

**THESIS OF DOCTORAL (Ph.D.) DISSERTATION**

**The Composition of African Baobab Leaves and Fruits in Different Regions  
and Habitats: Contribution to Food Security and Nutritional Intervention**

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# 1 Introduction

## 1.1 Food security and inadequate dietary

Food security is achieved when all people worldwide have access to a necessary, safe, and nutritious diet that meets their nutritional needs for an active and healthy life (Solarin & Gil-Alana, 2025). The most important factor influencing human health is the adequate supply of nutrients to the diet (Singh et al., 2023). Millions of people worldwide, including Africans, are affected by nutritional deficiencies that have led to various public health problems (Jha et al., 2024). In addition, there are widespread diseases in tropical areas, such as anemia, which is positively correlated with inadequate dietary iron intake (Bushra et al., 2010).

The discovery of natural areas completely covered with underutilized and valuable plant species is one of the most important strategies for alleviating food insecurity and poverty problems related to human health. For example, African regions and habitats are rich in novel tree species that are believed to have health benefits, but have not yet been fully explored and utilized by the global community (Lamien-Meda et al., 2008). The baobab (*Adansonia digitata* L.) is a native and iconic tree in Africa with a massive trunk (Hendam et al., 2024; Lamien-Meda et al., 2008), belonging to the *Bombacaceae* family and *Malvaceae* subfamily. It is widespread in the Sahel (Baum et al., 2004; De Caluwé et al., 2010), with a stem diameter of up to 10 m and height of up to 25 m. This tree is well known because of its size Figure 1 and life expectancy, which can exceed hundreds of years. It is widespread in the warm and dry zones of tropical Africa (Gebauer et al., 2016). The baobab is native to numerous sub-Saharan countries and thrives mainly in dry savannah regions such as South Africa, Mozambique, the Ivory Coast, Malawi, Sudan, Zimbabwe, Kenya, Cameroon, Burkina Faso, Senegal, and Uganda (Sidibe M, 2002). A common characteristic of the baobab tree is the possession of very large, spectacular flowers that grow overnight (Baum, 1995). This tree grows in clay or sandy soils and in different ecological areas (El Amin, 1990).

## 1.2 The baobab tree products as a solution

The baobab tree has many benefits, with most of its parts playing a key role in promoting the livelihoods of poor people, especially in areas characterized by a lack of food sources (De Caluwé et al., 2010). The benefits of the baobab tree are recognized in over 300 African countries. Local

communities in several African societies consume baobab fruits and leaves throughout the year (Christine et al., 2010).



Figure 1. Baobab tree with a stem diameter of up to 10 meters and a height of up to 25 meters

### 1.3 Objectives

The main objective of this research was to discover a new plant resource with an adequate and healthy composition, such as the African baobab, to improve food security and contribute to nutritional intervention in rural and urban communities (different age groups in Sudan, Kenya, and Senegal).

We then propose a protocol for nutritional intervention using dried baobab leaves and fruit pulp powder to achieve the daily recommended reference values for proteins and minerals (K, Ca, Mg, Na, Fe, and Mn) for different target groups.

The specific objectives are:

- i. Determination of regional differences in nutrient content, such as protein, fat, ash, dry matter, pH, minerals (Na, Mg, K, Ca, Fe, Mn), total phenolic compounds (TPC), and total flavonoid compounds (TFC)
  - Baobab leaves were collected from two regions of Sudan, with three habitats (wetlands, plains, and mountains) in each region.

- Dried baobab fruits are available in the rural and urban markets of Sudan, Kenya, and Senegal.
- ii. Estimation of the amount of dried baobab leaves and fruit pulp powder required to meet the daily protein and mineral requirements of different age groups of the target population was based on the daily reference values recommended by the European Food Safety Authority.

## 2 Materials and Methods

### 2.1 Sample Site and Collection

#### 2.1.1 Baobab Leaves samples

Baobab trees were mainly distributed in two different regions in Sudan: North Kordofan (KR) and Blue Nile (BN). In addition, *Adansonia digitata* trees are found in different areas, including sloping areas such as mountains (El Amin, 1990). Samples of a mixture of young and old fresh leaves were collected in Sudan Figure 2 between July 15, 2022, and September 15, 2022. Two regions were covered: the Blue Nile in southeastern Sudan (coordinates: 11°15'00" N and 34°10'00" E) and North Kordofan, an arid zone in central Sudan (14°68'33" N and 29°93'33" E), as shown in Figure 3. Three habitats were selected for each region: mountain (M), wetland (W), and plain land (P). QGIS 3.20.1 software was used to create maps showing the areas where the baobab leaf samples were collected. Each area covered approximately 1500 km<sup>2</sup>. Ten trees were selected at each site, and two samples of fresh baobab leaves were collected per tree, a total of 3 kg of leaves per tree, to ensure representative sampling. The collected baobab leaves were dried in a shed at a room temperature of 25°C to preserve their nutritional properties and then packed in transparent, fully closed, and sealed polyethylene bags for analysis. Eighteen samples weighing approximately 500 g each were taken to the laboratory of the food science institute, University of Debrecen, Hungary, for nutritional values analysis.

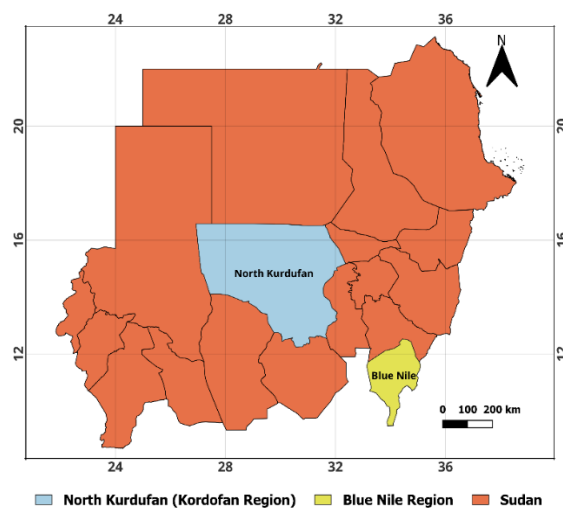


Figure 2. Sudan map: Source, QGIS 3.20.1 software, (Ahmed et al., 2024).

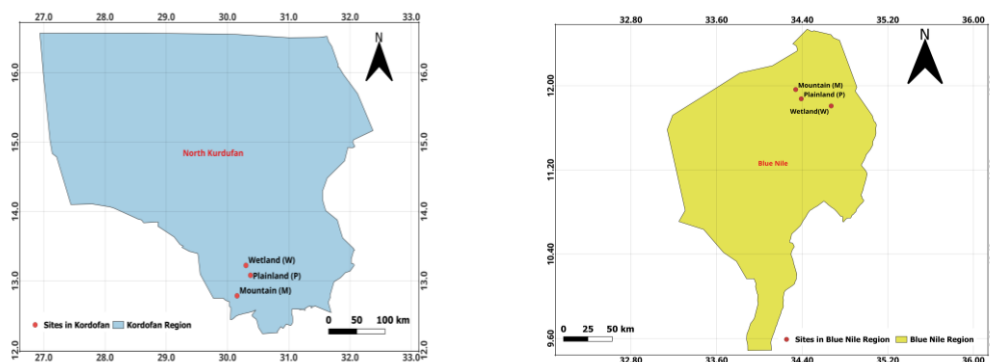


Figure 3. Kordofan and Blue Nile regions. Source: QGIS 3.20.1 software, (Ahmed, A. E. M. et al., 2024).

