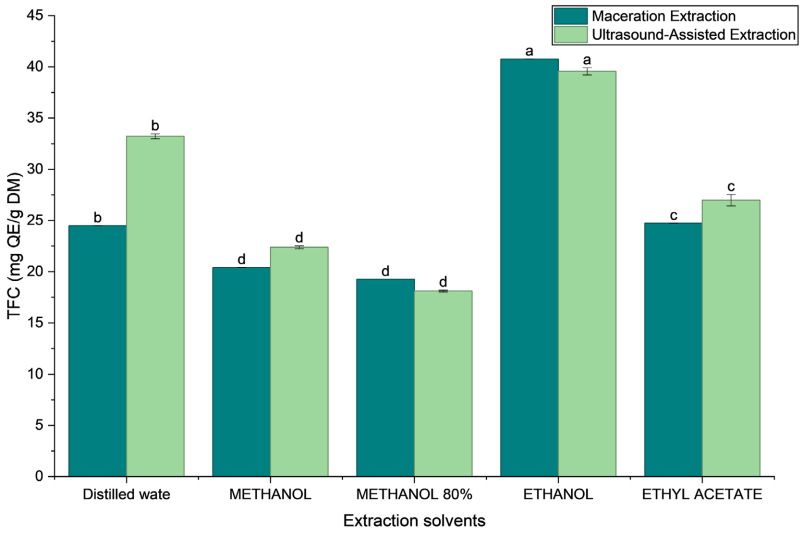


Figure 4. Total flavonoid content in seeds of the white variety of *Hibiscus sabdariffa* L. from Senegal obtained by ultrasound-assisted extraction and maceration extraction.

3.7. Antioxidant Activities

Antioxidants can be broadly defined as substances that, when present at concentrations lower than those of an oxidizable substrate, significantly delay or inhibit the oxidation of that substrate [41]. In other words, antioxidants are substances capable of slowing or halting the oxidation of other molecules by interfering with the initiation or propagation of chain oxidation reactions. Research has shown that free radicals in the human body cause oxidative damage to various molecules such as lipids, proteins, and nucleic acids and are thus associated with the initiation phase of certain degenerative diseases. Consequently, antioxidants can neutralize oxygen-derived free radicals, notably by inhibiting the oxidation of low-density lipoproteins [42].

3.7.1. Antioxidant Activities by FRAP

Figure 5 below shows the antioxidant activities of seeds from the white variety of *Hibiscus sabdariffa* originating from Senegal, as evaluated by the FRAP method. A positive correlation was observed between the antioxidant activities determined by the FRAP method and the polyphenol content. Ultrasound-assisted extraction proved to be the most effective method compared to maceration, regardless of the solvent used. Water (16.629 ± 0.155 mg AAE/g DM vs. 12.597 ± 0.525 mg AAE/g DM) and ethanol (15.177 ± 0.890 mg AAE/g DM vs. 13.226 ± 0.182 mg AAE/g DM) consistently yielded the best results for the evaluation of antioxidant activity. Next came methanol, ethyl acetate, and 80% methanol, with ultrasound-assisted extraction consistently yielding the best results for the evaluation of antioxidant activity. The results obtained in this study are superior to those reported for a sample analyzed in Malaysia, where the activity ranged from 25.23 ± 2.97 to 183.54 ± 3.86 µg AAE/g DM, depending on the method and solvent used [43].

