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Research Article

Predictive Bioavailability of Iron, Calcium, and Zinc in Traditional and Composite Flours Made from Roasted Corn, Soybean, and Peanut Powders

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Abstract

In Ivory Coast, roasted corn kernels are used to produce roasted corn flour, which is rich in carbohydrates but low in protein, vitamins, and minerals. To enhance the nutritional value of this flour, 5% roasted peanut powder and 5% roasted soybean powder were added. The objective is to highlight the nutritional and health benefits by assessing the predictive bioavailability of nutrients such as calcium, zinc, and iron in the composite flour formulated from roasted ingredients. The methodology involved determining the levels of calcium, zinc, and iron using atomic absorption spectrophotometry, analyzing antinutritional factors (phytic acid, oxalate), and calculating predictive bioavailability based on molar ratios. The results showed that the levels of zinc, iron, calcium, oxalate, and phytic acid, in the composite flour, were 2.67 mg/100 g MS; 1.44 mg/100 g MS; 132.45 mg/100 g MS; 8.03 mg/100 g MS; and 3.48 mg/100 g MS, respectively. In addition, the molar ratios phytates/Ca, phytates/Fe, phytates/Zn, Calcium×Phytate/ Zinc et oxalates/Ca were well below their critical values, indicating high bioavailability. It is therefore necessary to promote the use of soybean and peanut powders in the production of composite flours in order to improve the nutritional quality and health benefits of foods made from local agricultural resources.

Keywords

Composite Flours, Micronutrients, Malnutrition, Antinutrients, Predictive Bioavailability, Absorption

1. Introduction

Malnutrition remains a major public health problem affecting infants and young children in developing countries [1, 2]; particularly in South Asia and sub-Saharan Africa [3]. In infants and young children, it affects growth as well as height-for-age, psychomotor, and socio-emotional development [4]. Severe acute malnutrition is responsible for the deaths of one-third of children under the age of 5 worldwide, estimated at nearly 8 million each year [5].

Ivory Coast, like other sub-Saharan African countries, is no exception. Studies have shown that malnutrition is widespread there [6]. According to World Food Programme, the prevalence of global acute malnutrition among children under 5

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years of age is 3.7%, and the stunting rate is projected to reach 21.4% by 2025 [7].

In fact, malnutrition can result from a deficiency or excess of macronutrients (carbohydrates, fats, or proteins) or micronutrients (vitamins and minerals), but also from the toxic effects of these macronutrients and/or micronutrients in the body [8-10]. For infants, after six months of exclusive breastfeeding, it is important to introduce appropriate and adequate complementary foods whose nutrient content (carbohydrates, proteins, fats, vitamins, and minerals) can meet their nutritional needs in order to keep them healthy and promote their healthy growth.

For dietary supplements to be fully effective, it is essential that the nutrients they contain be bioavailable. In other words, once ingested, these nutrients must be able to be absorbed and utilized effectively by the body [11, 12]. It is an important factor in food quality control that makes it possible to predict the fate of a nutrient after it is ingested, absorbed, and utilized by target organs. There are several methods for assessing the bioavailability of nutrients in a food product. These include in vivo methods based on animal testing, in vitro methods based on simulated digestion, and predictive methods based on molar ratios.

Of all these techniques, the method based on molar ratios was used to predict the bioavailability of iron, zinc, and calcium contained in a composite flour formulated from corn, soybeans, and peanuts, intended for infant nutrition. Analyses of this flour indicated the presence of antinutritional factors, including phytate and oxalate. These antinutritional factors are known for their chelating effects on divalent cations (Fe, Zn, Ca), thereby reducing their likelihood of being absorbed by the body [13, 14]. It is therefore necessary to reduce their levels in foods because of their impact on nutrition.

In this context, the raw materials (corn, soybeans, and peanuts) used to produce the composite flour underwent a technological process (roasting) to improve its nutritional composition. This study therefore aims to investigate the predictive bioavailability of calcium, iron, and zinc in the composite flour made from roasted corn, soybeans, and peanuts.