### 2.1.2 Baobab dried fruit source and collection

The samples of dried baobab fruit pulp (DBFP) were collected in three different African countries: Sudan, Kenya and Senegal. Rural and urban markets were targeted, and the DBFPs were collected (i) from the rural market of El Obeid in North Kordofan in Central Sudan with coordinates 14°68'33" N, 29°93'33" E; (ii) from the rural market of Garissa in the northeastern province of Kenya with coordinates 0° 27' 14.99" " N, 39° 39' 17.99" E; and (iii) from the urban market of Mombasa in southeastern Kenya with coordinates of 4.04348 N and 39.66821 E. DBFP samples from Senegal were ordered from the Hungarian market using the following data (Table 2).

Table 1. Information on collected dried Baobab samples from the Hungarian market

Sample code	Sample brand	Sample type	Producer	Distributor	Sealer in the Hungarian market	Source
WA1	Zena	Baobab Fruit	Manufactured by Zena exotic fruits Dakar-Senegal <a href="http://www.zenaexoticfruits.com">www.zenaexoticfruits.com</a>	Imported and distributed by Unidex B. V. Netherland. <a href="http://www.unidexholland.com">www.unidexholland.com</a>	Kohinoor Bazar Kft. Budapest	Samples were ordered by the author
WA2	Karam Aliment	Baobab fruits	Produced in Senegal Exported by MSN Sarl Senegal.	Distributed by Touba Palene SAS Italy.	Kohinoor Bazar Kft. Budapest.	

## 2.2 Sample Preparation

The dried baobab leaves were manually cleaned of all foreign matter and air-dried. The samples were then ground using an electric mill with a mesh size of 10 µm. The resulting powder was stored in labeled hygienic plastic containers until further use. The dried baobab fruits from Kenya, Sudan, and Senegal were stripped of all plant matter. A Retsch PM100 planetary ball mill was used to separate the pulp and seeds of baobab fruit. The DBFP powder was homogenized and packaged for analysis.

## 2.3 Proximate composition

2.3.1 Dry matter determination (ISO 6496:2001)

2.3.2 Nitrogen and crude protein content (ISO 5983-2:2009)

2.3.3 Crude fat content (ISO 11085:2015)

2.3.4 Crude ash content (ISO 5984:2022)

2.3.5 pH value determination (Hungarian standard MSZ-08-0206-2:1978)

## 2.4 Determination of antioxidant content

A gallic acid stock solution was used to prepare the calibration solutions. The chemicals used were 3,4,5-trihydroxybenzoic acid (Alfa Aesar GmbH & Co. KG, Karlsruhe, Germany), sodium carbonate (Sigma-Aldrich Chemie GmbH, Germany), methanol (Scharlab S.L., Spain), and Folin-Ciocalteu reagent (VWR International S.A.S., France). The results of total phenolic content (TPC) were expressed as mg gallic acid equivalent (GAE)/100 ml (Jiménez et al., 2010; Vida, 2021; Singleton et al., 1999).

The total flavonoid content (TFC) was expressed as mg catechin equivalent (CE)/100 ml (Hong & Kim, 2010; Vida, 2021). Nine replicates were performed for all the above studies.

## 2.5 Estimation of baobab leaves and fruit intakes (BLI and BFI)

The estimated amount of BLI or BFI to be included in the diet of the target groups (children 1-3 years, C1; children 4-6 years, C2; children 7-10 years, C3; children 10-18 years, C4; adults ≥ 25 years, AD; pregnant women, PQ; lactating women, LQ) was calculated as follows:

$$BLI, BLF(g/day) = \left( \frac{DRV}{a \times ANB} \right) \times 1000$$

where DRV is the dietary reference value recommended by the European Food Safety Authority for a specific nutrient (Table 3), ANB is the average amount of a specific nutrient in BLI

or BFI and  $\alpha$  is the in vitro bioavailability value. According to (Habte et al., 2021), the values of  $\alpha$  for Ca and Mg were 31.5% and 59%, respectively.

Table 2. Dietary reference values recommended by the European Food Safety Authority

Group/Age	Potassium (mg/day)	Calcium (mg/day)	Magnesium (mg/day)	Sodium (g/day)	Protein (g/kg/day)	Iron (mg/day)	Manganese (mg/day)
Children (1-3 years)	800	450	170	1.1	0.66	7	-
Children (4-6 years)	-	800	230	1.3	0.66	7	-
Children (7-10 years)	-	800	230	1.7	0.66	11	-
Children (10-18 years)	3,500	1,150	B: 300, G: 250	2.0	0.66	B: 11, G: 13	-
Adults ( $\geq$ 25 years)	3,500	750	M: 350, W: 300	2.0	0.83	M: 11, W: 16	3
Pregnant Women	3,500	750	300	2.0	1 g (1 <sup>st</sup> *), 9 g (2 <sup>nd</sup> *), 28g (3 <sup>rd</sup> *)	16	3
Lactating Women	4,000	750	300	2.0	19 g (FI), 13 g (AF)	16	3

1<sup>st</sup> trimester, 2<sup>nd</sup> trimester, 3<sup>rd</sup> trimester. “B”: Boys, “G”: Girls, “M”: Men, “W”: Women, “-” value is not available or not applicable. “FI”: (First 6 months), “AF”: (After 6 months). Source: (EFSA, 2017; “Scientific Opinion on Dietary Reference Values for Manganese,” 2013).

## 2.6 Statistical analysis

Data analysis was performed using the programming environment R (version 3.6.1, R Core Team). Descriptive statistics (mean and standard deviation) were calculated for all nutrients across different habitats and regions. Analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) post hoc tests were performed to test for differences in BL and DBFP nutrients between habitats. A two-sample t-test was performed to test for differences in BL nutrient levels between the Sudanese regions. A reduction of variables was achieved by performing principal component analysis (PCA) on the correlation matrix to describe the relationships between the analytical data and the geographical origin of the samples (regions and habitats). To better understand the basic statistical concepts used in this study, a brief explanation is provided below.

### 3 Results

The normality of the data was checked using the Shapiro test, and the results are described as follows:

#### 3.1 Simple variance analysis

##### 3.1.1 The composition of baobab leaves in different regions

Table 3. The concentration (means and SDs; n =9) of nutrients in dried baobab leaves from the North Kordofan and Blue Nile regions of Sudan.