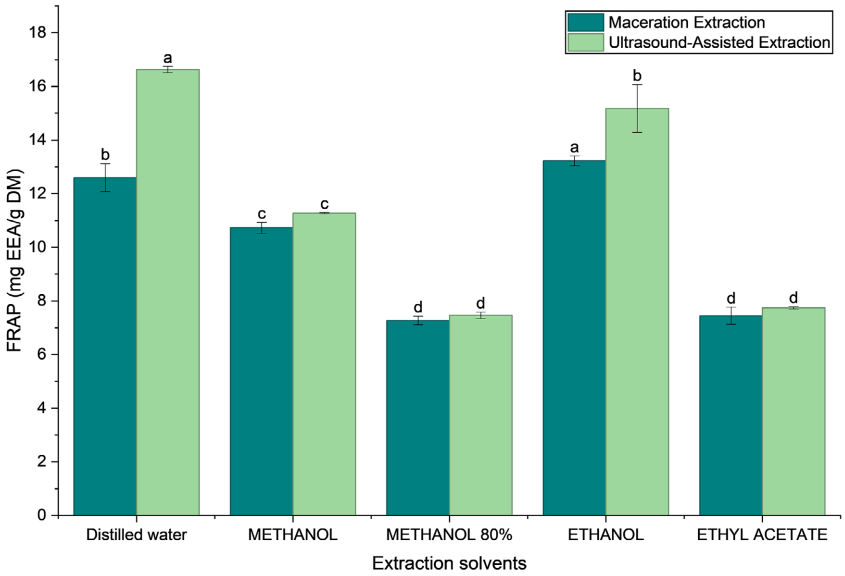


Figure 5. FRAP antioxidant activity of seeds from the white variety of Senegalese *Hibiscus sabdariffa* L. obtained via ultrasound-assisted extraction and maceration extraction.

3.7.2. Antioxidant Activities by DPPH

The free radical-scavenging activity of *Hibiscus sabdariffa* seed extracts was evaluated by measuring hydrogen-donating or radical-scavenging capacity using the stable DPPH (2,2-diphenyl-1-picrylhydrazyl) radical. The DPPH free radical exhibits a dark purple color that turns yellow when the antioxidant compounds present in the *Hibiscus sabdariffa* seed extracts interact with it. The results correlate with polyphenol content, with water and ethanol yielding the highest levels of antioxidant activity, regardless of the extraction method used (**Figure 6**). It is also worth noting that ultrasound-assisted extraction resulted in higher antioxidant activities than maceration for all solvents: water (71.305% ± 0.417% vs. 67.305% ± 1.633%), ethanol (65.385% ± 0.417% vs. 63.850% ± 1.088%), 80% methanol (62.430% ± 2.927% vs. 61.925% ± 0.544%), ethyl acetate (58.580% ± 1.668% vs. 55.765% ± 0.544%), and methanol (34.025% ± 0.417% vs. 32.690% ± 3.804%).

Furthermore, these data corroborate the results reported by [44] [45] who observed strong positive correlations between total phenolic content and antioxidant activity. It has been suggested that the enhanced free radical scavenging activity was attributable to the higher quantity of antioxidants present in the extract.

Seeds from the white variety of *Hibiscus sabdariffa* originating from Senegal exhibited significantly higher levels than those analyzed in Thailand (48.28% ± 1.35%) [2], and by [27] (44.70%), as well as compared to a sample studied in Egypt (56.94%). This phenomenon illustrates how various factors such as the concentration of antioxidant compounds, temperature, pH, and cultivation conditions across geographic regions can strongly influence the antioxidant activity of the crude *Hibiscus sabdariffa* seed extract. All these factors directly affect the synthesis of essential plant substances, particularly bioactive compounds [46]-[48]. Consequently, *Hibiscus sabdariffa* seeds constitute a valuable source of beneficial nutrients and are rich in bioactive compounds, notably antioxidants that are essential for consumers.

