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Influence of Culinary Practices on the Physicochemical, Rheological, and Functional Properties of *Irvingia gabonensis* Kernels Harvested in the East Cameroon Region

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ABSTRACT

This study aimed to investigate and assess the effects of cooking treatments on the techno-functional properties of *Irvingia gabonensis* kernels. Roasting, smoking, and solar drying were the main processing methods used. The treatments significantly ($p < 0.05$) influenced the chemical composition. Roasting had the greatest effect on water content, while lipid and protein content decreased with drying, followed by roasting (10.55%) and simple roasting (52.45%). Calcium and phosphorus were the most abundant minerals in the kernels. The pH decreased with the cooking treatments, from 6.01 to 4.31. Water and oil retention capacity and swelling rate varied between 23% and 50%, 53.79% and 61.21%, and 72.93% and 83.88%, respectively. All treatments reduced the phytate content, while the opposite effect was observed with oxalates. Roasting and blanching played a crucial role in removing saponins and tannins. Drying followed by roasting resulted in a significant browning of the kernels. All the rheological parameters decreased significantly with the treatments ($p < 0.05$). Drying + boiling yielded the most amino acids (10), whereas roasting yielded the least (6). Given these results, it would be important to take into account the type of cooking treatment when using *I. gabonensis* kernels in order to benefit from the desired properties.

1 | Introduction

Food security is defined as access by all people, at all times, to sufficient, safe, and nutritious food for an active and healthy life. However, malnutrition, which is related to the lack of certain nutrients in the diet, is a huge and persistent problem in developing countries like Cameroon (FAO 2010). In Cameroon, 29% of children under five are stunted or chronically malnourished, and 14% are severely stunted. Wasting also affects 4% of children and 2% in its severe form. Finally, underweight affects 11% of children under the age of five, and 3% are severely underweight (NIS 2018). In the East Cameroon Region, 37% of children under five suffer from chronic malnutrition, making this region the second most affected by malnutrition (NIS 2018). To address this problem, the people of this forested area try as best they can to obtain quality food from market outlets, but given the prevalence of poverty, this supply remains limited in time. They are therefore turning to conventional and non-conventional agroforestry products, including the kernels of many fruits such as Irvingia. In the search for nutritious foods and in-depth knowledge of these foods, emphasis has been placed on the development of local products, especially forest

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Summary

- Before using *Irvingia gabonensis* kernels for their sauces, we encourage the populations of the East Cameroon Region to subject the kernels to the combination of culinary practices such as roasting + boiling (G + B) or drying + roasting + boiling (S + G + E) or (drying + roasting) S + G or drying + boiling (S + E) in order to optimize the nutritional quality of the meal.
- One of the primary challenges encountered during dietary diversification in infants is micronutrient deficiency. These deficiencies are not always due to inadequate intake, but are often caused by anti-nutritional factors that interfere with nutrient absorption. Based on our findings, we recommend that *I. gabonensis* kernels be roasted (G) prior to their introduction in the diets of infants and young children, as this treatment was the most effective in reducing anti-nutrient levels.
- Our study also revealed that *I. gabonensis* kernels are rich in calcium, regardless of the processing method applied. However, the combined drying and roasting treatment (S + G) resulted in the highest calcium concentration. This processing method may therefore be particularly recommended for incorporating *I. gabonensis* kernels into the diets of older adults, with the aim of supporting optimal bone and dental mineralization.

products, which have a very high nutritional potential. These non-wood products are of vital importance in nutrition and the fight against many diseases. According to the World Health Organization (WHO), wild products help to meet the health and nutritional needs of almost 80% of the population and contribute to their cultural and economic development (Andel 2006). *Irvingia gabonensis* is also known as the "wild mango of Africa" and is known by different names depending on its origin: "andok" in Ewondo, "ando'o" in Bulu, "ndoka" in Bassa (Matig et al. 2006). For centuries, local people in West Africa have used the seeds of this tree for their medicinal properties.

Nutritionally, the studies on *I. gabonensis* kernels showed a composition average of 4% water, 697 kcal of metabolizable energy, 8.5% protein, 67% lipids, and 15% carbohydrates (Veronika et al. 2018). *I. gabonensis* kernels are also an important source of micronutrients such as calcium (120 mg/100 g). However, the nutrient bioavailability and digestibility of *I. gabonensis* kernels are negatively impacted by the presence of anti-nutrients. In fact, oxalates (380 mg/100 g), tannins (660 mg/100 g), and phytates (20 mg/100 g) can interfere with the absorption of key nutrients (Onojah et al. 2018). The presence of these anti-nutrients, therefore, suggests the development or application of strategies aimed at reducing their concentrations. Authors such as Bayomy et al. (2023) reported that roasting reduced the anti-nutrient content but also affected color, protein digestibility, and amino acid availability. Similarly, Gindo et al. (2020) reported that boiling (95°C) for 45 min and roasting at 120°C for 45 min followed by solar drying resulted in a significant reduction in anti-nutrient content. None of these studies investigated the combined effect of cooking treatments such as drying plus grilling, drying plus boiling (blanching), boiling plus roasting, and drying plus grilling plus boiling. Furthermore, we did not find any studies on the effect of cooking treatments on *I. gabonensis* almonds in Cameroon. Because of the above, the general objective of this work was to assess the effect of a few locally applied culinary practices on the physico-chemical and functional properties of *I. gabonensis* kernels harvested in the East Cameroon Region.

2 | Materials and Methods

2.1 | Material

2.1.1 | *Type of Study*

The study was carried out in two phases: a descriptive phase consisting of a survey of culinary practices involving *I. gabonensis* kernels in the town of Batouri and an experimental phase based on an analysis of the physico-chemical and techno-functional properties of *I. gabonensis* kernels that have undergone various processes.

2.1.2 | *Study Area*

The town of Batouri (4°25′ North; 14°22′ East) is located in the Department of Kadey, 90 km from the capital of the East Cameroon region by tarmac road. It is bordered to the north by the division of Ketté, to the east by the Central African Republic, to the south-east by the division of Kentzou, to the south by the divisions of Mbang and Ndélelé, and to the west by the departments of Lom and Djerem. The average annual temperature in Batouri is 32°C, and rainfall averages 513.3 mm.

2.1.3 | *Material Used*

The material used consisted of survey forms for collecting data on knowledge of the fruit and pods of *I. gabonensis* from which the fresh kernels were extracted (Figure 1).

2.2 | Methods

2.2.1 | *Knowledge Survey*

In order to assess the level of consumption and the various processing techniques for *I. gabonensis* kernels in the East Cameroon region, knowledge surveys were carried out in the town of Batouri using a questionnaire in July 2023 on a random sample of 60 people, mainly female. The questionnaire was designed to provide important information, particularly on the variety of kernels and the culinary practices commonly used. During each interview, the emphasis was placed on the different cooking methods and information on the nutritional and therapeutic virtues. The questionnaire was semi-administered, and the respondent had the opportunity to select many answers. Each interview lasted around 15 min.

2.2.2 | *Sampling and Processing of* I. gabonensis *Kernels*

Once the surveys had identified the variety of *I. gabonensis* kernel most commonly consumed and the common culinary



FIGURE 1 | *Irvingia gabonensis* kernels.

practices and conditions, the kernels were collected from merchants in the town of Batouri, broken to extract the kernels, and transported in an icebox to the Biochemistry Laboratory of the University of Dschang, Cameroon, for processing. The kernels obtained were separated into six batches of 120 g each. The first batch was dried at 50°C for 35 h, the second was dried under the same conditions before being roasted at 120°C for 7 min, the third, after drying, was boiled at 90°C for 7 min before another drying stage, and the fourth batch was dried + roasted + boiled under the same conditions as above. The fifth and sixth batches were respectively roasted (fresh *kernels*) and boiled (fresh *kernels*) under the aforementioned conditions before drying, as well as under the aforementioned conditions. The dry *kernels* obtained were ground using an Anton Moulinex (800 W power for five cycles of 1 min each). The samples obtained were stored in polyethylene bags and then placed in a desiccator before being analyzed.

2.2.3 | *Determination of the Physicochemical and Functional Properties of* I. gabonensis *Kernels*

2.2.3.1 | *Physicochemical Analyses*

Moisture content was assessed according to the protocol described by the International Union of Pure Applied Chemistry (IUPAC 1979) after drying at 105°C in a ventilated oven ("Venticell") until a constant mass was obtained after two weighings. The Soxhlet method of Association of Official Analytical Chemists (AOAC 1990) using hexane as the extraction solvent was used to quantify total lipids. The transformation of organic nitrogen into ammoniacal nitrogen following the mineralization of the proteins by concentrated sulfuric acid made it possible to determine the total protein content (AOAC 1990). The protein content was deduced from the nitrogen content according to the following formula:

$$\%\text{Protein} = \%N \times \text{conversion factor} \quad (1)$$

where the conversion factor is equal to 6.25 if it does not exist.

The AOAC (AOAC 1990) standard method was used to quantify total fibers after digestion with 1.25% sulfuric acid under a hot plate previously calibrated at 90°C for 30 min. Total ash was obtained after incineration of the samples at 550°C in a Perkin Elmer (USA) muffle furnace in an oxidizing atmosphere (AOAC 1990). Digestible carbohydrates were obtained by difference according to the following formula (AOAC 1990):

$$\%\text{Digestible carbohydrate} = 100 - (\%\text{protein} + \%\text{lipid} + \%\text{ash} + \%\text{fiber}) \quad (2)$$

Metabolizable energy expressed in kcal/100 g was determined using the coefficients of Atwater and Rosa (1899) and calculated according to the following equation:

$$\text{Metabolizable energy (kcal/100g)} = \%\left((\text{lipids} \times 9) + (\text{proteins} \times 4) + (\text{glucids} \times 4)\right) \quad (3)$$

The various minerals Ca, Mg, Na, K, P, Zn, and Fe were determined on ash digested with the HNO3/HCl mixture (AOAC Association of Official Analytical Chemists 1990). The digestate was read using an atomic absorption spectrophotometer (BIOBASE BK-D590, spectrophotometer) at different wavelengths characteristic of the ions to be quantified. The Ca:Mg, Ca:P, and Na:K ratios were also assessed.

2.2.3.2 | *Assessment of Anti-Nutrient Content and Anti-Nutrient/Mineral Ratio*

Oxalate content was determined using the method described by Day and Underwood (1986). This consisted of extracting the oxalates in 1.5 M H_2SO_4 for 24 h, followed by colorimetric titration with 0.1 M $KMnO_4$ until the solution turned a

persistent pink color for 30 s. The oxalate content, expressed in mg/100 g, was determined using the following formula:

$$0.\ 1\ \text{mL}\ 0.\ 1\ \text{M}\ KMNO_4 = 4.50\ \text{mg oxalate} \quad (4)$$

The standard titrimetric method described by the AOAC (1990) was used to quantify the phytates in the various samples. Two (2) g of sample were placed in a 250 mL Erlenmeyer flask, 100 mL of 2% HCL was added, and the flask was left to stand for 15 h. Fifty (50) mL of filtrate was added to a 250 mL Erlenmeyer flask with 107 mL of distilled water, then 10 mL of 0.3% KSCN was added, and the whole was titrated with a solution of $FeCl_3{\cdot}6H_2O$ containing 0.00195 g of iron per mL. The phytate content, expressed in mg/100 g, was determined using the following formula:

$$\text{Phytates} = \frac{X \times 1.19}{0.00195} \quad (5)$$

with X corresponding to the descent of the buret.