Region	Blue Nile		North Kordofan	
	Means	SDs	Means	SDs
key				
Ash content g/100 g	11.9 <sup>a</sup>	0.7	9.9 <sup>b</sup>	0.8
Ca concentration (mg/100 g) dw	2689 <sup>a</sup>	305	2354 <sup>b</sup>	293
Cu concentration (mg/100 g) dw	0.801 <sup>a</sup>	0.203	0.806 <sup>a</sup>	0.072
Dry m. (m/m)%	92 <sup>a</sup>	0.4	92 <sup>a</sup>	0.2
Fat content g/100 g	1.8 <sup>a</sup>	0.3	1.9 <sup>b</sup>	0.2
Fe concentration (mg/100 g) dw	13 <sup>a</sup>	1.4	17.0 <sup>b</sup>	2.8
K (mg/100 g) dw	1660 <sup>a</sup>	132	1324 <sup>b</sup>	259
Mg concentration (mg/100 g) dw	444 <sup>a</sup>	14	556 <sup>b</sup>	56
Mn concentration (mg/100 g) dw	2.3 <sup>a</sup>	0.4	5.7 <sup>b</sup>	3.2
Na concentration (mg/100 g) dw	6.9 <sup>a</sup>	0.5	7.8 <sup>b</sup>	0.9
pH	5.9 <sup>a</sup>	0.1	5.8 <sup>b</sup>	0.1
Protein content g/100 g	15.5 <sup>a</sup>	1.2	15.3 <sup>a</sup>	1.5
TFC CE (mg/100 g)	1328 <sup>a</sup>	91	1471 <sup>b</sup>	64
TPC GAE (mg/100 g)	361 <sup>a</sup>	26	361 <sup>a</sup>	9
Zn concentration (mg/100 g) dw	2.5 <sup>a</sup>	0.6	1.8 <sup>a</sup>	0.2

Means followed by different letters are significantly different at the alpha level of 0.05.

The nutritional value of baobab leaves in Table 4 shows that the calcium and potassium contents were higher in the Blue Nile region ( $2689 \pm 305$  mg/100 g and  $1660 \pm 132$  mg/100 g, respectively). In contrast, the magnesium and sodium values were higher in the Kordofan region ( $556 \pm 55.6$  mg/100 g and  $7.8 \pm 0.9$  mg/100 g). In the simple analysis of variance, a two-sample t-test was performed at significance levels of 0.05, 0.01, and 0.001 Figure 4. The mean concentrations of the macroelements (Ca, K, Mg, and Na) differed significantly between the two regions ( $p < 0.001$ ). Analysis of the content of trace elements in the baobab leaves revealed that significantly ( $p < 0.001$ ) higher levels of iron and manganese ( $17.2 \pm 2.8$  mg/100 g) and  $5.7 \pm 3.2$  mg/100 g) were found in Kordofan and higher levels of zinc ( $2.6 \pm 0.6$  mg/100 g) in the Blue Nile region. However, the actual difference in the mean copper concentration between the two regions was not significantly different.

The results of the proximate analysis of the additional nutritional values also differed. Blue Nile had higher ash ( $11.9 \pm 0.7$  g/100 g), protein ( $15.5 \pm 1.2$  g/100 g), and pH ( $5.9 \pm 0.1$ ), while Kordofan had higher fat (1.9 g/100 g), TFC ( $1470 \pm 64$  mg CE/100 g), and TPC ( $362 \pm 8.7$  mg GAE/100 g). Dry matter values were the same in both regions (92 m/m%). A t-test confirmed that there were no significant differences between the mean values of protein, dry matter, and TPC.

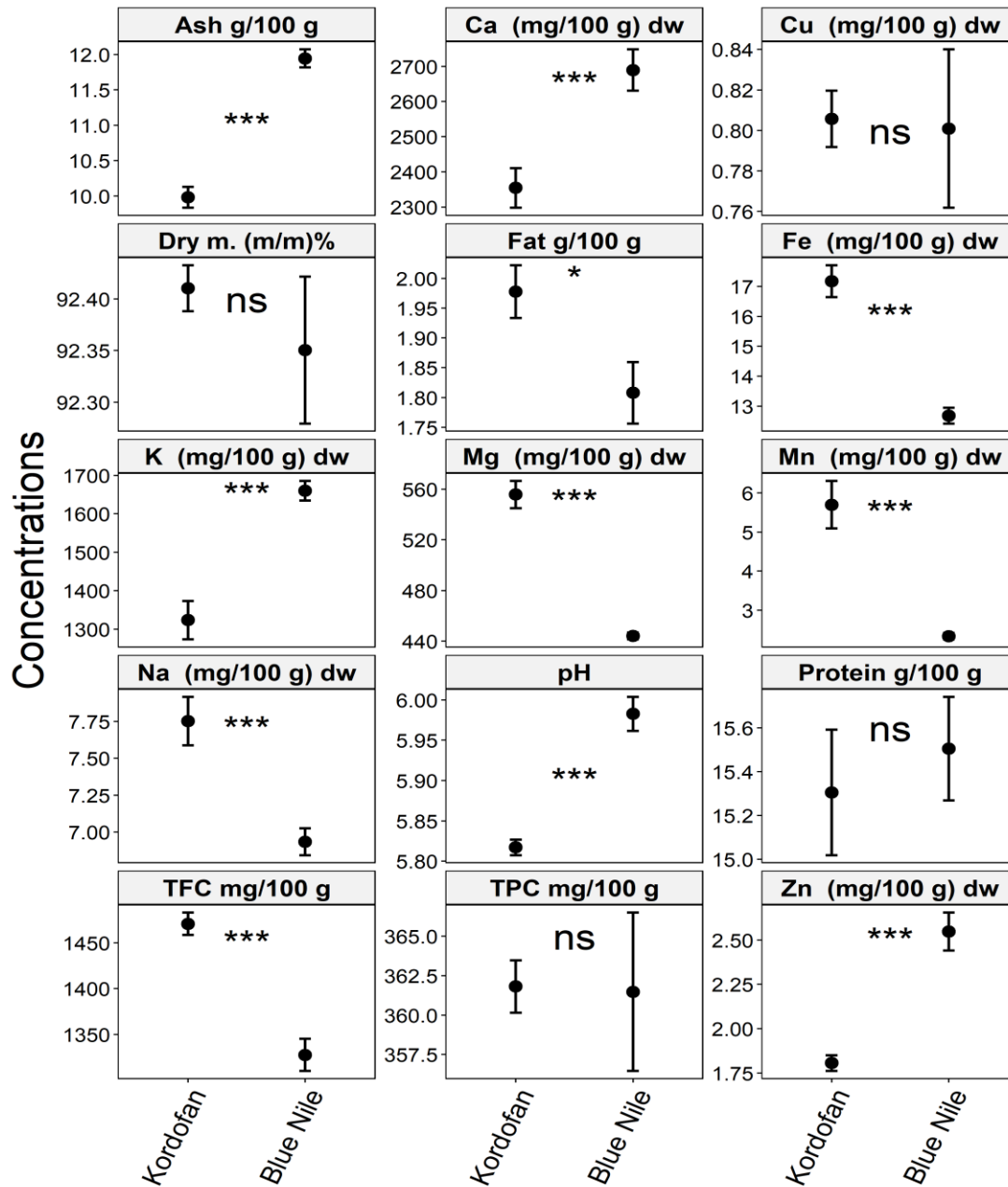


Figure 4. Mineral concentrations of baobab leaves in two regions (Blue Nile and North Kordofan) of Sudan. Significance codes: at the  $p < 0.05$  (\*), and  $p < 0.001$  (\*\*\*) levels. ns, not significant.