2. Materials and Methods

2.1. Plant Materials

The plant material, consisting of common yellow corn (Zea mays L.), widely cultivated and used for human consumption in Ivory Coast, as well as soybean (Glycine max) and groundnut (Arachis hypogaea L.) seeds, was purchased at the Gouro market in Adjamé, Abidjan, Ivory Coast. The samples, which were relatively dry (with a moisture content between 10% and 12%), were transported to the Biotechnology Laboratory of the Department of Biosciences at Félix Houphouët-Boigny University in sterile, airtight polypropylene containers.

2.2. Processing Plant Material into Flour

2.2.1. Procedure for Making Traditional Roasted Corn Flour

The roasted corn flour was produced by making a slight modification to the method described in [15]. The corn kernels were carefully cleaned and sorted by hand to remove impurities (stones, wood debris, dirt). They were then roasted in a Memmert-type convection oven (Modèle UN160, Memmert™ Universal Oven, Germany) at 120 ℃ for 20 minutes. After roasting, the kernels were left to cool at room temperature, in a controlled atmosphere to prevent them from absorbing water, then were ground using a grinder with their pericarp to produce a flour, which was then successively sieved using sieves with progressively finer mesh sizes (250 µm, 200 µm, 150 µm) to obtain a fine particle size distribution. The resulting flour, after the 150 µm sieve, was stored at 4 ℃ in the Electrolux refrigerator (Electrolux professional HPe, France), in sterile, airtight glass bottles, for subsequent analysis.

2.2.2. Procedure for Producing Roasted Soybean Flour

The roasted soy flour was produced by making a slight modification to the method described in [15]. The soybeans were cleaned and sorted by hand to remove solid impurities (stones, wood debris, dirt). They were then roasted in a Memmert-type convection oven (Modèle UN160, Memmert™ Universal Oven, Germany) at 120°C for 20 minutes. After roasting, the seeds were left to cool at room temperature, in a controlled atmosphere to prevent them from absorbing water, then were ground using a grinder with their film to produce flour, which was then successively sieved using sieves with progressively finer mesh sizes (250 µm, 200 µm, 150 µm) to achieve a fine particle size. The roasted soybean powder, obtained after the 150 µm sieve, was stored at 4°C in an Electrolux refrigerator (Electrolux professional HPe, France), in sterile, airtight glass bottles, for subsequent analysis.

2.2.3. Dried Peanut Flour Production Process

The peanut seeds were first cleaned and sorted by hand to remove stones, dirt, and wood debris. They were then dried at 80°C for twenty-four (24) hours in a Memmert-type convection oven (Modèle UN160, Memmert™ Universal Oven, Germany), and subsequently, after removing the seed skins, ground seeds using a high-powered grinder to produce a powder. Finally, the resulting powder was successively sieved using sieves with progressively finer mesh sizes (250 µm, 200 µm, and 150 µm) and then the dried Peanut powder, obtained after the 150 µm sieve stored at 4°C in an Electrolux refrigerator (Electrolux professional HPe, France), in sterile, airtight glass bottles, for subsequent analysis.

2.3. Composite Flour Formulation

The composite flour was prepared by successively mixing 90 g of corn flour, 5 g of soybean powder, and 5 g of peanut powder. The mixture was homogenized until a uniform flour was obtained, then stored in airtight glass bottles and kept at 4°C in the laboratory's Electrolux refrigerator (Electrolux professional HPe, France).

2.4. Determination of the Zinc, Iron, and Calcium Content of Composite Flour

A mineral extract was prepared by incinerating 0.5 g of each sample at 600°C overnight. The ashes were dissolved in a dilute hydrochloric acid solution (1:3, HCl to distilled water, v/v) to which a few drops of concentrated nitric acid had been added. The extracted solution was diluted to 50 mL with distilled water and then filtered, using Whatman type filter paper (Grade 40; 8 µm). The calcium, iron and zinc contents were determined by atomic absorption spectrophotometry (Perkin-Elmer, 403, United States), according to the method described by [16].