Regarding condensed and hydrolysable tannins, the method described by Gaytán-Martínez et al. (2017) was used to quantify them after extraction in a 1% MeOH/HCl solution. Condensed tannins were quantified by mixing 1 mL of the extract collected with 5 mL of the reagent solution (50 g vanillin and 8 mL hydrochloric acid in 100 mL distilled water), and the whole was incubated at 30°C for 20 min, then the absorbance was read at 500 nm against a blank. Hydrolysable tannins were read at 660 nm after mixing 500 µL of extract with 1.75 mL of reagent solution (0.01 M $FeCl_3{\cdot}6H_2O$ in 0.001 M HCl). The tannin content, expressed as mg catechin equivalent per gram of extract (mg CE/g), was calculated using a catechin calibration line.

The saponin content was determined using the method described by Kozioł (1992), which involved measuring the height of the foam in each sample consisting of 0.5 g of powder and 5 mL of distilled water.

The bioavailability of minerals was also determined by evaluating the molar ratios between oxalates, phytates, and divalent cations.

2.2.3.3 | *Assessment of pH, Techno-Functional Properties, and Color Parameters*

The standard AOAC (1990) method was used to measure the pH of the samples. Water and oil retention capacities (WRC and ORC) were assessed using the protocol described by Lin et al. (1974) and partially modified by Tambo, Klang, Ndomou, Teboukeu, et al. (2019) and Tambo, Klang, Ndomou, Kohole, et al. (2019). To do this, 10% (W/V) powder solutions were prepared and left at room temperature for 20 min, then centrifuged at 4500 rpm for 15 min. The volume of water or oil not absorbed was measured, and the results expressed in % were determined according to the following formula:

$$\text{WRC/ORC}(\%) = ([(V_i - V_f) \times 100])/V_i \quad (6)$$

where V_i is the initial volume of water or oil, V_f is the volume of water or oil after centrifugation, and WRC/ORC is the water or oil retention capacity.

The water or oil affinity of each sample was assessed by determining the ORC/WRC ratio.

CIELAB parameters were assessed using a Colorflex-EZ colorimeter (Hunter Associates, Reston, VA, USA). To achieve this, a white-colored paper was used as a standard and calibration tool before 10 g of each sample was placed at the bottom of the glass cone (the entire surface), and a flash from the device brought out the values of the parameters l^*, a^*, and b^*. The degree of browning was calculated using the following equation from Felisberto et al. (2015).

$$\text{Browning Index} = \frac{100 \times (X - 0.31)}{0.\ 172} \quad (7)$$

with

$$X = \frac{a^* + 1.75l^*}{5.645l^* + (a^* - 3.012b^*)}$$

2.2.3.4 | *Assessment of Rheological Properties*

The protocol described by Sánchez et al. (2009) was used to assess the rheological or techno-functional potential of the different samples. To do this, 3 g of each sample was mixed with 20 mL of distilled water (15% concentration), and the whole was introduced into the Rapid ViscoAnalyser (MCR-52, Anton Paar) previously calibrated at 50°C. Measurement began with an initial rotation at 960 rpm for 10 s before lowering and maintaining at 160 rpm. The analysis parameters were measured in the following stages: holding at 50°C for 1 min, heating from 50°C to 90°C at a velocity of $6°C{\cdot}min^{-1}$, cooling at 50°C at a rate of $12°C{\cdot}min^{-1}$ and finally holding at 50°C for 2 min. The results of the rheological profile were analyzed using RHEOPLUS/32 Service V3.62 21000071-33086, and parameters such as pasting temperature (PT), pasting time (PTim), peak viscosity (PV): first peak viscosity following the pasting), holding viscosity (HS), and finally final viscosity (FV) were determined. In addition, four parameters were then calculated: the breakdown (BD) (PV-HS), the Set-Back (SB) estimated by (FV-HS), the Stability Ratio (STR) (HV/PV), and the Set-Back Ratio (SBR) (FV/HV). (BD) (PV-HS), the set-back (SB) estimated by (FV-HS), the stability ratio (STR) (HV/PV), and the set-back ratio (SBR) (FV/HV).

2.2.3.5 | *Determination of Thermal Properties and PRAL Index*

Additivity equations were used to determine the thermal properties of *I. gabonensis* seeds according to the formula of Akeem Olayemi and Rahman (2013). These parameters (specific heat capacity, thermal conductivity and thermal diffusivity) were evaluated according to the weight content of moisture, lipids, ash, protein, and carbohydrate using the following equations:

$$\begin{aligned}\text{Specific heat capacity}\left(C_p\ \text{in}\frac{\text{kJ}}{\text{K}}\right) = {} & 1.\ 424 \times \text{glucids} \\ & + 1.\ 549 \times \text{proteins} \\ & + 1.\ 675 \times \text{lipids} \\ & + 0.\ 837 \times \text{ash} \\ & + 4.\ 187 \times \text{moisture}\end{aligned} \quad (8)$$

$$\text{Thermal conductivity}\left(K \text{ in}\frac{W}{m.k}\right) = 0.25 \times \text{glucids} + 0.155 \times \text{proteins} + 0.16 \times \text{lipids} + 0.135 \times \text{ash} + 0.58 \times \text{moisture} \quad (9)$$

$$\text{Thermal diffusivity} \quad (D \text{ in } m^2/s) = (0.082 \times \text{glucids} + 0.0075 \times \text{proteins} + 0.10 \times \text{lipids} + +0.146 \times \text{moisture}) \times 10^{-6} \quad (10)$$

The PRAL score was evaluated to determine the degree of acidity or basicity released by the seeds after consumption. It was determined according to the following equation:

$$\text{PRAL score} = ((0.0366 \times P + 0.488 \times \text{proteins}) - (K \times 0.0205 + 0.0125 \times Ca + +0.0263 \times Mg) \quad (11)$$

2.2.3.6 | *Determination of Amino Acid Composition*

The amino acid profile expressed in mmol/L was assessed following the protocol described by John et al. (1999) and Savych et al. (2022). Extraction and digestion consisted of complete hydrolysis of 0.5 g of each sample in 50 mL of 6 M HCl at 110°C for 17 h. After digestion, the digestion solvent was removed by rotavapor concentration, and the residue was suspended in 25 mL citrate buffer pH 2.2, then filtered through a millipore membrane (0.45 μm). A volume of 1 μL of each filtrate was injected into the first column (Pursuit XRs C18 Analytical column, 150 mm × 4.6 mm × 3 μm) and then a second (Zorbax Eclipse Plus C18, 4.6 mm × 12.5 mm × 5 mm) of an Ultra High-Performance Liquid Chromatography (Agilent 1290 Infinity II) fitted with a Diode Array Detector (1260 Infinity II). The column temperature was calibrated at 40°C, and the flow rate of each sample was 1.5 mL/min. The peaks corresponding to each amino acid were detected at 230 nm emission and 360 nm excitation. The results were analyzed using OpenLab CDS software.

2.3 | Statistical Analysis

Data processing was carried out using Microsoft Excel 2013 and Sphinx Plus^2 Edition Lexica-V5 for the descriptive study. The results of the experimental analysis were expressed as the mean ± standard deviation, and the statistical differences between the values were established using the analysis of variance (ANOVA) test. Significant differences were compared using Fisher's test at the 5% probability level, using Minitab 18.1 software. XLSTAT 2014 was used to perform the principal component analysis (PCA).

3 | Results and Discussion

3.1 | Knowledge Survey on *I. gabonensis* Kernels

3.1.1 | *Socio-Demographic Data*

Figure 2 shows the results of the socio-demographic survey. It shows that of the 60 people chosen at random for our survey, the majority were female and from the Eastern Region (33 people), representing 55% of all respondents. This can easily be explained by the fact that the Eastern Region was the one used for this study, and in this region, as almost everywhere else in Cameroon, women are responsible not only for work in the fields but also for cooking.

3.1.2 | *Knowledge and Supply of* Kernels

The time and place of supply of *kernels* are shown in Figure 3A,B. According to the people interviewed, *kernels* are very common in the town because they are consumed by the local population, and the supply period is between July (35.10%), August (56.10%), and September (8.80%). The main sources of *kernels* are the market (88.30%) and harvesting in the forest (6.70%). These results corroborate those of Harris (1993), who showed that the almond harvesting period extended from July to September, with *kernels* being harvested preferentially in markets. Apart from the harvest periods, 96.70% of respondents knew *I. gabonensis* kernels by different names depending on the locality, such as "Ndo'o," "Biba," "Nouak," "Andok," "Diba,"

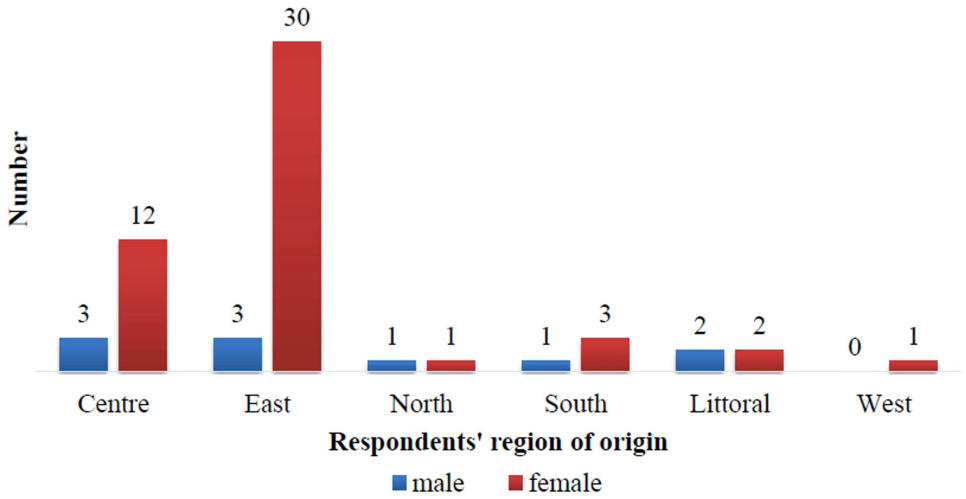


FIGURE 2 | Socio-demographic data for participants based on gender.

and "Mangoro," but the best known was "wild mango" (Harris 1993). This variation in names is undoubtedly linked to the ethnic diversity of the populations.

3.1.3 | *Culinary Practices for Kernels*

Of the different methods of processing *kernels* (Figure 4), 57% of people use drying, 50% roasting or toasting, 42% blanching, 14% smoking, and 8% oil frying. The preponderance of solar drying, roasting, and smoking can be explained by the fact that these different methods are easy to implement. In fact, solar drying is the main method of post-harvest conservation of kernels because the Eastern Region is an area where the average temperature is 30°C throughout the year. Because of its rural nature, people have granaries in their kitchens where they can dehydrate all the produce from the fields, such as seeds and *kernels*. Roasting, meanwhile, is an old cooking method that is commonly used to cook *kernels* and pulses, hence its widespread use.