### 3.1.2 The composition of baobab leaves in different habitats

Table 4. The concentration (means and SDs; n =9) of nutrients in dried baobab leaves from different habitats in Sudan.

Habitats	Mountains (M)		Plain land (P)		Wetland (W)	
	Means	SDs	Means	SDs	Means	SDs
Ash content g/100 g	11.7 <sup>a</sup>	1.19	10.1 <sup>b</sup>	1.2	11.1 <sup>c</sup>	0.6
Ca concentration (mg/100 g) dw	2903 <sup>a</sup>	187	2236 <sup>b</sup>	169	2426 <sup>c</sup>	222
Cu concentration (mg/100 g) dw	0.67 <sup>a</sup>	0.09	0.83 <sup>b</sup>	0.09	0.92 <sup>c</sup>	0.15
Dry m. (m/m)%	92.0 <sup>a</sup>	0.1	92 <sup>a</sup>	0.3	93.0 <sup>a</sup>	0.1
Fat content g/100 g	1.9 <sup>a</sup>	0.4	2.0 <sup>b</sup>	0.2	1.8 <sup>c</sup>	0.1
Fe concentration (mg/100 g) dw	14.0 <sup>a</sup>	0.6	15.0 <sup>a</sup>	4.2	14.0 <sup>a</sup>	3.3
K (mg/100 g) dw	1477 <sup>a</sup>	365	1345 <sup>b</sup>	185	1654 <sup>c</sup>	34
Mg concentration (mg/100 g) dw	499 <sup>a</sup>	41	529 <sup>b</sup>	101	471 <sup>c</sup>	32
Mn concentration (mg/100 g) dw	3.9 <sup>a</sup>	1.6	5.9 <sup>b</sup>	3.9	2.3 <sup>c</sup>	0.3
Na concentration (mg/100 g) dw	7.4 <sup>a</sup>	0.3	6.9 <sup>b</sup>	0.5	7.7 <sup>c</sup>	1.2
pH	5.9 <sup>a</sup>	0.2	5.8 <sup>b</sup>	0.1	5.9 <sup>c</sup>	0.1
Protein content g/100 g	13.6 <sup>a</sup>	0.5	16.6 <sup>b</sup>	0.3	15.9 <sup>c</sup>	0.3
TFC CE (mg/100 g)	1368 <sup>a</sup>	76	1396 <sup>a</sup>	163	1434 <sup>a</sup>	26
TPC GAE (mg/100 g)	350 <sup>a</sup>	13.9	374 <sup>b</sup>	23	361 <sup>c</sup>	11
Zn concentration (mg/100 g) dw	2.2 <sup>a</sup>	0.1	1.9 <sup>b</sup>	0.3	2.5 <sup>c</sup>	0.8

Means followed by different letters are significantly different at the alpha level of 0.05.

The ANOVA test showed that the concentrations of all macro elements in baobab leaves were significantly different in all three habitats at a significance level of 0.05 (Table 5). Calcium was highest ( $2903 \pm 187$  mg/100 g) in the M sites, potassium ( $1654 \pm 34$  mg/100 g) and Na ( $7.7 \pm 1.2$  mg/100 g) in the W sites, and magnesium in the P sites ( $529 \pm 101$  mg/100 g) (Table 5). In addition, the Tukey HSD mean comparison test showed significant differences in Ca levels between each pair of study habitats. For Mg and Na, the test also showed a significant difference between the pairs of habitats studied, except between (W-P) for Mg and (M-W) for Na. The K content also differed significantly between the ecological zone pair (W-P). For the trace elements in baobab leaves analyzed in different habitats, the highest levels of copper ( $0.9 \pm 0.2$ ) and zinc ( $2.5 \pm 0.8$ ) were found in ecological zone W, and the highest levels of iron ( $15 \pm 4$ ) and manganese ( $5.9 \pm 0.3.9$ ) were found in ecological zone P. ANOVA showed that the mean concentrations of all trace elements, except iron, were significantly different ( $p < 0.05$ ) within the different habitats (W, P,

and M). Tukey's HSD multiple comparison test of means showed a significant difference in the values of Cu between all habitat pairs; for Mn in all pairs except (P-M), there were significant differences only between the W-M pair. Proximate analysis of nutrients in baobab leaves showed that the highest values for ash ( $11.7 \pm 1.2$  g/100 g) and pH (5.9) were found in the M sites. The highest content of protein ( $16.6 \pm 0.3$  g/100 g) and TPC 373.7 mg/100 g) was found in P sites. The highest contents of dry matter (93.6 m/m%) and TFC (1433 mg/100 g) were found in the W sites. The ANOVA test showed significant differences for all mean values except TFC and fat content ( $p = 0.181$  and  $0.062$ , respectively).

More details of Tukey's post-hoc results were provided to understand the most substantial differences in the content of Ca, K, Mg, and Na in baobab leaves among the three studied sites (P, W, and M), Figure 5. This statistical test controls for family-wise error rates and offers pairwise evaluations of the means across the sites, in addition to confidence intervals (CIs) and familiar p-values. Significance of mean differences (Tukey HSD) at the  $p < 0.05$  (\*),  $p < 0.01$  (\*\*),  $p < 0.001$  (\*\*\*), and  $p < 0.0001$  (\*\*\*\*) levels. ns, not significant.