2.5. Determination of Antinutritional Factor Content

2.5.1. Determination of Phytate Content

The phytic acid content of the flours samples was determined using spectrophotometric methods described by [17]. The samples was prepared by taking around 0.1 g of flour sample into a screw-capped test tube and 1 mL of 1 M HCl (1 mL) added. The mixture was heated in a boiling water bath (100°C) for 45 min. Then, the tubes are cooled to room temperature and centrifuged for 5 min at 13,000×g. Supernatant aliquots (500 µL) were transferred to new centrifuge tubes and diluted with 2 mL of deionized water. The FeCl3 (800 µL) was added to the diluted solution (400 µL) then this mixture was incubated at 100 ◦C for 45 min in a shaking water bath. Further, samples were cooled in an ice bath for 15 min to allow the formation of an iron-phytate precipitate and subsequently centrifuged at 13,000×g for 10 min at 0 ◦C. Supernatant aliquots (600 µL) were mixed with the 800 µL of the complexing reagent (consisting of 1 g of 2, 2-bipyridine, and 0.13 mL thioglycolic acid in 100 mL 0.2 M HCl) and absorbance was measured at 540 nm, the same procedure was followed for the standard phytic acid solution to get the standard curve. The Phytic acid content in the samples was determined by the slandered graph.

2.5.2. Determination Des Teneurs En Oxalates

Oxalate levels were measured using the method described by Abaza as cited by [18]. One (1) g of flour was finely ground and then homogenized in 75 mL of H_2SO_4 (3 M) under magnetic stirring for one (1) hour. The mixture was filtered through a Whatman No. 4 filter paper, and a 25 mL volume of this filtrate was taken and titrated hot with a $KMnO_4$ (0.05 M) solution until a persistent pink color developed. The oxalate content was calculated using the following formula:

$$Oxalate\ \ (mg/100g) = \frac{(2{,}2\ \times\ Veq\ \times\ 100)}{me} \times 100 \qquad (1)$$

Veq: volume obtained at equivalence
me: mass of the sample

2.6. Assessment of Mineral Bioavailability

The relative bioavailability of calcium, iron, and zinc was assessed by calculating the molar ratios phytate/calcium, phytate/fer, phytate/zinc et oxalate/calcium, according to the method [19] that made it possible to predict the bioavailability of minerals. The molar ratios were calculated as follows:

$$Molar\ \ ratio = \frac{Antinutrient\ \ Mole}{Mineral\ \ Mole} \qquad (2)$$

$$Antinutrient\ \ Mole = \frac{Antinutrient\ \ (mg)}{Atomic\ \ mass\ \ (g/mol)} \qquad (3)$$

$$Mineral\ \ Mole = \frac{Mineral\ \ (mg)}{Atomic\ \ mass\ \ (g/mol)} \qquad (4)$$

2.7. Statistical Analysis

A one-way analysis of variance and Duncan's test were used to determine the significance of differences between mean values at a significance level of 0.05. The results were expressed as the mean of three analyses, each conducted in triplicate. Statistical analyses were performed using SPSS software (Systat statistical program, version 21, SPSS Inc., United States).

3. Results

3.1. Effect of Roasting and Supplementation on Nutriments

The results presented in Figure 1 show significant differences ($p < 0.05$) in the zinc, iron, and calcium contents of the two flours studied. The MAS5% composite flour has zinc (2.67 ± 0.50 mg/100 g), iron (1.44 ± 0.09 mg/100 g), and calcium (132.45 ± 0.90 mg/100 g) that are significantly higher than those of the traditional TRCF flour (control sample), which contains 1.66 ± 0.25 mg/100 g, 1.32 ± 0.01 mg/100 g, and 131.02 ± 0.20 mg/100 g, respectively.