3.1.4 | *Approximate Duration of the Various Treatments (Drying, Smoking, Blanching, and Roasting)*

Figure 5 shows the approximate duration of the various treatments listed above. The necessary times for these different practices were brought to our attention, and it follows that 58.90% of the respondents (Figure 5A) carried out solar drying for 1–3 weeks, while 41.10% did so for 1–3 days. These solar drying times also resulted in a water loss of almost 88% and limited the attack of mold on the food, thus improving preser-

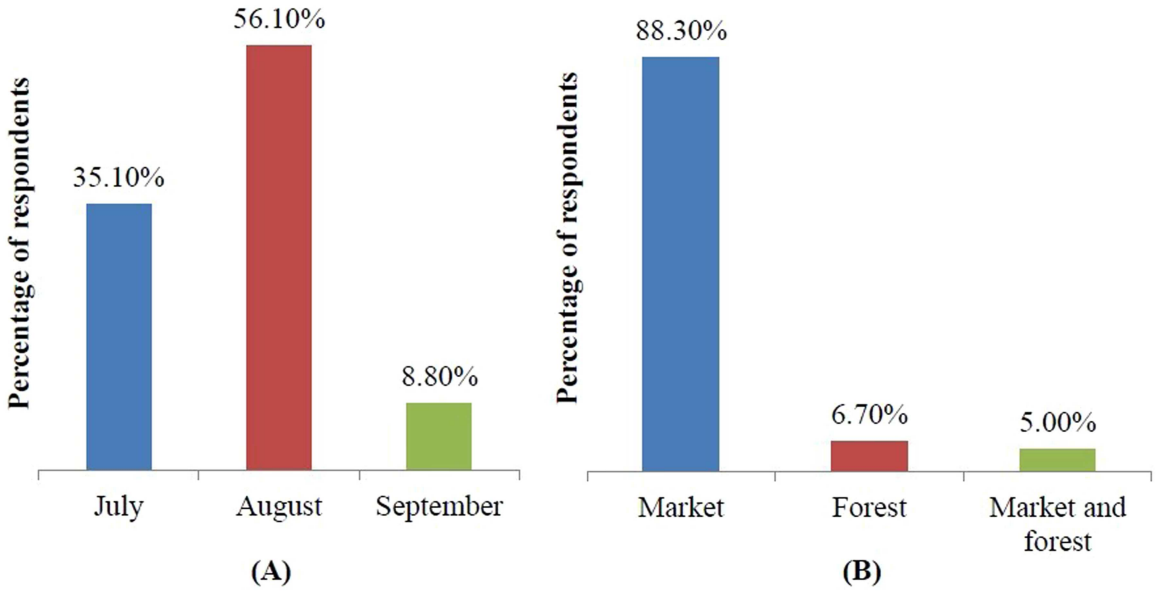


FIGURE 3 | Period (A) and place of supply (B) of *kernels*.

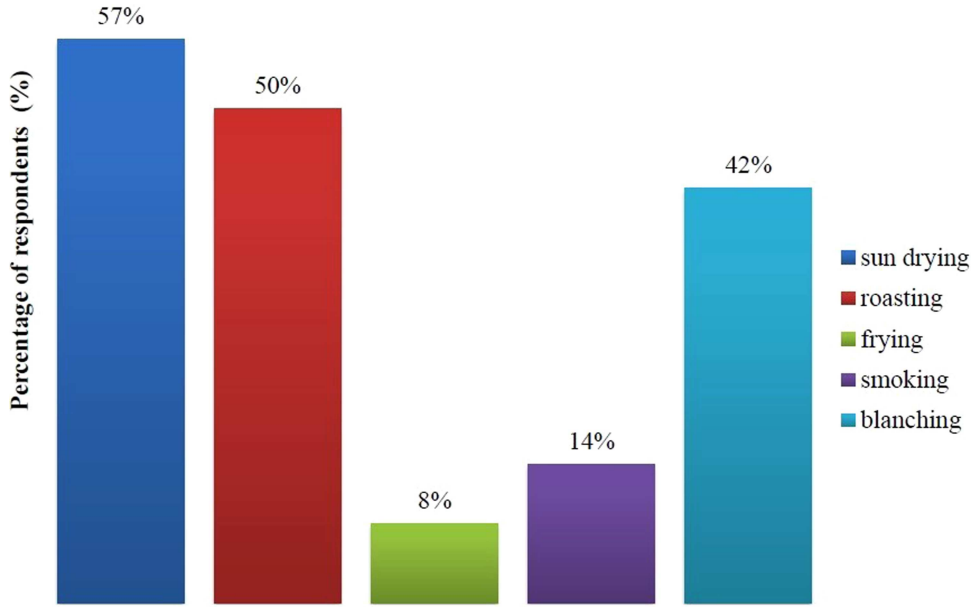


FIGURE 4 | The different ways of cooking *kernels*.

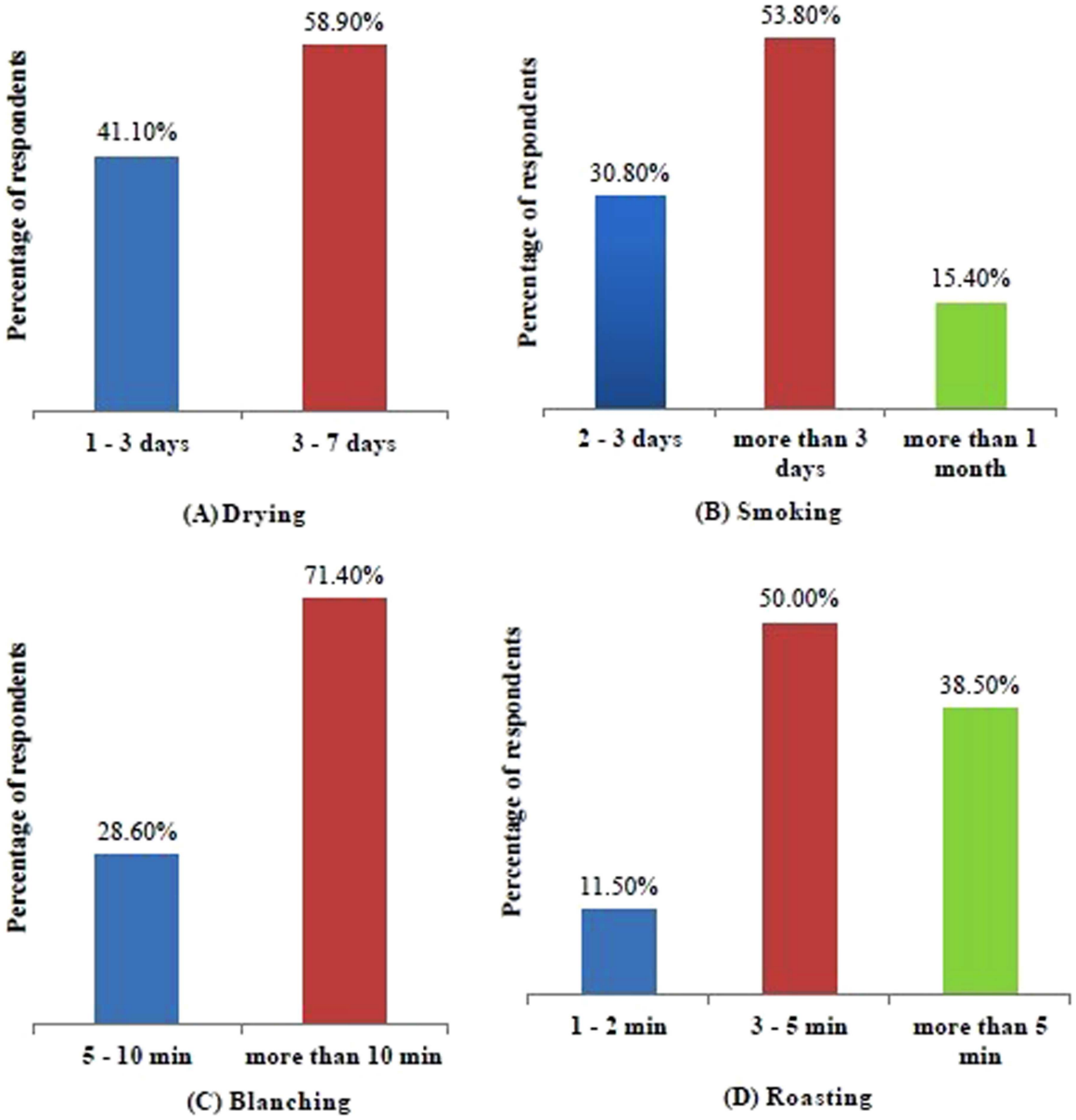


FIGURE 5 | Approximate duration of the various treatments. (A) Drying. (B) Smoking. (C) Blanching. (D) Roasting.

vation. As for smoking (Figures 5B), 53.80% took more than 3 days, 30.80% 2–3 days, and 15.40% more than a month. For blanching (Figure 5C), 71.40% took more than 10 min, and 28.6% between 5 and 10 min. Figure 5D shows that 50% of respondents roasted *kernels* for 3–5 min, while 38.50% did so for more than 5 min and 11.50% for between 1 and 2 min. These data reveal the diversity of culinary practices associated with *I. gabonensis kernels* and underline the importance of this resource for the diet of local populations. It was reported during the survey that processing time has a significant impact on the texture of the final product. Indeed, participants revealed that reducing the roasting time would reduce the texture of the final product. Indeed, participants revealed that lowering the roasting time also reduced the stickiness of dishes cooked with these *kernels* and improved the taste and smell. The work carried out by Awono and Manirakiza (2007) also demonstrated a loss of viscosity as the roasting time increased. It is therefore necessary to limit the roasting time of *kernels* to obtain better viscosity. In addition to the importance of these treatments for preservation, the people surveyed also reported an influence of the treatment conditions on the nutritional properties, in particular the glucose, iron, fiber, and vitamin C content, but also on the therapeutic properties, such as the treatment of coughs, ringworm, and stomach aches. What's more, the nature of the treatment also determines the nature and name of the dish. So there are several names for these dishes, including Glutinous Sauce, Ndo'o Sauce, Nouak Sauce, Biba Sauce, Ndika Sauce, Glutinous Peanut Sauce, and Ndoko'o Sauce.

3.2 | Proximate Chemical Composition of *I. gabonensis* Kernels

Moisture content predicts the stability of a product during storage and transport (Tambo, Anicet, et al. 2024; Tambo, Ndomou, et al. 2024). Table 1 shows a significant increase

TABLE 1 | Proximate chemical composition of *Irvingia gabonensis* kernel samples.