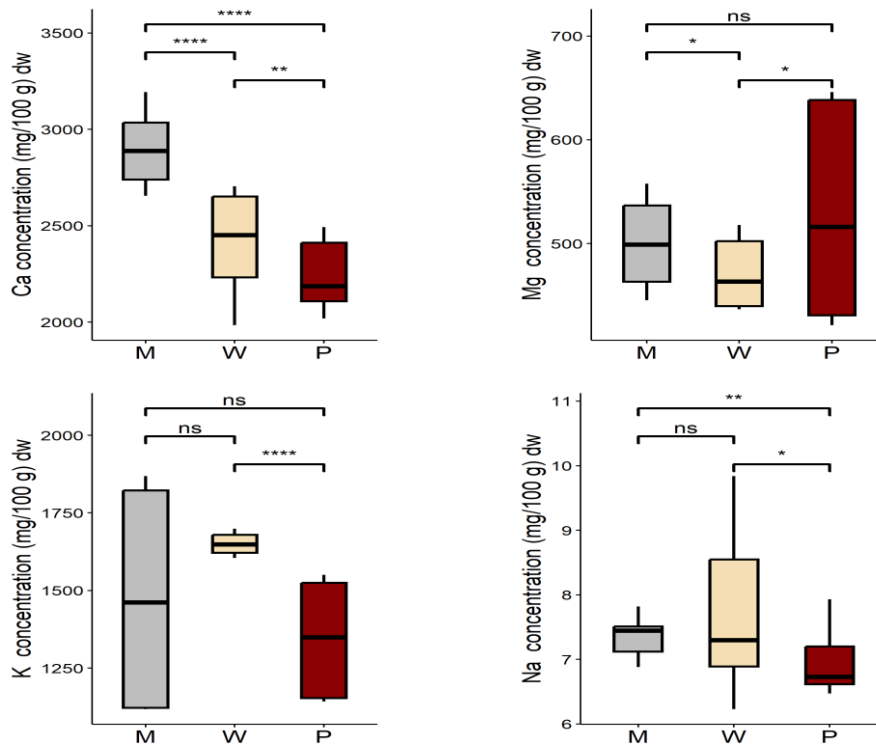


Figure 5. Calcium, magnesium, potassium, and sodium content in baobab leaves from three different habitats (W) wetland (P) plain land, and (M) mountain in Sudan.

Tukey's post-hoc result for proximate analysis (Ash, protein, fat contents, and dry matter) in baobab leaves is shown in Figure 6. The results of ash content are described as follows: site P versus site M showed a highly significant p-value of 0.0001. Site P had a significantly lower ash content than site M. The large negative mean difference ( $-1.56$ ) indicates a notable decrease in ash content at P. The confidence interval (CI) of ( $-2.41, -0.72$ ) does not include zero, indicating statistical significance. Site W vs. M resulted in a mean difference of 0.59 and a p-value of 0.2231, which was not significant. The CI crosses zero ( $-1.43$  to  $0.26$ ), signifying that experiential difference may be due to random variation. Sites (W–P) resulted in a mean difference of ( $+0.98$ ), a significant p-value of ( $0.0196$ ), and a CI of ( $0.13, 1.82$ ) to highlight that site W has a higher ash content when compared to site P. This difference indicates that site-specific factors may have increased the ash level at site W.

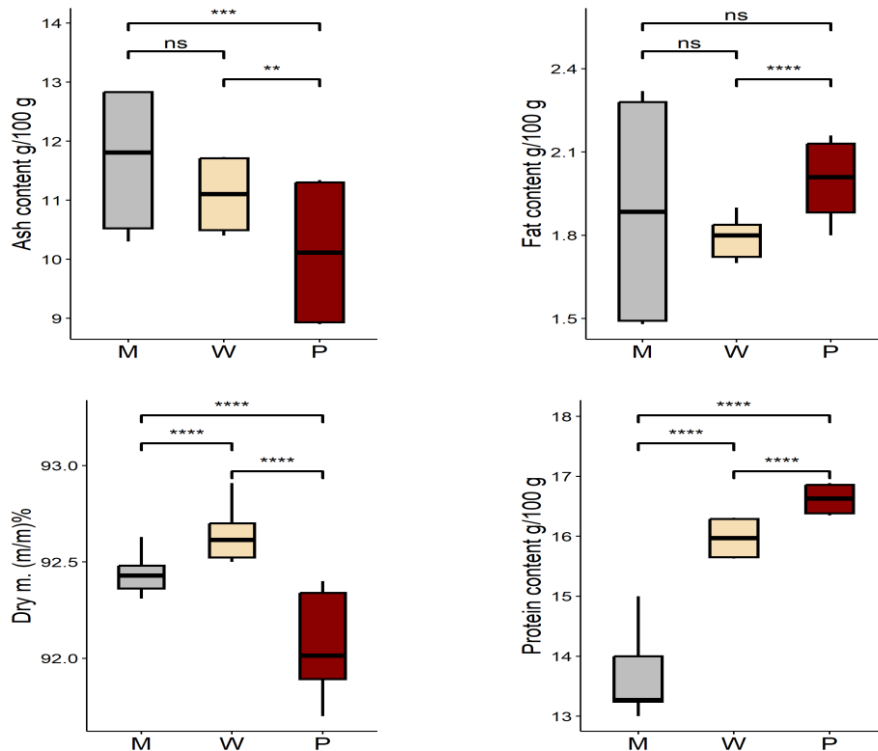


Figure 6. Ash, fat, dry matter, and protein content in baobab leaves from three different habitats: (W) wetland (P) plain land, and (M) mountain in Sudan.

### 3.1.3 The composition of dried Baobab fruit pulp in different regions

Table 5. The concentration (means and SDs; n=9) of nutritional values in dried baobab fruit pulp obtained from Kenya, Senegal, and Sudan.

Region	Kenya		Senegal		Sudan	
key	Means	SDs	Means	SDs	Means	SDs
Ash content g/100 g dw	6.9 <sup>a</sup>	1.9	4.8 <sup>b</sup>	0.2	5.4 <sup>c</sup>	0.2
Ca Level (mg/100 g) dw	286 <sup>a</sup>	19	313 <sup>b</sup>	3.0	329 <sup>c</sup>	0.5
Cu Level (mg/100 g) dw	0.759 <sup>a</sup>	0.058	1.131 <sup>b</sup>	0.441	1.160 <sup>c</sup>	0.046
Dry m. (m/m)%	90 <sup>a</sup>	0.7	89 <sup>b</sup>	1.7	88 <sup>c</sup>	0.5
Fat content g/100 g dw	1.6 <sup>a</sup>	0.6	0.94 <sup>b</sup>	0.33	0.69 <sup>c</sup>	0.03
Fe Level (mg/100 g) dw	18 <sup>a</sup>	9.7	4.9 <sup>b</sup>	0.1	6.36 <sup>c</sup>	0.4
K level (mg/100 g) dw	2145 <sup>a</sup>	635	1742 <sup>a</sup>	113	1907 <sup>a</sup>	0.5
Mg Level (mg/100 g) dw	107 <sup>a</sup>	57	191 <sup>b</sup>	10	175 <sup>c</sup>	0.4
Mn Level (mg/100 g) dw	0.9 <sup>a</sup>	0.2	0.9 <sup>a</sup>	0.1	0.91 <sup>a</sup>	0.04
Na Level (mg/100 g) dw	6.6 <sup>a</sup>	4.2	5.4 <sup>a</sup>	1.1	6.4 <sup>a</sup>	0.1
PH	2.9 <sup>a</sup>	0.1	3.3 <sup>b</sup>	0.1	3.2 <sup>c</sup>	0.1
Protein content g/100 g dw	3.9 <sup>a</sup>	0.9	2.9 <sup>b</sup>	0.3	2.9 <sup>c</sup>	0.1
TFC. CE (mg/100 g)	414 <sup>a</sup>	42.0	844 <sup>b</sup>	30.0	734 <sup>c</sup>	24
TPC GAE (mg/100 g)	358 <sup>a</sup>	3.8	367 <sup>b</sup>	10.0	370 <sup>c</sup>	13.9
Zn Level (mg/100 g) dw	1.2 <sup>a</sup>	0.2	0.8 <sup>b</sup>	0.2	1.1 <sup>c</sup>	0.1

Means followed by different letters are significantly different at the alpha level of 0.05.