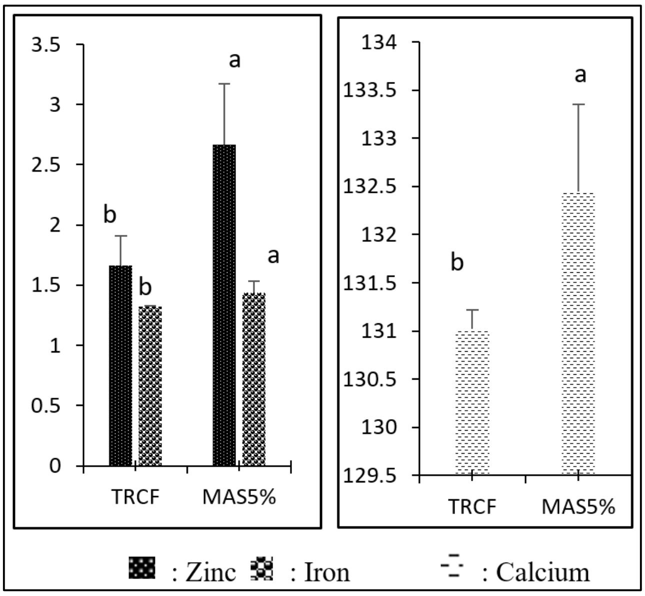

Figure 1. *Zinc, iron, and calcium content of TRCF and MAS 5% flours.*

Each value is the mean of triplicate analyses. Values marked with different letters (a > b) show significant differences at the 5% significance level. TRCF: Traditional Roasted Corn Flour; MAS5%: composite flour made from roasted corn.

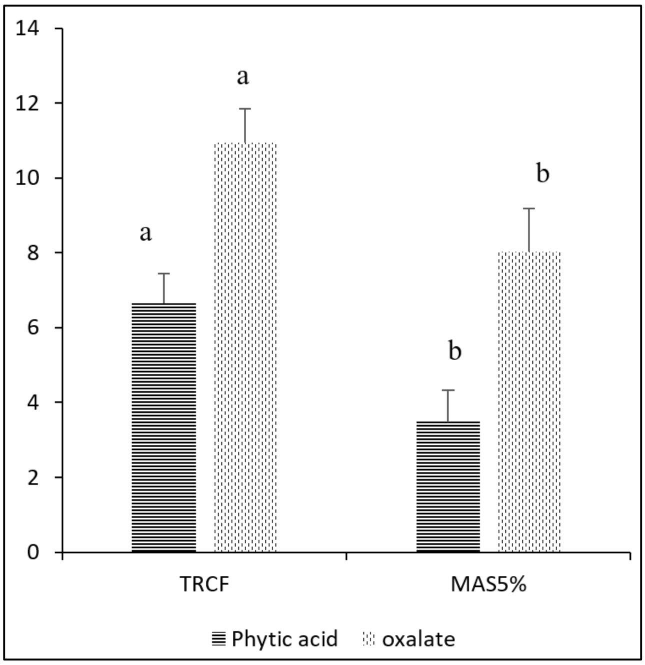

Figure 2. *Antinutrient composition of traditional flour and composite flour made from roasted corn.*

Each value is the mean of triplicate analyses. Values marked with different letters (a, b) show significant differences at the 5% significance level. TRCF: Traditional roasted corn flour; MAS5%: composite flour made from roasted corn.

3.2. Effect of Roasting and Supplementation on Antinutritional Factors

Figure 2 illustrates the composition of antinutritional factors in the two flours: the MAS5% composite flour and the traditional roasted maize flour (TRCF) (control sample). A significant difference ($p < 0.05$) in phytic acid and oxalate levels was observed in the composite flour compared to the traditional roasted corn flour. Regarding phytic acid, the values decreased from 6.65 ±0.80 mg/100 g in the traditional roasted maize flour (TRCF) to 3.48 ±0.84 mg/100 g in the composite flour, representing a reduction of 47.67%. As for oxalates, the concentrations went from 10.95 ±0.90 mg/100 g in traditional roasted corn flour TRCF to 8.03 ±1.15 mg/100 g in composite flour, a decrease of 26.67%.

3.3. Predicted Bioavailability of Minerals in Various Foods

Table 1 presents the five molar ratios used to assess the predictive bioavailability of calcium, iron, and zinc in the two flours. For the traditional TRCF flour (control sample), the phytate/Ca, phytate/Fe, phytate/Zn, oxalate/Ca, and [Ca]×[phytate]/[Zn] ratios are, respectively, 0.0031 ± 0.000; 0.4275 ±0.01; 0.3945 ±0.001; 0.0380 ±0.002; and 0.0013 ± 0.000. In the MAS5% composite flour, these same ratios are 0.0016 ± 0.000; 0.2051 ± 0.003; 0.1284 ± 0.004; 0.0276 ± 0.001; and 0.0004 ±0.000.