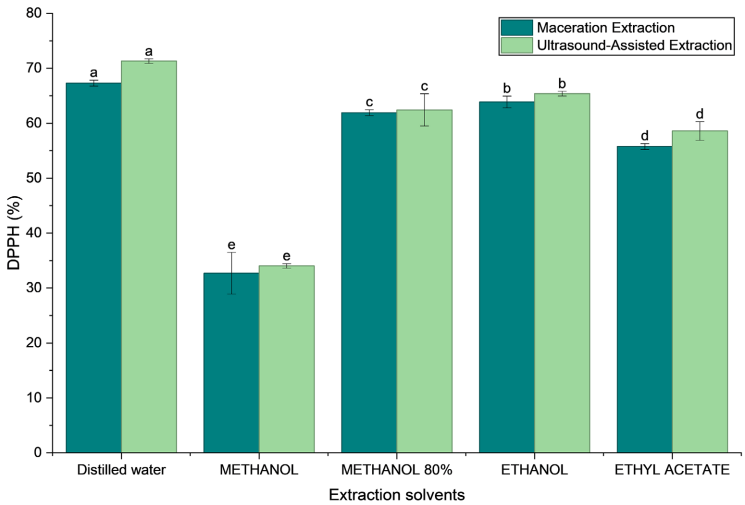


Figure 6. DPPH antioxidant activity of seeds from the white variety of *Hibiscus sabdariffa* L. from Senegal, obtained via ultrasound-assisted extraction and maceration extraction.

3.8. Oil Content

The oil extracted from the seeds of white-flowered *Hibiscus sabdariffa* native to Senegal is greenish-yellow in color. The oil yield (19.12%) obtained in this study is close to that reported for samples from Egypt (18.98%) [49] and Sudan (21.1%) [50], but lower than that observed for samples from Côte d'Ivoire (24.53%) [51] and Congo-Brazzaville (23.27%) [52]. However, this yield is higher than those recorded in Nigeria (17.8%) [53] and Benin (13.6%) [11].

Nevertheless, the oil content obtained via mechanical pressing was significantly lower than that obtained via solvent extraction (MEWHS: 6.03% ± 0.327% vs. SEWHS: 19.12% ± 0.564%).

The observed differences may be attributed to soil characteristics, the harvest period, storage conditions, or the type of treatment applied to the plant material prior to vegetable oil extraction.

3.9. Fatty Acid Profile (FAP)

Fatty acid composition analysis is essential for evaluating both the nutritional value and the oxidative stability of vegetable oils [54]. Examination of the lipid profile of oil extracted from white *Hibiscus sabdariffa* seeds from Senegal via mechanical pressing and solvent extraction revealed a predominance of unsaturated fatty acids, as illustrated in **Table 3**, particularly linoleic acid, (C18:2) (MEWHS: 41.76% ± 0.020% vs. SEWHS: 40.495% ± 0.455%) and oleic acid (C18:1) (MEWHS: 27.380% ± 0.060% vs. SEWHS: 26.685% ± 0.275%). The higher fatty acid levels observed in the oil obtained by mechanical pressing may be attributed to the fact that the heat applied during Soxhlet extraction can break chemical bonds, thereby resulting in lower levels of (C18:1) and (C18:2) in the oil extracted using that method. Among the saturated fatty acids, palmitic acid (C16:0) is the most abundant (MEWHS: 22.990% ± 0.010% vs. SEWHS: 23.145% ± 0.275%), followed by stearic acid (C18:0) (MEWHS: 5.630% ± 0.030% vs. SEWHS: 7.135% ± 1.155%).

Table 3. Fatty acid profiling of oil extracted from the seeds of the white variety of *Hibiscus sabdariffa* L. from Senegal, obtained by Soxhlet extraction (SEWHS) and mechanical pressing (MEWHS).

FAP	MEWHS	SEWHS
C12:0	0.290 ± 0.010^{b}	0.620 ± 0.010^{a}
C14:0	0.465 ± 0.015^{b}	0.615 ± 0.015^{a}
C16:0	22.990 ± 0.010^{a}	23.145 ± 0.275^{a}
C16:1	0.505 ± 0.015^{a}	0.460 ± 0.020^{a}
C17:0	0.125 ± 0.005^{a}	0.110 ± 0.000^{a}
C17:1	0.115 ± 0.005^{a}	0.115 ± 0.005^{a}
C18:0	5.630 ± 0.030^{b}	7.135 ± 1.155^{a}
C18:1	27.380 ± 0.060^{a}	26.685 ± 0.275^{a}
C18:2	41.76 ± 0.020^{a}	40.495 ± 0.455^{a}