The result of the analysed nutritional values in DBFP in Table 6 shows that the highest values of dry matter (90± 0.7%), fat content (1.6±0.6 g/100 g dw), protein content (3.9 ± 0.8 g/100 g dw), Fe (18±9.7 mg/100 g), K (2145±635 mg/100 g), Na (6.6 ±4.2 mg/100 g) and Zn 1.2±0.2 mg/100 g) were reported in Kenya. The highest levels of Mg (191±10 mg/100 g), Mn (0.96±0.11 mg/100 g), pH (3.3±0.1 mg/100 g), and TFC 844±30 mg/100 g) were found in Senegal. In contrast, the highest levels of Ca (329±0.5 mg/100 g), Cu (1.2 ±0.1 mg/100 g), and TFC (370±14 mg/100 g) were found in Sudan. The ANOVA test showed that all nutrient and mineral contents of all DBFP samples differed significantly ( $p < 0.05$ ), except for K, Na, and Mn.

Turkeys HSD multiple comparison tests of means at a significance level of 0.05 were used to examine the difference between pairs of values for all nutrients, and the results in Figure 7 and Figure 8 showed that there was a significant difference between all pairs of ash, Ca, fat, Fe, Mg, pH, and other nutrients among different regions Kenya (KEN, Senegal (SEN) and (SUD). Nevertheless, there was no significant difference between the mean values of some pairs; for example, between all pairs of Mn, (KEN-SEN, and KEN-SUD for K and Na, SEN-SUD for protein and Cu, and KEN-SEN for dry matter. This statistical test controls family-wise error rates and

offers pairwise evaluations of the means across the sites, in addition to confidence intervals (CIs) and familiar p-values. Significance of mean differences (Tukey HSD) at the  $P < 0.05$  (\*),  $P < 0.01$  (\*\*),  $P < 0.001$  (\*\*\*), and  $P < 0.0001$  (\*\*\*\*) levels. ns, not significant. The ash content, dry matter, fat content, and protein content results are shown in Figure 7 and described as follows:

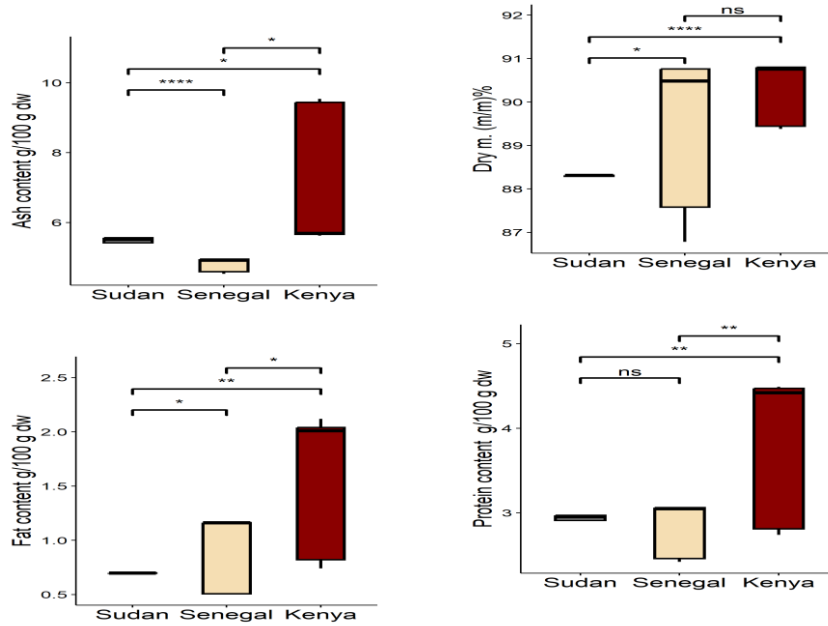
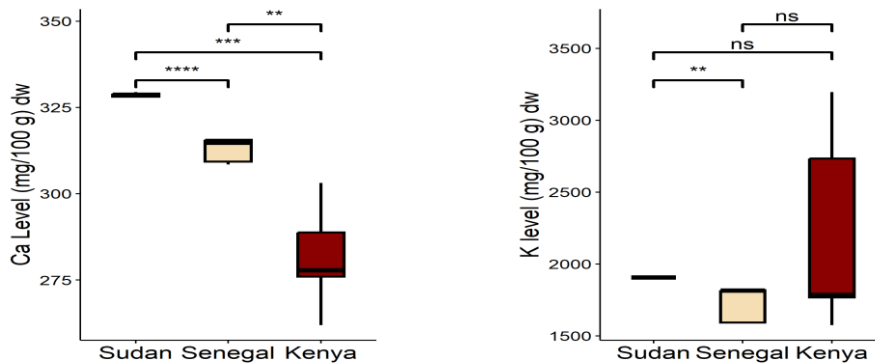


Figure 7. Ash, fat, dry matter, and protein content in baobab fruit pulp from three different countries.



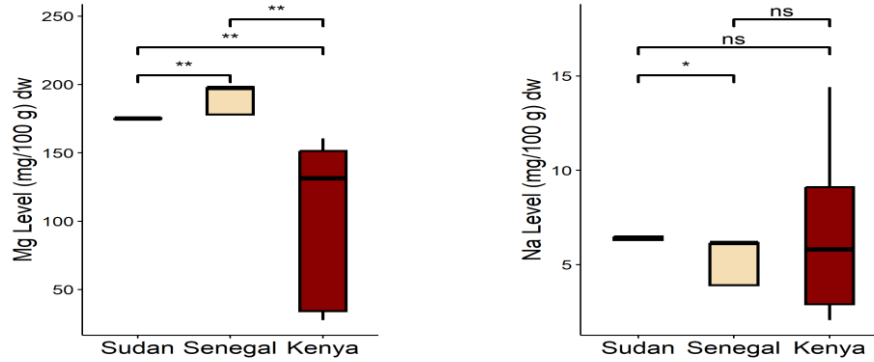


Figure 8. Calcium, magnesium, potassium, and sodium content in dried baobab fruit pulp from three different countries.