Table 1. *Molar ratios between antinutrient molecules and the bioavailability of minerals in composite corn flour and traditional roasted corn flour.*

	Phytate/Ca	Phytate/Fe	Phytate/Zn	Oxalate/Ca	[Calcium]×[Phytate]/ [Zinc]
TRCF flour	$0,0031^{a}$±0,000	$0,4275^{a}$±0,01	$0,3945^{a}$±0,001	$0,0380^{a}$±0,002	$0,0013^{a}$±0,000
MAS5% flour	$0,0016^{b}$±0,000	$0,2051^{b}$±0,003	$0,1284^{b}$±0,004	$0,0276^{b}$±0,001	$0,0004^{b}$±0,000
Standards	< 0,24	< 1	< 15	< 1	< 0,5

Each value is the mean of triplicate analyses. The same letter in the same line indicate no statistical difference (p< 0.05). Values marked with different letters (a > b) show significant differences at the 5% significance level. TRCF: Traditional roasted corn flour; MAS5%: Composite flour made from roasted corn

4. Discussion

The higher mineral content of the composite flour ((2.67 ± 0.50 mg/100 g), iron (1.44 ± 0.09 mg/100 g), and calcsium (132.45 ± 0.90 mg/100 g)) is due to the intrinsic mineral content of soybeans and peanuts, each of which makes up 5% of the formulation. Indeed, these two legumes are recognized as important sources of zinc, iron, and calcium [20-22]. Enriching corn flour with these two oilseeds thus increases the mineral density of the final product, in line with the recommended fortification strategy for improving the nutritional value of local foods intended for young children [23]. Furthermore, the nutrient contents obtained are comparable to those reported for other composite flours made from cereals and legumes used as complementary foods in West Africa.

These findings are particularly significant in the context of child malnutrition in Ivory Coast, where the stunting rate among children under 5 years of age was 21.4% in 2025, according to the [7]. Increasing the concentration of essential minerals such as zinc, iron, and calcium is, in fact, of paramount importance: zinc is essential for a child's growth, immune function, and cognitive development; iron is crucial for tissue oxygenation and neurological development; and calcium is essential for bone mineralization [1]. Given its enriched mineral profile, MAS5% composite flour therefore appears to be a nutritionally superior alternative to traditional TRCF flour for preventing micronutrient deficiencies in young children.

Furthermore, this reduction in phytic acid and oxalate levels in MAS5% flour is a particularly favorable outcome from a nutritional standpoint, resulting from the combination of two factors. On the one hand, roasting, a thermal process applied to the three raw materials, is known to alter the tertiary structure of proteins, thus causing the dissociation of mineral-antinutrient complexes and releasing minerals and considerably reducing their ability to inhibit enzymatic digestion [24]. On the other hand, roasting alone is generally not sufficient to explain such a marked reduction in phytates; the dilution effect resulting from the incorporation of soybeans and peanuts, whose phytate contents differ from those of corn, also contributes to the modulation of the final antinutrient content of the composite flour.

The nutritional benefit of this reduction is all the more significant given that phytate is the primary antinutrient that limits the bioavailability of divalent cations in cereal-based foods by forming insoluble complexes with iron, zinc, and calcium in the gastro-intestinal tract [14]. The 47.67% reduction in phytic acid content observed in MAS5% compared to TRCF therefore represents a real nutritional benefit, consistent with the findings of [25, 26], which confirmed that heat treatments such as roasting and cooking result in a significant reduction in phytate levels in cereal and legume flours. Similarly, the 26.67% reduction in oxalate levels in MAS5% is beneficial, as oxalic acid is known to precipitate calcium in the form of insoluble calcium oxalate and thereby reduce its intestinal absorption [27].

These results suggest that the composite formulation, combined with the roasting of raw materials, constitutes an effective technological strategy for improving the nutritional quality of complementary flours intended for infants. The heat applied during roasting, combined with the diluting effect of soybeans and peanuts, contributes to the breakdown of antinutrients, thereby improving the bioavailability of minerals and promoting the absorption of essential nutrients in young children.