Treatments	Moisture (%)	Ash (%)	Fibers (%)	Glucids (%)	Proteins (%)	Lipids (%)	Energy (kcal/100 g)
G	12.98 ± 3.98^{a}	3.80 ± 0.28^{a}	4.65 ± 0.04^{a}	11.87 ± 1.88^{a}	14.24 ± 0.45^{c}	52.45 ± 2.88^{b}	576.56 ± 31.64^{b}
S	4.00 ± 0.99^{b}	2.65 ± 0.07^{c}	2.30 ± 0.17^{c}	7.89 ± 1.16^{b}	16.18 ± 0.45^{b}	66.97 ± 2.72^{a}	699.06 ± 18.00^{a}
S + G	3.99 ± 0.98^{b}	3.55 ± 0.07^{a}	2.11 ± 0.02^{c}	11.36 ± 4.29^{a}	10.55 ± 0.18^{e}	68.43 ± 4.78^{a}	703.57 ± 26.63^{a}
S + E	6.23 ± 0.48^{b}	1.85 ± 0.07^{d}	3.48 ± 0.29^{b}	14.21 ± 2.14^{a}	12.36 ± 0.18^{d}	61.26 ± 2.57^{a}	663.32 ± 13.88^{a}
G + E	7.59 ± 1.96^{b}	3.15 ± 0.07^{b}	4.89 ± 0.07^{a}	2.00 ± 0.68^{d}	14.11 ± 0.27^{c}	68.26 ± 3.07^{a}	678.85 ± 23.80^{a}
S + G + E	6.07 ± 0.12^{b}	2.85 ± 0.07^{b}	2.67 ± 0.44^{c}	5.40 ± 0.09^{c}	19.43 ± 0.45^{a}	63.59 ± 0.15^{a}	671.64 ± 0.77^{a}

Note: S = drying; G = grilling (roasting); S + G = drying+grilling; S + E = drying+boiling (blanching); G + E = boiling roasting; S + G + E = drying + grilling + boiling. The means ± standard deviations bearing different letters in the same column are significantly different at the 5% probability threshold.

($p < 0.05$) in this parameter following simple roasting of the kernels, although the value remained below the 14% recommended by Ndangui (2015) as being conducive to good storage of foodstuffs. The results obtained are lower than those of Kouame et al. (2015), whose contents ranged between 16.39% and 20% on *I. gabonensis* seeds. These variations in the literature data can be explained by the nature of the treatments, the variety, and the collection area (Awono et al. 2009).

The inorganic residues that remain after the water and organic matter have been removed by calcination are commonly known as ash. They provide information about the mineral content of food and are essential to the body because of their metabolic and physiological functions. The ash content of the different samples varied between 1.85% (dried and then blanched *kernels*) and 3.80% (roasted *kernels*). There was a significant reduction ($p < 0.05$) with the boiled samples. As ash is soluble, boiling would have caused it to leach out (Dongmo et al. 2020). Overall, the values obtained are higher than those of Onojah et al. (2018), who obtained 1.71% for fresh *I. gabonensis* kernels. The contents obtained are within the range of values (< 5%) recommended by Codex Stan for supplement foods, thus making this plant an ideal candidate for food formulation and infant nutrition.

Fiber helps improve intestinal function by contributing to the regulation of intestinal transit, increasing the volume of stools, promoting their passage through the digestive tract, and reducing LDL blood cholesterol and blood glucose levels (Onojah et al. 2018). This content ranged from 2.11% ± 0.02% (kernels dried then roasted) to 4.89% ± 0.07% (kernels roasted then blanched). The significant reduction during triple treatment and drying, then roasting can be explained by thermal hydrolysis of the osidic bonds, transforming them into simple sugars, and loss by hydrosolubilization. The results of this study are higher than the 2% obtained by Tchimmoe et al. (2023) on the sample roasted and then boiled, but lower than the 10.40% obtained by Onojah et al. (2018) on fresh kernels. In addition, drying, drying + roasting, and drying + roasting + boiling yielded values below the 3% considered to be the recommended value for supplement feeding.

Digestible carbohydrates are the body's main source of metabolizable energy. The metabolism of this class of nutrients provides the body with 4 kcal/g (Tambo et al. 2022). This content varied between 2.00% (roasted then blanched kernels) and 14.21% (dried then blanched kernels). There was a significant reduction with roasting + blanching and triple treatment. The triple treatment and roasting + blanching would be responsible for a Maillard reaction resulting in a loss of carbohydrates but also thermal hydrolysis and leaching of membrane carbohydrates into the blanching water (Dangang et al. 2024). The results obtained are much lower than those of Amalia et al. (2020), which were 71% in canistel nuts (*Pouteria campechiana*), suggesting that these kernels should be supplemented with carbohydrate sources for a good supplement diet. These data could explain the use of these kernels in sauces to accompany cassava roots.

Proteins promote sustainable satiety, helping to regulate food intake and body weight (Fromentin et al. 2011). They help regulate metabolism as enzymes, transport nutrients in the blood, and act as a repairing element (Tambo et al. 2022). The protein content varied from 10.55% (kernels dried, then roasted) to 19.43% (kernels dried, roasted, and then blanched). Use as a substrate in caramelization reactions would explain the reduction during drying and then roasting. Similarly, the improvement with triple treatment would be linked to a decomplexation of phenols and membrane fibers, resulting in high availability. In addition, the results obtained are within the range of 10% to 20% recommended for complementary foods and would therefore contribute between 90% and 140% of the recommended daily protein requirements of children aged 6–59 months (FAO/WHO 2006).

Lipids, also known as fats, play a crucial role in the body, particularly as a source of energy, a thermal insulator, a membrane constituent, and a precursor of vitamins and hormones (Onuegbu and Iwu 2020). The lipid content of the different samples varied from 52.45% (roasted kernels) to 68.43% (dried then roasted kernels). The levels obtained are close to those of Ogunsina et al. (2012), which were 68.40%. The levels obtained are well above the values recommended (5%–10%) by the standard for supplementary feeds (FAO/WHO 2006). This suggests that these kernels should be supplemented with other sources of nutrients to reduce the lipid content. In addition, consumption of these kernels would contribute more than 200% of the recommended daily intake of this nutrient for children aged between 12 and 59 months, confirming their fatty nature (Ngondi et al. 2005).

The energy value is linked to the composition of lipids, carbohydrates, and metabolizable proteins. This value expressed in kcal/100 g of dried *kernels* varied between 576.56 ± 31.64 (roasted *kernels*) and 703.57 ± 26.63 kcal (dried then roasted *kernels*). It was significantly ($p < 0.05$) lowered by grilling, and this could be explained by its low lipid content, as shown by the weak correlation between this treatment and the lipid content

TABLE 2 | Mineral composition of *Irvingia gabonensis* kernel samples.

Samples	G	S	S + G	S + E	G + E	S + G + E
Ca (mg/100 g)	881.00 ± 1.41^{e}	1197.00 ± 4.24^{b}	1768.00 ± 11.31^{a}	1044.00 ± 5.65^{c}	970.00 ± 14.14^{d}	1202.00 ± 2.82^{b}
Mg (mg/100 g)	187.57 ± 2.78^{a}	127.22 ± 1.21^{d}	58.42 ± 0.14^{f}	111.81 ± 0.04^{e}	136.14 ± 0.08^{c}	164.42 ± 1.15^{b}
Fe (mg/100 g)	0.31 ± 0.01^{c}	0.30 ± 0.007^{c}	0.14 ± 0.01^{d}	0.07 ± 0.01^{e}	0.87 ± 0.01^{a}	0.61 ± 0.01^{b}
Zn (mg/100 g)	0.00 ± 0.00^{d}	1.01 ± 0.14^{c}	0.00 ± 0.00^{d}	26.05 ± 1.27^{a}	20.04 ± 0.42^{b}	2.01 ± 0.42^{c}
Na (mg/100 g)	22.18 ± 1.29^{a}	23.46 ± 2.26^{a}	22.18 ± 1.29^{a}	18.48 ± 0.15^{c}	18.12 ± 1.95^{c}	19.74 ± 0.49^{b}
K (mg/100 g)	330.70 ± 6.34^{a}	243.78 ± 1.09^{b}	215.25 ± 3.08^{c}	187.07 ± 2.88^{d}	234.63 ± 9.66^{b}	215.25 ± 3.08^{c}
P (mg/100 g)	192.88 ± 3.44^{b}	210.75 ± 2.29^{a}	185.97 ± 1.72^{c}	170.12 ± 1.14^{d}	164.43 ± 1.14^{d}	167.28 ± 4.02^{d}
Na/K	0.07 ± 0.003^{c}	0.10 ± 0.01^{a}	0.10 ± 0.004^{a}	0.10 ± 0.001^{a}	0.08 ± 0.01^{bc}	0.09 ± 0.004^{ab}
Ca/Mg	4.70 ± 0.08^{d}	9.41 ± 0.12^{b}	30.26 ± 0.12^{a}	9.34 ± 0.05^{b}	7.12 ± 0.10^{c}	7.31 ± 0.07^{c}
Ca/P	4.57 ± 0.09^{e}	5.68 ± 0.08^{e}	9.51 ± 0.03^{a}	6.14 ± 0.01^{c}	5.90 ± 0.13^{cd}	7.19 ± 0.19^{b}

Note: S = drying; G = roasting (grilling); S + G = drying + grilling; S + E = drying + boiling (blanching); G + E = grilling + boiling; S + G + E = drying + grilling + boiling. The means ± standard deviations with different letters on the same line are significantly different at the 5% probability level.

(PCA diagram). The values obtained are 3–4 times lower than those of Onojah et al. (2018), which were 2560.60 kcal/100 g in raw kernels. This demonstrates the ability of culinary treatments to reduce the content of certain nutrients, particularly lipids and proteins. The values obtained demonstrate that the consumption of 100 g of kernels would contribute between 45% and 120% of the recommended daily energy needs in children aged 6–59 months (FAO/WHO 2006). The energy value is linked to the composition of lipids, carbohydrates, and metabolizable proteins.

3.3 | Mineral Composition of *I. gabonensis* Kernels

Table 2 presents the mineral composition of *I. gabonensis* kernels, indicating that these kernels exhibit a wide variety of minerals, making them good candidates in the fight against hidden hunger. Among the seven quantified minerals, calcium (Ca) was the most abundant, followed by potassium (K) and phosphorus (P). Calcium plays both a structural and functional role, particularly as a cofactor for metabolic enzymes, a second messenger, and in the mineralization and solidification of bones and teeth, as well as in coagulation and nerve impulse transmission (Naga Raju et al. 2012). The Ca content varied between 1768 mg/100 g (drying + roasting) and 881 mg/100 g (roasting). This variation could be explained by the fact that roasting alone did not release intracellular calcium molecules, particularly those from membranes and nuclear receptors. Additionally, the richness in chelating agents for divalent cations (phytates) could account for this low availability. These results are confirmed by the presence of these two factors in a negative zone of the correlation circle. The values obtained are higher than those reported by Tchimmoe et al. (2023), which were 127.80/100 and 125.80 mg/100 g in boiled and boiled-roasted samples of *I. gabonensis* collected from the South Cameroon region. This difference may be attributed to the varying climatic conditions of the agroecological zones of harvest and, especially, the different treatment conditions. Given this composition, only the samples subjected to drying + grilling and drying + grilling + boiling could meet the daily requirements of 1200 mg/day for this macroelement (Özcan and Akbulut 2008). The evaluation of the bioavailability of this element was determined by the Ca/Mg and Ca/P ratios. These analyses indicate that the bioavailability of Ca is compromised in all samples, particularly those subjected to drying + grilling, due to the significantly higher ratios than 1. Indeed, a high proportion of Ca compared to Mg and P would create steric hindrance at the calcium receptors, favoring the entry of Mg^{2+} ions and phosphate at the expense of Ca^{2+} (FAO/WHO 2001).