Continued

C18:3	**0.180 ± 0.000[a]**	**0.215 ± 0.015[a]**
C20:0	0.555 ± 0.015[a]	0.390 ± 0.090[b]
C20:1	-	-
AGS	30.055 ± 0.025[b]	32.015 ± 0.765[a]
AGMI	28 ± 0.040[a]	27.260 ± 0.300[b]
AGPI	41.940 ± 0.020[a]	40.710 ± 0.559[a]

The results of this study show that oils derived from the seeds of the white variety of *Hibiscus sabdariffa* cultivated in Senegal are characterized by a predominance of polyunsaturated fatty acids (PUFAs), followed by saturated fatty acids (SFAs), while monounsaturated fatty acids (MUFAs) are present in lower proportions. This composition gives the oil significant nutritional and cosmetic value, although the high content of unsaturated fatty acids may affect its thermo-oxidative stability. However, these observations are corroborated by previous studies conducted by other researchers on *Hibiscus sabdariffa* oil, such as those by [55] in Benin, and [56] in Nigeria. This fatty acid profile is also comparable to that of cactus oil [18] [57], sunflower oil [58] and black cumin oil [19], whose lipid composition is primarily dominated by these four fatty acids (linoleic, oleic, palmitic, and stearic acids).

3.10. Induction Time

The Rancimat test evaluates the oxidative stability of oils by measuring their induction period, which reflects their ability to resist oxidation when exposed to high temperatures and oxygen [59]. Numerous studies have demonstrated that oxidation resistance is a key characteristic of vegetable oils. Indeed, the oxidation of vegetable oils involves a complex series of reactions leading to the development of unpleasant odors, rancidity, and flavor deterioration [60]. This phenomenon is a decisive factor in oil quality during both production and storage. It is also the process most detrimental to the final nutritional and sensory quality of the oils [61]. Consequently, the shelf life of vegetable oils depends on their oxidative stability [62] [63]. t should also be noted that during the oxidation process, toxic compounds such as reactive carbonyls can contribute to the formation of advanced lipid peroxidation products, which may pose a risk to human health [64]. Many factors can contribute to oil oxidation, including high temperatures, storage conditions, high oxygen availability, fatty acid composition and the degree of polyunsaturation, as well as the presence of pro-oxidant substances such as chlorophyll, heavy metals, and metal ions (Fe^{3+} and Cu^{2+}) [65] [66].

The results of this study show that the induction times obtained via the Rancimat test for oils extracted from the seeds of the white *Hibiscus sabdariffa* variety originating from Senegal at various temperatures were higher for oils obtained by mechanical pressing than for those obtained by solvent extraction. At 100˚C, the oils exhibited induction times of 12.64 h (MEWHS) versus 11.48 h (SEWHS), in-

dicating superior stability for the mechanically pressed oil. These observations were confirmed at 110˚C, a temperature at which the mechanically extracted oil again demonstrated greater stability (MEWHS: 6.84 h vs. SEWHS: 6.75 h). The induction time obtained in this study is slightly shorter than that reported by [67], which was 15.53 h, as well as that reported by [49] whose induction times ranged from 12 h to 20 h depending on the extraction method used. The high induction times observed for *Hibiscus sabdariffa* oil confirm the good stability of this oil derived from seeds little known in Senegal while demonstrating superior stability for the oil extracted by mechanical pressing.

4. Conclusion

Varietal difference, in the nutritional profile, antioxidant activity and fatty acid composition of white *Hibiscus sabdariffa* were assessed. The seeds showcased a good source of minerals as well as high level of bioactive compound, especially flavonoids, resulting in strong antioxidant capacity. At the same time, Soxhlet extraction yielded a higher oil output than mechanical screw-press extraction. A high proportion of unsaturated fatty acids was obtained, dominated by linoleic and oleic acids, alongside saturated fatty acids such as palmitic and stearic acids. In addition, favorable oxidation stability was achieved with the oil obtained from mechanical extraction. These particular richness in phytochemicals could be used in the future in nutraceuticals, pharmaceutical devices and cosmetics formulations.

Conflicts of Interest

The authors declare no conflicts of interest.

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