### 3.2 Principal component analysis (PCA)

#### 3.2.1 Analytical characteristics of baobab leaves samples

Principal component analysis (PCA) was used to evaluate the relationships between the analytical characteristics of the leaf samples and their geographical origins (region and sites). The first two PCs explain 63.5% of the variance in the samples. The PC1 component, defined by the x-axis, explained a larger proportion of the variance (41.9%), indicating that it captured the main difference in the data. The PC2, as the y-axis explained (21.5%) of the variance, is also significant, but it captures less variation than PC1. This could help further refine or separate the samples vertically, but its lower explained variance suggests that it plays a minor role in discriminating between regions.

The loading plot in Figure 9b shows that the concentrations of TFC, Mg, Mn, and Fe had the highest positive loadings on PC1, whereas ash content and pH had negative loadings. PC2 was influenced mainly by dry matter (positive loading) and TPC (negative loading). Positive linear correlations (vectors pointing in the same direction) were found between Mg and TFC ( $r = 0.771$ ), between Mg and Fe ( $r = 0.810$ ), and between TFC and Mn ( $r = 0.738$ ). The strongest inverse correlation (variables arranged in opposite directions with respect to the origin of the axis and far from the origin of the plot) was found between Mg and pH ( $r = -0.629$ ). The scores plotted in Figure 9a show the distribution of the samples on the plane defined by PC1 and PC2. PC1 was effective in discriminating between geographic regions: higher levels of Fe (15.8 – 14.9 vs. 14.1 mg/100 g), TFC (1433-1396 vs. 1368 CE (mg/100 g), Mn (25.9 - 3.9 vs. 2.3 mg/100 g) and Mg (528 – 500 vs. 471 mg/100 g) drew samples collected in the Kordofan region to positive loadings on PC1. The samples from the Blue Nile region showed negative loadings on PC1, mainly due to

the higher dry matter (92.6 – 92.4 vs. 92.1 m/m%), ash content (11.7 – 11.1 vs. 10.1 g/100 g), Zn (2.5 – 2.2 vs. 1.8 mg/100 g), Ca (2426– 2236 vs. 2903 mg/100 g) and K (1653–1476 vs. 1345 mg/100 g) than the samples from Kordofan. The range of variables along the x-axis (PC1) suggests that PC1 is the most important factor for discriminating between samples. Therefore, PC1 is likely to be more effective in discriminating between regions as it captures the most variance. PC2 was able to discriminate the samples by zone, but in different ways for samples from different regions. The P and M samples from Kordofan and the P and W samples from the Blue Nile had positive loadings for PC2.

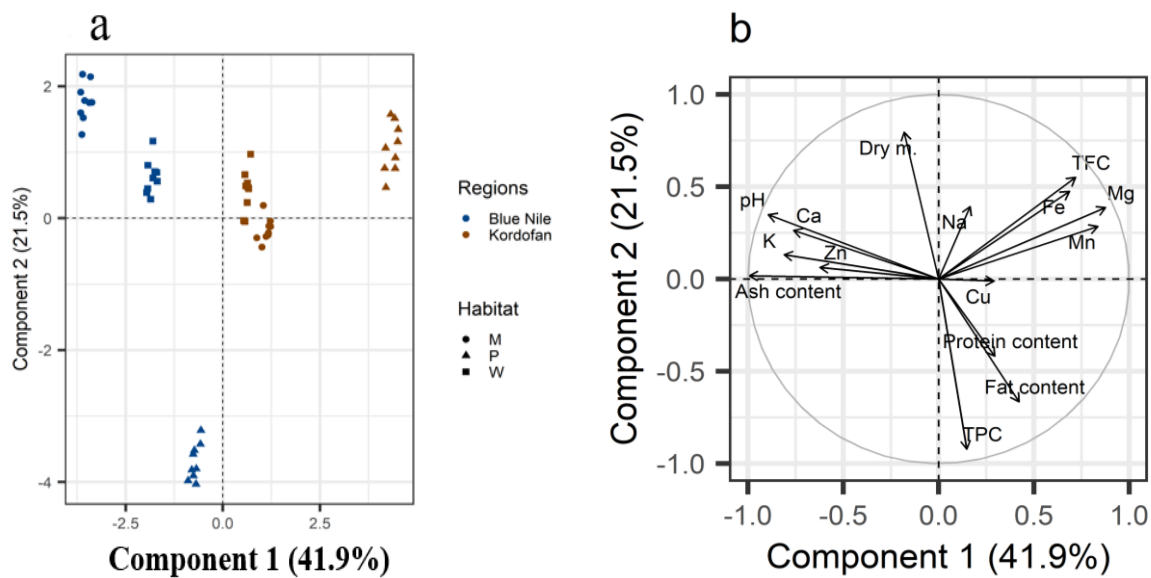


Figure 9. PCA score plots of the Baobab leaves samples (a) and PCA loadings plots of the variables on the first two components (b). The groups are blue (Blue Nile) and red (Kordofan). Zones are in plus signs (M), cross signs (P), and triangles (W).

### 3.2.2 Analytical characteristics of baobab fruit samples

Principal component analysis (PCA) was performed to visualize the relationships between the variables and the ecological origin of the fruit samples. The x-axis (PCA 1) explains 46.3% of the variance in the data and is thus the actual axis for distinguishing between the regions. The spread along the x-axis indicates that it played a major role in distinguishing the samples. The y-axis (PCA 2) clarifies 19.9% of the variance and contributes to further differentiation along the y-axis, but is secondary to PC1 in discriminating between regions. These two components capture 66.2% of the variance and provide an excellent representation of the underlying data structure.

The loading plot in Figure 10b shows that the ash, Fe, K, and protein contents had positive loadings in PCA 1. The strongest positive linear correlations (vectors pointing in the same direction) were found between ash and Fe ( $r = 0.853$ ), and protein and K ( $R = 0.641$ ). The strongest inverse correlation (variables arranged in opposite directions with respect to the origin of the axis and far from the origin of the plot) was found between Fe and Ca ( $r = -0.821$ ), K and Mg ( $r = -0.844$ ), and Fe and pH ( $r = -0.712$ ). Figure 10a shows the score plot used to reduce the multidimensionality of the data and to visualize the relationships between the samples studied on the plane indicated by PC1 and PC2. There is a clear separation between the samples from Kenya (blue), Senegal (brown), and Sudan (green) in PCA 1 and PCA 2, indicating that the samples from the three countries have different characteristics as captured by PCA. The samples from Sudan and Senegal were similar, indicating less variability. On the other hand, the closed samples from Senegal and Sudan were further away from the Kenyan samples, indicating greater variability. The highest mean contents of ash, Fe, protein, and K were observed in the samples from Kenya. In contrast, the highest mean values for Mg, TFC, and Ca were found in the samples from Senegal and Sudan. This discontinuity helps us to understand which parameters are important in differentiating the samples, which probably reflects the differences between the regions in terms of their nutrient components.