Magnesium is one of the microelements that the body needs at an average of 100 mg per day. It plays a role in the energy metabolism of eukaryotic cells as a cofactor, participates in the replication and expression of genes, and has an antidiabetic effect (Djouhou et al. 2021). It was significantly ($p < 0.05$) reduced by drying and roasting, while grilling alone improved it. These results are significantly higher than those of Tchimmoe et al. (2023), who, using similar treatments, obtained only 0.04 mg/100 g of material. This highlights the importance of considering the agroecological zone in sample collection as well as the conditions of culinary treatments. The values obtained (except for the dried + grilled kernels) could meet the daily needs of children aged 7–84 months (IOM Institute of Medicine 1997). Similarly, the Ca/Mg ratio greater than 1 in all samples provides good bioavailability of this mineral.

Iron and zinc are the least abundant minerals in these kernels. They are responsible for oxygen transport in the blood, have anti-anemic properties, participate in the formation of red blood cells, are antidiabetic, and promote cognition and cardiac activity (Kordas and Stoltzfus 2004). Analysis of the composition of these two minerals shows that they are below the FAO/WHO (2001) standard, which recommends 2.1–28 mg of Fe per day for children aged 6–59 months. This confirms the need to pair these kernels with sources of zinc and iron to prevent cognitive deficiencies and anemia in young children. Table 2 indicates that the roasting + boiling sample yielded the highest value (0.87 mg/100 g) for iron, while the drying + boiling treatment recorded the lowest value (0.07 mg/100 g). Regarding zinc, it was significantly ($p < 0.05$) improved by boiling, while roasting led to its reduction. The variation observed between the two minerals could be explained by the strength and nature of the interactions linking them to other molecules in the plant. Dangang et al. (2024) and Tambo, Anicet, et al. (2024)

demonstrated that phytate-iron interactions were more easily broken by dry energy (roasting), unlike phytate-zinc interactions, which require aqueous and thermal hydrolysis. These results are supported by the negative correlation in the correlation circle between these treatments and the levels of these different minerals. Sodium is part of the body's buffering system and plays a role in the transmission of nerve impulses. Its content varied between 18 and 22 mg/100 g and was significantly ($p < 0.05$) reduced by boiling. This reduction could be explained by its ability to dissolve or melt in water. This demonstrates the benefit of increasing the boiling time to make this food suitable for hypertensive individuals. Nevertheless, the Na content remains below the standard (< 2 g/day) for hypertensive individuals, thus allowing for the recommendation of these kernels in a hypotensive diet (FAO/WHO 2001). These observations are confirmed by Na/K ratios lower than 0.25 (Djouhou et al. 2021).

Potassium is one of the most abundant mineral elements in the kernels of this plant. The Na/K ratios, all below 0.20, make this plant a good source of nutrients for individuals with hypertension (Akinyeye et al. 2010). Potassium plays a role in nerve impulse transmission and musculo-cognitive activities (Naga Raju et al. 2012). This parameter varied between 330.70/100 (roasted) and 187.07 mg/100 g (roasted + boiled). The significant reduction ($p < 0.05$) after boiling is due to a loss of this mineral through leaching. The results obtained are significantly higher than those reported by Onojah et al. (2018) and Tchimmoe et al. (2023), which were 84.50/100 and 0.53 mg/100 g, respectively. However, these values are below the recommended daily intake for this mineral (0.6−6 g/day) and would therefore require supplementation from a potassium source.

Phosphorus, along with calcium, contributes to the mineralization of bones and also to techno-functional properties by promoting the binding of water molecules. The highest value was obtained with the control sample, while the lowest was found in the grilled + boiled sample, showing a significant decrease ($p < 0.05$) across the different treatments. Indeed, the treatments would lead to a loss of amylose, the main phosphorus-binding molecule, resulting in its reduction. Furthermore, the values obtained for this mineral are all within the range of 120–1200 mg recommended by the FAO/WHO (2001) standards for complementary foods.

3.4 | Influence of Culinary Treatments on the Anti-Nutrient Content and the Anti-Nutrient/Mineral Ratio in *Irvingia gabonensis* Kernels

Phytates and oxalates are negatively charged compounds capable of binding divalent cations such as Ca, Mg, Fe, Zn, and Cu through electrostatic interactions, leading to a decrease in their intestinal absorption (Haddadi 2005). They also limit protein digestibility by promoting their precipitation through the electrostatic interactions they form with basic amino acids and reduce enzyme activity by chelating their metal cofactors or binding the substrates of proteolytic enzymes (Haddadi 2005). As shown in Table 3, the phytate content ranged from 21.35 ± 4.31/100 (dried and then roasted kernels) to 51.87 ± 4.31 mg/100 g (dried kernels), while oxalate levels varied between 11.25/100 (dried and roasted kernels) and 24.75 mg/100 g (roasted then blanched kernels). The phytate levels obtained are lower than those reported by Gindo et al. (2020), which were 391.53 mg/100 g for the species *Irvingia smithii*, thus confirming the effectiveness of the various treatments. Except for the control and roasted kernels, all other treatments resulted in oxalate levels exceeding the 12.15 mg/100 g reported by Gindo et al. (2020). The evaluation of the bioavailability of minerals with phytates and oxalates (Table 4) has shown that, except for the phytate/Fe and oxalate/Fe ratios of all samples, which are greater than 1, the various treatments improved the bioavailability of Ca and Mg. This bioavailability was significant during the grilling + boiling (G + E) treatment and the drying + grilling + boiling (S + G + E) treatment. These nuts are not recommended for combating anemia and should be paired with sources of iron. Tannins limit the solubility and digestibility of proteins as well as the absorption of dietary iron (Atelor 1993). They also lead to the formation of colon and esophageal cancer when consumed in amounts exceeding 560 mg/day (Emmanuel-Ikpeme et al. 2012). In light of these results, the consumption of *I. gabonensis* nuts would therefore not promote the occurrence of cancer. The analysis of these results reveals that the roasted sample had the lowest levels of condensed and hydrolysable tannins, measuring 2.97 and 0.62 mg CE/g, respectively. In contrast, the blanched nuts showed levels of 7.06 and 10.90 mg CE/g for condensed and hydrolysable tannins, respectively. These observations demonstrate that these molecules are not soluble but rather thermolabile. Indeed, dry heat would lead to the destruction of tannins through the hydrolysis of their intramolecular bonds.

TABLE 3 | Anti-nutrients content in *Irvingia gabonensis* kernel samples.

Samples	G	S	S + G	S + E	G + E	S + G + E
Phytates (mg/100 g)	42.71 ± 0.00^{b}	51.87 ± 4.31^{a}	21.35 ± 4.31^{d}	36.61 ± 0.00^{c}	24.41 ± 0.00^{d}	36.61 ± 0.00^{c}
Oxalates (mg/100 g)	11.25 ± 0.00^{b}	11.25 ± 0.00^{b}	15.75 ± 3.18^{b}	18.00 ± 0.00^{a}	24.75 ± 0.00^{a}	15.75 ± 0.00^{b}
Condensed tannins (mg CE/g of extracts)	2.97 ± 0.14^{e}	3.85 ± 0.15^{d}	4.52 ± 0.24^{d}	7.06 ± 0.14^{a}	5.44 ± 0.04^{c}	6.32 ± 0.00^{b}
Hydrolysable tannins (mg CE/g of extracts)	0.62 ± 0.24^{f}	2.43 ± 0.17^{e}	2.40 ± 0.17^{d}	10.90 ± 1.39^{a}	4.21 ± 0.19^{c}	6.91 ± 0.97^{b}
Saponins (mg/100 g)	0.00 ± 0.00^{b}	0.10 ± 0.00^{a}	0.10 ± 0.00^{a}	0.10 ± 0.00^{a}	0.10 ± 0.00^{a}	0.10 ± 0.00^{a}

Note: S = drying; G = roasting (grilling); S + G = drying + grilling; S + E = drying + boiling (blanching); G + E = grilling + boiling; S + G + E = drying + grilling + boiling. The means ± standard deviations with different letters on the same line are significantly different at the 5% probability level.

Furthermore, a comparison between hydrolysable and condensed tannins shows that their reductions are entirely dependent on the nature of the treatments. The so-called hydrolysable tannins were the most eliminated, except for the blanched kernels, because the interactions binding them to other molecules and those intramolecular ones are of very low energy. The levels of condensed tannins obtained in this study are higher than those reported by Onojah et al. (2018), which were 0.66 mg/100 g in kernels harvested in Nigeria. This could be explained by the fact that the thermal action applied to the samples led to an improvement in the availability of these compounds due to the thermal decomplexation of other molecules. Saponins can lead to the occurrence of numerous pathologies such as obesity, diabetes, and hepatic toxicity, and they interfere with nutrient absorption, causing undesirable effects such as gastrointestinal disturbances when consumed in high concentrations (Awe and Sodipo 2001). They also possess astringent properties and impart a bitter taste to fruits (Awe and Sodipo 2001). This parameter varied between 0/100 (roasted kernels) and 0.10 mg/100 g for the other samples. This significant reduction ($p < 0.05$) observed with roasting could be explained by the thermolabile nature of these substances. The results obtained are similar to those of Gindo et al. (2020), who worked on another species of Irvingia (*I. smithii*) and did not detect saponins in those samples. This low level thus demonstrates that the kernels of *I. gabonensis* are highly valued and that their consumption would not promote the occurrence of diet-related pathologies.

3.5 | Influence of Culinary Treatments on the pH, Functional Properties, and Color of *I. gabonensis* Kernels

pH impacts the organoleptic and techno-functional properties of foods (Tambo, Ndomou, et al. 2024). A pH close to neutrality would promote good food intake and water retention capacity (Klang, Tambo, Doungmo, et al. 2019; Klang, Tambo, Nguemguo, et al. 2019). It is evident from Table 5 that this parameter varies from 4.31 (roasted nuts) to 6.01 (dried nuts). The samples that underwent double treatment improved this parameter, although it remains significantly lower ($p < 0.05$) than that of the control. The significant decrease observed with simple roasting thus demonstrates the importance of drying in eliminating the organic acids synthesized in the plant during its growth and may also be a consequence of a richness in acidic amino acids in this sample. The values obtained are lower than those reported by Ndamitso et al. (2012), which were 6.62 in Irvingia nuts harvested in Niger. Nevertheless, these values close to neutrality would limit the negative impact of treatments on the flavor, texture, and storage stability of kernels.