All values obtained for the two flours remain well below the critical thresholds reported in the literature (phytate/Ca < 0.24; phytate/Fe < 1; phytate/Zn < 15; oxalate/Ca < 1; [Ca]×[phytate]/[Zn] < 0.5), and are consistently lower in MAS5% than in TRCF, indicating satisfactory and, overall, better predicted bioavailability of the minerals studied in the composite flour. These results are particularly encouraging, as phytate is recognized as the primary inhibitor of mineral absorption in plant-based foods [14, 28].

The phytate/Ca and oxalate/Ca ratios, both of which are well below their respective critical thresholds (0.24 and 1), According to [29], the results indicate that neither phytate nor oxalate is a significant limiting factor for calcium absorption in either flour. However, the lower value obtained for MAS5% on these two indicators suggests that calcium availability is slightly higher in the composite flour.

The phytate/iron ratio for two flours remains below the critical threshold of 1, which suggests acceptable absorption of non-heme iron [30]. However, this prediction should be qualified, as [31] point out that molar ratios are a predictive approach and not a direct measure of in vivo bioavailability, as actual iron absorption can be influenced by factors such as ascorbic acid, the presence of animal proteins, or the individual's nutritional status.

The phytate/zinc ratio for two flours remains well below the threshold of 15 recommended by [29, 32]. Similarly, the [Ca]×[phytate]/[Zn] ratio, which takes into account the ternary interactions between calcium, phytate and zinc, is also very low in two flours, indicating a negligible risk of mineral competition that could compromise zinc absorption. According to [33], a [Ca]×[phytate]/[Zn] ratio of less than 0.5 is associated with good predictive bioavailability of zinc, a finding that was fully confirmed in the two flours studied.

For all five indicators, the MAS5% values are consistently lower than those for TRCF, confirming that the inclusion of soya and peanuts, combined with roasting, improves not only the absolute mineral content but also their predicted bioavailability. This finding is consistent with the observations of [23], according to which supplementing cereal flours with pulses significantly improves the bioavailability of micronutrients. These results must, however, be interpreted with caution, as the molar ratio approach does not take into account all dietary factors, whether they promote or inhibit absorption, nor individual physiological factors such as the child's iron status. Further in vivo or in vitro studies, using simulated digestion models or retention trials in animals, would be necessary to validate these conclusions [34].

5. Conclusions

The aim of this study was to assess the predicted bioavailability of iron, calcium and zinc in a traditional roasted maize flour (TRCF) and a MAS5% composite flour made up of 90 g of roasted corn flour enriched with 5g of roasted soybean flour and with 5g of dried peanut flour. The results showed that MAS5% has higher mineral content and lower levels of antinutrients, resulting in molar ratios well below the critical thresholds. These findings suggest that MAS5% offers superior predictive bioavailability compared with TRCF. In the context of combating child malnutrition in Côte d'Ivoire, MAS5% flour appears to be a local, accessible and effective nutritional alternative that can help reduce the deficiency in Zinc, Iron and Calcium.

Abbreviations

TRCF	Traditional Roasted Corn Flour
MAS5%	Composite Flour Made from Roasted Corn

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Author Contributions

Rougbo Ndjomon Paterne: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing

Kouadio Natia Joseph: Data curation, Methodology, Writing – original draft, Writing – review & editing

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Conflicts of Interest

The authors declare no conflicts of interest.

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Research Field

Rougbo Ndjomon Paterne: Enzymology, Biotechnology, Biochemistry, Nutrition, Food Technology, Food Chemistry, Food

Safety

Kouadio Natia Joseph: Biotechnology, Biochemistry, Nutrition, Food Technology, Food Chemistry, Food Safety

Konan Kouakou Ahossi: Food Microbiology, Environmental Microbiology and Biowaste Valorization and Bioindustries, Food Safety, Fermentation, Biotechnology

Sea Tehi Bernard: Enzymology, Biotechnology, Biochemistry, Nutrition, Food Technology, Food Chemistry, Food Safety