The water retention capacity provides information on the potential viscosity of the kernels and the behavior of starch molecules and amino acids of proteins at a certain temperature about water molecules (Klang, Tambo, Nguemguo, et al. 2019). This parameter varied between 23% and 50% and was significantly ($p < 0.05$) reduced by roasting. This reduction would be explained by the richness in phytates that chelate divalent cations, such as Ca, responsible for interactions with water in

TABLE 4 | Anti-nutrient-mineral ratio of *Irvingia gabonensis* kernel samples.

Samples	G	S	S + G	S + E	G + E	S + G + E
Phytates/Fe	11.54 ± 0.26^{b}	14.44 ± 0.33^{b}	12.42 ± 0.60^{b}	42.26 ± 4.05^{a}	2.38 ± 0.02^{c}	5.01 ± 0.06^{c}
Phytates/Ca	0.003 ± 0.00^{a}	0.003 ± 0.00^{a}	0.001 ± 0.00^{c}	0.002 ± 0.00^{b}	0.002 ± 0.00^{b}	0.002 ± 0.00^{b}
Phytates/Mg	0.008 ± 0.00^{d}	0.015 ± 0.00^{a}	0.013 ± 0.00^{b}	0.012 ± 0.00^{c}	0.007 ± 0.00^{e}	0.008 ± 0.00^{d}
Oxalates/Fe	11.14 ± 0.25^{c}	11.48 ± 0.27^{c}	33.57 ± 1.62^{b}	76.18 ± 7.29^{a}	8.83 ± 0.07^{c}	7.91 ± 0.09^{c}
Oxalates/Ca	0.003 ± 0.00^{c}	0.002 ± 0.00^{d}	0.002 ± 0.00^{d}	0.004 ± 0.00^{b}	0.006 ± 0.00^{a}	0.003 ± 0.00^{c}
Oxalates/Mg	0.008 ± 0.00^{f}	0.012 ± 0.00^{e}	0.036 ± 0.00^{a}	0.022 ± 0.00^{c}	0.025 ± 0.00^{b}	0.013 ± 0.00^{d}

Note: S = drying; G = roasting (grilling); S + G = drying + grilling; S + E = drying + boiling (blanching); G + E = grilling + boiling; S + G + E = drying + grilling + boiling. The means ± standard deviations with different letters on the same line are significantly different at the 5% probability level.

TABLE 5 | Influence of cooking treatments on the pH, functional properties, and color of *Irvingia gabonensis* kernels.

Samples	G	S	S + G	S + E	G + E	S + G + E
pH	4.21 ± 0.08^{c}	6.01 ± 0.00^{a}	5.96 ± 0.05^{a}	5.65 ± 0.07^{b}	5.58 ± 0.11^{b}	5.52 ± 0.01^{b}
WRC (%)	23.00 ± 4.24^{c}	37.00 ± 4.24^{b}	39.00 ± 4.24^{b}	50.00 ± 2.82^{a}	49.00 ± 1.41^{a}	50.00 ± 2.82^{a}
ORC (%)	53.79 ± 0.19^{e}	57.78 ± 0.31^{a}	59.83 ± 0.47^{a}	61.21 ± 1.17^{a}	58.35 ± 6.67^{a}	59.25 ± 5.51^{a}
ORC/WRC	2.38 ± 0.43^{a}	1.57 ± 0.17^{b}	1.54 ± 0.18^{b}	1.23 ± 0.05^{b}	1.19 ± 0.17^{b}	1.18 ± 0.04^{b}
l^*	67.97 ± 0.01^{c}	78.54 ± 0.01^{b}	58.47 ± 0.00^{e}	59.48 ± 0.01^{d}	53.63 ± 0.01^{f}	79.06 ± 0.01^{a}
a^*	6.83 ± 0.01^{c}	3.32 ± 0.00^{d}	9.07 ± 0.01^{a}	6.91 ± 0.01^{b}	2.50 ± 0.01^{f}	3.19 ± 0.01^{e}
b^*	23.79 ± 0.01^{b}	21.00 ± 0.01^{f}	30.77 ± 0.02^{a}	23.45 ± 0.01^{c}	22.13 ± 0.03^{e}	22.96 ± 0.01^{d}
BI	49.10 ± 0.02^{d}	33.22 ± 0.01^{f}	82.55 ± 0.06^{a}	56.99 ± 0.01^{b}	54.57 ± 0.01^{c}	36.15 ± 0.02^{e}

Note: S = drying; G = roasting (toasting); S + G = drying + roasting; S + E = drying + boiling (blanching); G + E = roasting boiling; S + G + E = drying + roasting + boiling. The means ± standard deviations bearing different letters on the same line are significantly different at the 5% probability level.
Abbreviations: BI, browning index; ORC, oil retention capacity; WRC, water retention capacity.

the plant. Regarding the samples that underwent the double treatment, particularly those that were boiled, Amalia et al. (2020) report that boiling promotes the gelatinization of plant starch, thereby enhancing its ability to retain water molecules. The samples with a high-water retention capacity would therefore be easier to cook, thus saving time and energy. The values obtained in this study are in the same range as those of Ndamitso et al. (2012). Nevertheless, the roasted sample would be more stable for preservation as it would absorb less ambient water and, at the same time, maintain the viscosity of the food (Kim et al. 1989).

The oil retention capacity is closely related to that of water and influenced by temperature. It is also responsible for the organoleptic properties and facilitates food preservation by preventing the diffusion of oxygen (Tambo 2024). This parameter did not significantly ($p > 0.05$) vary with the treatments, although the roasted sample exhibited the lowest capacity (53.79%). This low capacity of roasted kernels would also be related to their lower content of hydrophobic amino acids and the existence of a nearly intact crystalline structure within the proteins and starch. The results obtained are higher than those of Ndamitso et al. (2012), which were 26.30% in raw kernels. This difference could be explained by the fact that the treatments allowed the fats to be released from the membranes, thus facilitating hydrophobic interactions with the added oil.

The evaluation of the affinity with water or oil was determined by calculating the oil retention capacity/water retention capacity ratio. It follows from this that all the kernels have a strong affinity for oil, with ratios ranging from 2.38 to 1.19. This parameter was significantly ($p < 0.05$) improved by roasting, and this important ratio demonstrates that they would be inappropriate for emulsion stabilization or contraindicated in emulsified dispersions. The influence of culinary treatments on color (l^*, a^*, b^*) and the degree of browning shows that all treatments significantly affect these parameters. The whiteness of the kernels marked by the parameter l^* shows an improvement with the drying, grinding, and boiling treatment and a significant reduction with the roasting and boiling treatment. Indeed, during roasting, there is an oxidation of lipids and fat-soluble vitamins as well as browning of carbohydrates and proteins, leading to the formation of brown, black, and yellow-colored compounds (Arıcı et al. 2016). On the other hand, the application of boiling and drying after roasting during the triple treatment would be responsible for the loss of colored compounds formed during this stage due to the leaching phenomenon, resulting in a return to the initial color. The value obtained with roasting (G) would be the consequence of a richness in free water that would have reduced the rate of oxidation and non-enzymatic browning reactions, leading to color preservation. As for the a^* (redness) and b^* (yellowness) parameters, they were respectively improved by drying and roasting but decreased by roasting and boiling. Drying with roasting facilitates the Maillard reaction and lipid oxidation in the kernels and consequently the formation of colored compounds. Moreover, the high lipid content in this sample would also explain these results. The values obtained by Pertiwi et al. (2022) on canistel starches are in the same range as those recorded in this study. The previous observations are confirmed by the browning index (BI), which was higher in the dried + roasted kernels (82.55). Given the high whiteness and low browning index of the triply treated samples, they could be used in the formulation of dietary supplements due to their good color, but they would also present a low level of health risk, considering the carcinogenic nature of the Maillard reaction products.

3.6 | Influence of Culinary Treatments on the Rheological Properties of *I. gabonensis* Kernels

Rheological properties provide information on the cooking parameters of a food to the behavior of its constituents (Klang, Tambo, Nguemguo, et al. 2019). The gelatinization time and temperature, respectively, provide information on the time and energy required to cook a product (Amalia et al. 2020). It follows from Table 6 that the treatments increased the gelatinization time while significantly reducing the gelatinization temperature, except for roasting. Dongmo et al. (2020) also noted similar phenomena in corn flour. The reduction in the

TABLE 6 | Influence of culinary treatments on the rheological properties of *Irvingia gabonensis* kernels.

Samples	G	S	S + G	S + E	G + E	S + G + E
Peak time (s)	383.50 ± 2.12^{c}	356.32 ± 0.18^{f}	432.45 ± 0.78^{a}	370.55 ± 0.64^{e}	427.60 ± 0.57^{b}	375.50 ± 0.71^{d}
Pasting temperature (cP)	81.99 ± 0.02^{a}	69.43 ± 0.07^{b}	63.82 ± 0.01^{d}	67.28 ± 0.40^{c}	51.63 ± 0.52^{f}	54.76 ± 0.34^{e}
Peak viscosity (cP)	237.65 ± 0.49^{d}	1254.00 ± 1.41^{a}	197.50 ± 0.00^{e}	89.51 ± 0.05^{f}	385.35 ± 0.92^{b}	349.35 ± 0.64^{c}
Holding viscosity (cP)	63.98 ± 0.01^{e}	481.62 ± 0.18^{a}	167.65 ± 0.49^{d}	49.49 ± 0.71^{f}	294.30 ± 0.99^{b}	258.70 ± 0.99^{c}
Breakdown (cP)	171.65 ± 2.33^{b}	771.95 ± 0.07^{a}	30.61 ± 0.54^{f}	40.73 ± 0.23^{e}	91.56 ± 0.61^{d}	116.25 ± 0.35^{c}
Final viscosity (cP)	730.70 ± 0.42^{a}	662.65 ± 3.23^{b}	236.80 ± 0.28^{f}	272.42 ± 0.03^{e}	387.10 ± 1.27^{c}	374.75 ± 0.35^{d}
Set-back (cP)	666.70 ± 0.43^{a}	181.02 ± 3.15^{c}	69.16 ± 0.23^{f}	222.92 ± 0.67^{b}	92.83 ± 0.24^{e}	116.00 ± 1.41^{d}
Stability ratio (HV/PV)	0.27 ± 0.00^{f}	0.38 ± 0.00^{e}	0.85 ± 0.00^{a}	0.55 ± 0.01^{d}	0.76 ± 0.00^{b}	0.74 ± 0.00^{c}
Set-back ratio (FV/HV)	11.42 ± 0.00^{a}	1.38 ± 0.01^{cd}	1.41 ± 0.00^{c}	5.50 ± 0.08^{b}	1.31 ± 0.00^{d}	1.45 ± 0.01^{c}

Note: S = drying; G = roasting (toasting); S + G = drying+roasting; S + E = drying + boiling (blanching); G + E = roasting boiling; S + G + E = drying + roasting + boiling.
The means ± standard deviations with different letters on the same line are significantly different at the 5% probability level.
Abbreviations: FV, final viscosity; HV, holding viscosity; PV, peak viscosity.

gelatinization temperature to 51.63°C during roasting and boiling can be explained by a strong fission of intra- and intermolecular energy bonds within the food, thus facilitating cooking (Pertiwi et al. 2022). The opposite effect observed during roasting (G) can be explained by the presence of water, which protects the molecules present from the effects of heat, hence the interest in drying before treatment or double treatment. Although the treatments reduced the gelatinization temperature, they caused the opposite effect on the gelatinization time, which varied between 356.32 and 427.60 s. This time notably increased during roasting and was lower with boiling. The studies conducted by Amalia et al. (2020) reported that moist heat led to better dissociation of the crystalline complexes of plant molecules, resulting in a reduction in cooking time. The results obtained are lower than those of Amalia et al. (2020), who achieved 9.50 min and 93.50°C for time and gelatinization temperature during the rheological profiling of canistel nuts, thus confirming the importance of culinary treatments applied to kernels for saving cooking time and energy. These results also suggest that these different treatments could allow for the formulation of instant supplementary foods with these kernels. The viscosity obtained during the increase in temperature, which depends on the nature of the amino acids, the starch composition, and the ORC/WRC ratio, is called peak viscosity (Imoisi et al. 2024). It varied between 1254 (control) and 89.51 cP (drying + boiling). It was significantly ($p < 0.05$) reduced by the treatments, particularly boiling. The phosphorus content in the control kernels, the hydrolysis of macromolecules such as carbohydrates and proteins into simple molecules with low water retention capacity during the various treatments, and the formation of melanoidins (which reduce the available carbohydrates and amino acids and mask the hydrophilic groups of the food molecules) during non-enzymatic browning would explain the low peak viscosity of the treated kernels (Klang, Tambo, Nguemguo, et al. 2019). Similarly, the low pH obtained with the treatments would lead to a decrease in the stability of interactions with water, thus reducing the peak viscosity (Dongmo et al. 2020). The results obtained are lower than those of Zhang and Hamaker (2012), which were 2016 cP. These results suggest an application in the formulation of dietary supplements due to the low viscosity. The resistance of starch to shear phenomena is marked by the holding viscosity, and a low variation of this parameter indicates high stability or low retrogradation (Amalia et al. 2020). It varied between 481.62 and 49.49 cP and was significantly reduced by roasting (G). These results are confirmed by the low Ca^{2+} content and its low water retention capacity. Indeed, Ca^{2+} ions would participate with phosphate in the binding of water by starch and the polar regions of proteins. These observations are confirmed by the low stability ratio obtained during roasting (0.27) compared to the other samples. The same applies to the high value (11.42) of its set-back ratio.

The high stability (stability ratio) and low set-back obtained with dried-roasted kernels are in line with their richness in lipids, which, through interactions with carbohydrates and proteins, stabilize the molecular structure and increase its resistance to shear. The obtained Holding viscosity values are in the same range as those of Imoisi et al. (2024), which were between 228 and 676 cP in millet and cassava. The bursting followed by the reassociation of starch or amylose granules after thermal treatment is called Breakdown (Shafie et al. 2016). A high breakdown compared to the peak viscosity indicates significant degradation and low shear resistance (Shafie et al. 2016). It varied between 30.61 and 771.95 cP. It was lowered by all treatments, although roasting maintained the highest value among the treatments. This would thus confirm the low stability of the dispersions resulting from this treatment and its inadequacy in the formulation of supplementary foods. The low water retention observed with roasted kernels would also be one of the explanations for this phenomenon. Apart from the control and roasted kernels, the values obtained are lower than those of Chung et al. (2009), which were 161 cP on corn starch. Thus, the addition of these kernels to cereal and tuber flours during the preparation of complementary foods would stabilize the viscosity and facilitate food intake by children. The final viscosity is the one measured at the end of heating, and it is highly dependent on the ability of the molecular constituents to dissociate from water and reassociate into their initial molecular forms (Maldonado 2014). It is also the one that allows us to assess the suitability of flour for the formulation of complementary foods. The final viscosity of all the samples is below 1000 cP, thus confirming their suitability for the formulation of complementary foods (Dongmo et al. 2020; Tambo, Ndomou, et al. 2024). The final viscosity ranged between 236.80 (drying + roasting) and 730.70 cP (roasting). The significant value noted with roasting (G) would thus explain the low stability and high set-back ratios. Indeed, simple roasting does not lead to a significant loss of water in the plant, which remains bound to the molecules, causing either the granules to burst or the molecular complexes to dissociate during the evaluation of this parameter due to steric hindrance (Pertiwi et al. 2022). Given this high final viscosity, roasted kernels could easily be used in the formulation and stabilization of fresh products. The results obtained are lower than those of Amalia et al. (2020), which ranged between 812 and 864 cP in blanched canistel nuts. Set-back occurs when gelatinized foods form a consistent gel during cooling (Imoisi et al. 2024). This parameter significantly increased with roasting (G = 666.70 cP) and drying + boiling (S + E = 222.92 cP). This could be explained by the lower content of phosphorus and lipids in the two samples (Shafie et al. 2016). Amalia et al. (2020) reported that blanching was responsible for the disintegration of amylose molecules in canistel nuts and thus for the reduction of their cooling stability. The trend towards cohesion and hardness would therefore be observed with these kernels. The values obtained remain lower than those of Pertiwi et al. (2022), which ranged between 1127 and 1747 cP in modified and untreated canistel starches. Thus, although retrogradation phenomena are observed in these kernels, they remain weak, which gives them good suitability for the formulation of supplementary foods.

3.7 | Influence of Cooking Treatments on the Thermal Properties and PRAL Index of *I. gabonensis* Kernels

The results, presented in Table 7, demonstrate that the energy required to modify the temperature of the seeds by one Kelvin was significantly ($p < 0.05$) enhanced by roasting and roasting combined with boiling. This parameter ranged from 184.37 kJ/kg/K (roasting) to 166.83 kJ/kg/K (drying + roasting). The elevated water content present in roasted kernels might provide a rationale for these observations. Indeed, the substantial presence of water

TABLE 7 | Influence of cooking treatments on thermal properties and PRAL index of *Irvingia gabonensis* kernels.

Samples	G	S	S + G	S + E	G + E	S + G + E
Specific heat capacity (kJ/kg/K)	184.37 ± 10.11^{a}	167.45 ± 3.58^{b}	166.83 ± 2.90^{b}	170.67 ± 1.57^{b}	173.45 ± 4.54^{ab}	172.08 ± 1.03^{b}
Thermal conductivity (w/m·k)	21.61 ± 1.49^{a}	17.87 ± 0.16^{b}	18.22 ± 0.24^{b}	19.23 ± 0.12^{b}	18.43 ± 0.87^{b}	18.44 ± 0.13^{b}
Thermal diffusivity ($m^2/s \times 10^{-6}$)	8.22 ± 0.14^{ab}	8.05 ± 0.16^{bc}	8.44 ± 0.12^{a}	8.36 ± 0.07^{a}	8.20 ± 0.04^{ab}	7.83 ± 0.01^{c}
PRAL Index	-8.72 ± 0.42^{b}	-7.69 ± 0.31^{a}	-16.09 ± 0.23^{c}	-7.57 ± 0.00^{a}	-7.61 ± 0.29^{a}	-8.16 ± 0.01^{ab}

Note: S = drying; G = roasting (toasting); S + G = drying + roasting; S + E = drying + boiling (blanching); G + E = roasting boiling; S + G + E = drying + roasting + boiling. The means ± standard deviations with different letters on the same line are significantly different at the 5% probability level.
Abbreviations: FV, final viscosity; HV, holding viscosity; PV, peak viscosity.

has been shown to enhance nutrient retention and elevate the specific heat capacity (Yang et al. 2002). Furthermore, it is acknowledged that boiling leads to the dispersion of particles, resulting in an augmentation of the contact surface and, consequently, a diminution in the specific temperature (Raji et al. 2024). The values obtained in this study are consistent with those reported by Raji et al. (2024), which ranged from 177.31 to 196.45 kJ/kg/K. Thermal conductivity is defined as the capacity of a material to conduct heat within itself (Usman et al. 2019), and it has been demonstrated that this property can be enhanced through the process of roasting. Indeed, water, by producing heat in the form of steam, functions effectively as a heat carrier. In addition, Usman et al. (2019) reported that an increase in the EU content in food matrices would promote good thermal conductivity, with the values obtained falling within the same range as those reported by Raji et al. (2024). Thermal diffusivity is defined as the capacity of a food matrix to limit the loss of energy captured during processing and to distribute it throughout its surface (Akeem Olayemi and Rahman 2013). This capacity varied between 7.83×10^{-6} (triple treatment) and $8.44 \times 10^{-6}\ m^2/s$ (drying + torrefaction). The reduction observed with triple treatment can be attributed to the high protein content of the food matrix, which can impede heat diffusion and result in a reduction in the thermal diffusivity (Akeem Olayemi and Rahman 2013). The findings suggest that roasting and boiling could be effective methods for processing the seeds of this plant, thereby enhancing heat diffusion. The findings obtained in this study are consistent with those reported by Raji et al. (2024), who observed a range of $8.17–8.81 \times 10^{-6}\ m^2/s$ in various pasta formulations. The PRAL index (Dung et al. 2024) is a method of assessing the release of acids or bases into cells after consumption. The PRAL index values of these seeds are all below 0, which suggests that they are suitable for patients with metabolic disorders and renal insufficiency, as they limit the metabolic acidosis that can lead to renal tubular obstruction (Osuna-Padilla et al. 2019). The variation in the PRAL index across the different samples is attributable to variation in the content of the different ions and proteins following treatment.

3.8 | Influence of Culinary Treatments on the Amino Acid Profile of *Irvingia gabonensis* Kernels

The evaluation of the amino acid composition of the nuts presented in Table 8 shows that cooking treatments influence the composition and concentration of amino acids. The amino acid profile shows that the number varies between 6 and 10 amino acids, thus demonstrating the biological poverty of these proteins. This low variability in amino acids suggests the combination with cereals, legumes, or even animal proteins to improve the biological value and the prevention of protein-energy malnutrition (Tambo et al. 2022). Among the eight essential amino acids, only 2–4 were identified in these samples, depending on the treatment. This could be explained by the analysis method used and the utilization of the various metabolic reactions that occur during culinary treatments, which may have led to the observed effects in these kernels (Fitriani et al. 2021). Indeed, Tambo et al. (2023) revealed that the use of the acid method for the total extraction of amino acids led to the destruction of compounds such as L-Trp and the transformation of Gln and Asn into their acidic derivatives (Asp et Glu). In light of this profile, the absence of sulfur-containing amino acids such as Cys and Met is noted. Fellows (2000) reported a loss of these amino acids through solubilization and destruction during the caramelization reaction. The concentration of His increased with roasting (G) and the triple treatment S + G + E (drying + roasting + boiling), unlike Lys, which decreased with all treatments except roasting (G). The use of His as a substrate for Maillard reactions during roasting and the leaching of Lys during boiling could therefore explain these differences (Fitriani et al. 2021). Thr is a small glucose-forming amino acid with strong antioxidant activity. The decrease in its concentration with boiling and the destruction during roasting aligns with the work of Fitriani et al. (2021), who also noted the same phenomenon during culinary treatments on pigeon peas. Phe was identified only in the dried-boiled sample and is consistent with the work of Fitriani et al. (2021) on fried Kabau seeds. Seven non-essential amino acids were identified, including Arg, Ser, Gly, Pro, Glu, Asp, and Ala. The basic amino acid Arg was identified only in kernels that underwent roasting + boiling (0.547 mmol/L). This raises a concern about the sensitivity of the detection method as reported by Tambo et al. (2023). Ser, which is another amino acid with antioxidant properties (Guang and Phillips 2009), was destroyed during roasting (G), while it was improved during drying + boiling (S + E). All treatments improved the concentration of Gly, while the opposite effect was observed with Pro. These two hydrophobic amino acids are components of cell walls, which is why they are resistant to culinary treatments. The acidic amino acids (Asp and Glu) are responsible for the pleasant flavor and aroma of foods. Dermiki et al. (2013). Their concentrations decreased with boiling, while they increased with roasting. This is contrary to

TABLE 8 | Influence of cooking treatments on the amino acid profile of *Irvingia gabonensis* kernels.

Samples	G	S	S + G	S + E	G + E	S + G + E
Essential amino acid (mmol/L)						
His	0.097	0.083	0.044	0.264	0.162	0.052
Thr	0.00	0.034	0.00	0.024	0.00	0.032
Lys	1.979	1.890	1.474	1.660	1.612	1.566
Phe	0.00	0.00	0.00	0.002	0.00	0.00
Non-essential amino acid (mmol/L)						
Arg	0.00	0.00	0.00	0.00	0.547	0.00
Ser	0.00	0.113	0.021	0.328	0.121	0.021
Gly	0.133	0.094	0.134	0.629	0.441	0.146
Pro	1.140	1.414	0.431	1.497	1.170	0.550
Glu	0.024	0.012	0.031	0.003	0.091	0.084
Asp	0.805	0.794	0.828	0.549	0.589	0.732
Ala	0.00	0.00	0.00	0.287	0.801	0.00

Note: S = drying; G = roasting (toasting); S + G = drying + roasting; S + E = drying + boiling (blanching); G + E = roasting boiling; S + G + E = drying + roasting + boiling.

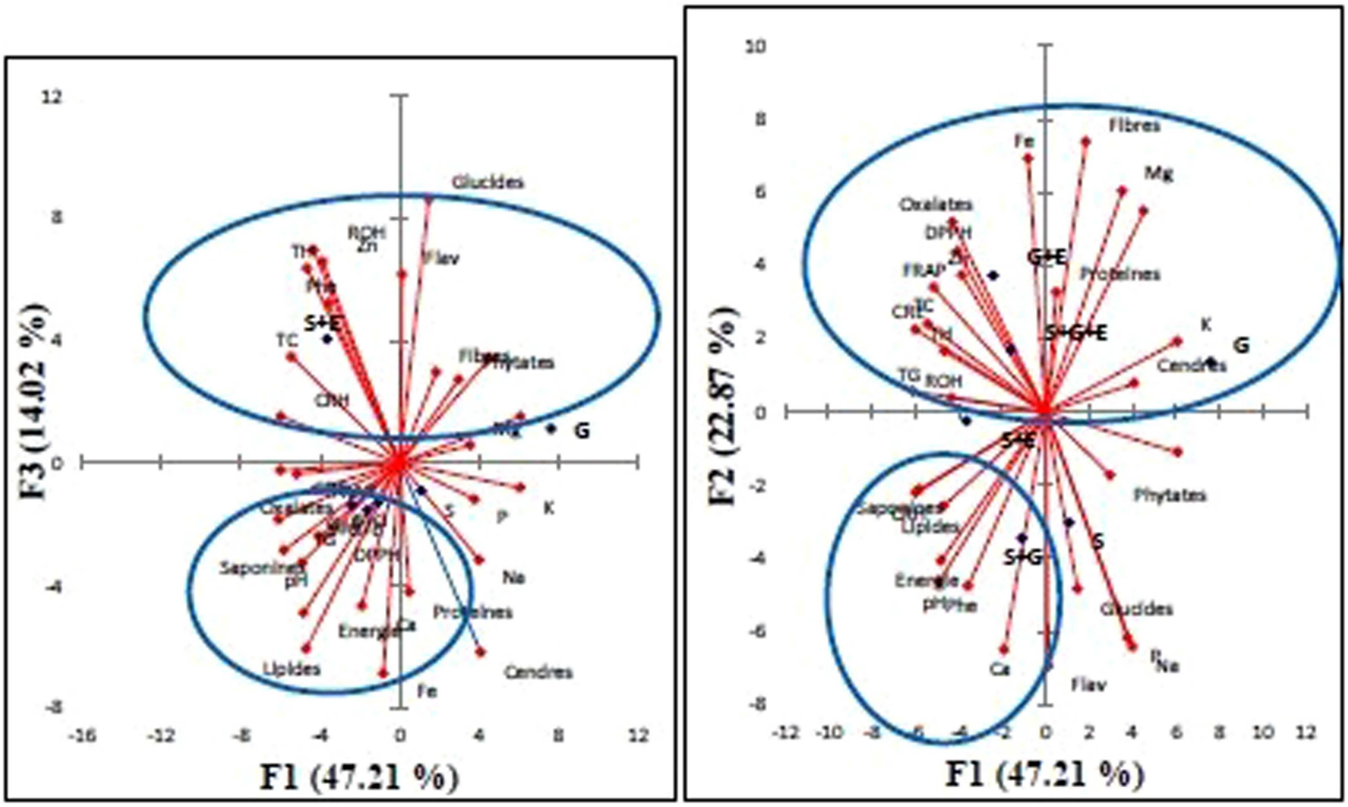


FIGURE 6 | Biplots of variables related to treatments performed on *Irvingia gabonensis* kernels. S = drying; G = roasting (toasting); S + G = drying+roasting; S + E = drying + boiling (blanching); G + E = roasting boiling; S + G + E = drying + roasting + boiling. Ca = calcium; CRE = water retention capacity; CRH = oil retention capacity; TC = condensed tannins; TH = water-soluble tannins.

the results of Fitriani et al. (2021). These results thus confirm the predominant choice of roasting as a culinary method by the survey participants. Ala was identified only in the drying + boiling (S + B) and grilling + boiling (G + B) samples at levels of 0.287 and 0.807 mmol/L, respectively. Thus, these results confirm that the proteins of these kernels are not of good biological quality.

3.9 | Study of the Correlations Between the Evaluated Characteristics and the Different Treatments

The PCA diagrams of the variables, also called correlation circles (Figure 6), allow for the visualization of the grouping between the variables and the observations. This figure not only allows for the visualization of correlations but also directly

TABLE 9 | Contributions and squared cosines of the observations.

Observations	Contributions			Squared cosines		
	F1	F2	F3	F1	F2	F3
G	70.84	4.57	5.08	0.94	0.02	0.02
S	1.46	23.22	3.45	0.06	0.47	0.04
S + G	1.41	30.11	6.97	0.05	0.52	0.07
S + E	16.13	0.16	66.84	0.44	0.00	0.54
G + E	7.00	34.71	7.85	0.22	0.55	0.07
S + G + E	3.14	7.21	9.78	0.17	0.18	0.15

Note: S = drying; G = roasting (toasting); S + G = drying + roasting; S + E = drying + boiling (blanching); G + E = roasting boiling; S + G + E = drying + roasting + boiling.

shows the proximities between culinary treatments and their properties. Keenan et al. (2012). This analysis demonstrated that the different treatments have a significant impact on the properties of the kernels. These diagrams show the difference between the measured variables (nutritional values, antioxidants, and antioxidant properties) and the three principal components. Thus, regarding the observations (marked here by the different treatments applied to the seeds of *I. gabonensis*), Table 9 illustrates the contributions of each observation. It appears that the F1 component, contributing 47.21%, is associated with the roasted treatment (G), and the F2 and F3 components, contributing 22.87% and 14.02%, respectively, are associated with the roasted then blanched treatment (G + E) and the dried then blanched treatment (S + E). Moreover, the observations are well represented when the square cosine is close to 1, with the highest square cosine for component F1 being 0.94, corresponding to the roasted treatment (G), for component F2 being 0.55, associated with the roasted then blanched treatment (G + E), and finally for component F3 being 0.54, associated with the dried then blanched treatment (S + E). The F1 component, which is strongly and positively correlated with the roasted treatment (G), seems to better represent nutritional values such as fiber, ash, protein, magnesium, and potassium, while the second component more closely reflects a low level of anti-nutrients (oxalates and tannins hydrosolubles). Thermal treatments play an important role in eliminating anti-nutritional factors.

4 | Conclusion

At the end of this work, which focused on identifying culinary practices influencing the physicochemical and techno-functional properties of *I. gabonensis kernels*, it is concluded that roasting, blanching, and drying are the treatment methods commonly applied to these *kernels* in the East Cameroon region. Roasting (G) significantly reduced the anti-nutrient content (tannins, saponines, phytates, and oxalates). The mineral composition (iron, zinc, phosphorus, calcium, sodium) and macronutrient composition (carbohydrates, lipids, and proteins) increased with drying (D) and roasting + boiling (G + B). The triple treatment drying + boiling + roasting (S + E + G) allowed for better functional properties and, above all, color preservation. The stability to thermal treatments (rheology) was better with the drying + roasting (S + G) treatment, whereas roasting alone (G) negatively affected these rheological properties. Roasting also resulted in a loss of amino acids, unlike boiling (S + E). Because of these results, it ultimately appears that culinary treatments have a significant impact on the evaluated properties, hence the necessity to take into account the conditions of the different treatments. *I. gabonensis* kernels, after undergoing the various processing methods studied, can be transformed into a range of products such as flour and edible oil, and serve as a key ingredient in several traditional culinary preparations like “biba soup” in the eastern region of Cameroon.

Author Contributions

Ulrich Landry Kamdem Bemmo: conceptualization (lead), investigation (equal), methodology (equal), writing – original draft (equal), writing – review and editing (equal). **Serge Cyrille Houketchang Ndomou:** data curation (equal), formal analysis (equal), writing – original draft (equal), writing – review and editing (equal). **Stephano Tene Tambo:** methodology (equal), writing – review and editing (equal). **Jean Marcel Bindzi:** investigation (equal), methodology (equal). **Sharon Greer Abio Bando:** investigation (equal), methodology (equal), writing – original draft (equal), writing – review and editing (equal). **Hilaire Macaire Womeni:** supervision (lead), validation (equal), writing – review and editing (equal). **François Ngoufack Zambou:** supervision (lead), validation (equal), writing – original draft (equal), writing – review and editing (equal).

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Ethics Statement

The conduct of the survey required the validation of our work protocol by the administrative authority of the University of Bertoua as well as the Regional Delegate of Public Health of East Cameroon. No note was necessary for the field visit. Participants were informed about the study, they could stop the interview at any point, written consent from all the participants to the study was obtained, and the researcher valued the rules of volunteer participation and confidentiality.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The article does not provide any additional information, but the raw data can be provided upon request.

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