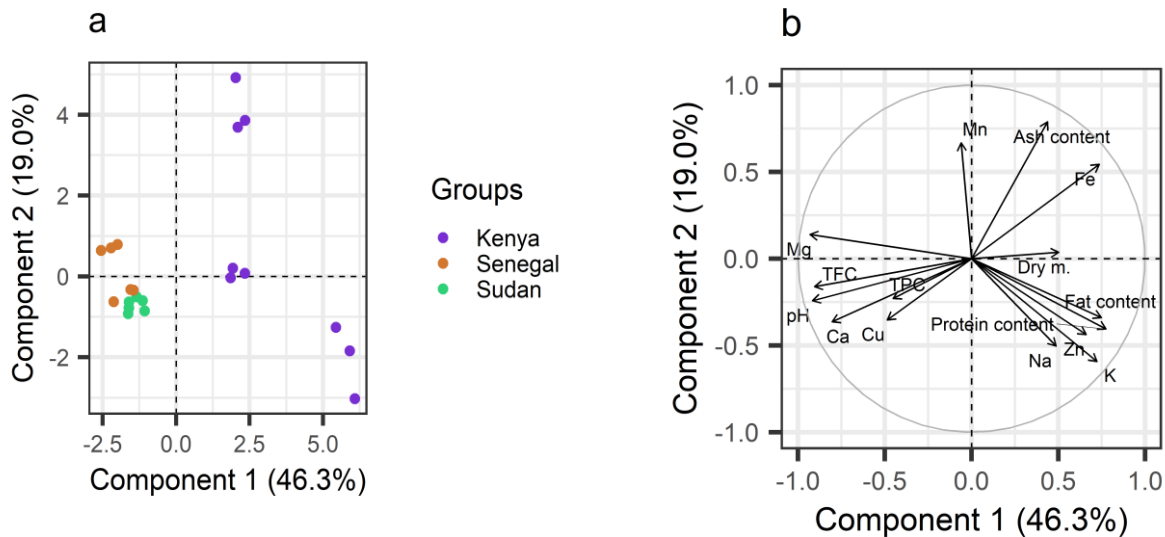


Figure 10. PCA score plots of the Baobab fruit samples (a) and PCA loadings plots of the variables on the first two components (b). The groups are blue (Kenya), brown (Senegal), and green (Sudan).

### 3.3 The estimated amount of baobab leaves (BLI) as a nutritional intervention

The estimated amounts of baobab leave daily intake (BLI g/day to meet the reference values of nutrients for different age groups are summarised in Tables 7–12. The BLI g/day was calculated based on the nutritional data in Table 5 and the dietary reference values in Table 3. Abbreviations used in all tables are explained as follows Age groups: Children (1-3 years) (C1), Children (4-6 years) (C2), Children (7-10 years) (C3), Children (10-18 years) (C4), adults ( $\geq 25$  years) (AD), Pregnant Women (PQ), and Lactating Women (LQ). 1<sup>st</sup> trimester, 2<sup>nd</sup> trimester, “3<sup>rd</sup> trimester. “B”: Boys, “G”: Girls, “M”: Men, “Q”: Women, “FI” :(first 6 months), “AF”:(after 6 months).

Table 6. The baobab leaves amount (BLI g/day) for the required potassium and manganese per day

Study Area	C1 (K)	C4 (K)	AD (K)	PQ (K)	LW (K)	AD (Mn)	PQ (Mn)	LQ (Mn)
Wetlands (W)	48	212	212	212	212	0.6	0.6	0.6
Plain’s land (P)	59	260	260	260	297	0.5	0.5	0.5
Mountains (M)	54	230	237	237	271	0.6	0.6	0.6

Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 7. The baobab leaves amount (BLI g/day) for the required calcium per day

Study Area	C1	C2	C3	C4	AD	PQ	LQ
Wetlands (W)	19	33	33	47	31	31	31
Plain land (P)	20	36	36	51	34	34	34
Mountains (M)	16	29	28	40	26	26	26

Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 8. The baobab leaves amount (BLI g/day) for the required magnesium per day

Study Area	C1	C2	C3	C4 - B	C4 - G	AD - M	AD - W	PQ	LQ
Wetlands (W)	36	48	49	64	53	74	64	64	64
Plain land (P)	32	44	44	57	47	66	57	57	57
Mountains (M)	34	46	46	60	50	70	60	60	60

Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 9. The baobab leaves amount (BLI g/day) for the required sodium per day

Study Area	C1	C2	C3	C4	AD	PQ	LQ
Wetlands (W)	14	17	22	26	26	26	26
Plain land (P)	14	19	24	29	29	29	29
Mountains (M)	15	18	23	27	27	27	27

Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 10. The baobab leaves amount (BLI g/day) for the required protein per day

Study Area	C	C	C	C	A	PQ	PQ	PQ	LQ	LQ
	1	2	3	4	D	(1st)	(2nd)	(3rd)	(FI)	(AF)
Wetlands (W)	4	4	4	4	5	6	56	175	119	81
Plain land (P)	4	4	4	4	5	6	54	168	114	78
Mountains (M)	5	5	5	5	6	7	66	206	140	95

Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 11. The baobab leaves amount (BLI g/day) for the required iron per day

Study Area	C1	C2	C3	C4 - B	C4 - G	AD - M	AD - Q	PQ	LQ
Wetlands (W)	47	47	74	74	87	74	107	107	107
Plain land (P)	44	44	69	69	82	69	101	101	101
Mountains (M)	50	50	78	78	93	78	114	114	114

Abbreviations used in this table were explained in sections 3.6 and 4.3.

The amount of BLI required to achieve the recommended daily potassium intake ranged from 44 g/day to 397 g/day in all study areas (W, P, and M). The highest intake across all the above sites was found in W, and the lowest in P. C1 had the lowest intake requirements. Groups C4, AD, PQ, and LQ had a uniform BLI of 212 g/day in site W. On the other hand, the dietary recommendations for manganese were limited to the AD, PQ, and LQ age groups, with no major differences between them in all study sites, the average being between 0.5 and 0.6 g/day (Table 7). The amount of BLI required to achieve the daily calcium reference intake for different age groups ranged from 16 to

51 g/day. The lowest intake was observed in M and the highest in P. Group C1 required a lower amount of BLI per day than groups C2-4, AD, PQ, and LQ (Table 8). The highest and lowest BLI g/day, to cover the daily reference intake of magnesium, were found in the W and P areas, respectively. The AD-M group required the highest BLI value of 74 g/day; in contrast, C1 had the lowest BLI amount at 32 g/day. C4-B required a higher BLI than C4-G in all study areas (57, 60, and 64 g/day compared to 47, 50, and 53 g/day) (Table 9). The lowest BLI for compliance with the recommended daily sodium reference values was found in the C1 group for leaves of W and P, whereas leaves of P had the highest BLI, especially for C4, AD, PQ, and LQ. The BLI increased with the age of the target group from C1 to the LQ. The AD, PQ, and LQ groups required the same BLI of 29 g/d (Table 10). To achieve the recommended daily iron intake, the lowest BLI value of 47 g/day was reported in the W area for the C1, C2, and C3 age groups, and the highest value of 114 g/day was reported for the AD-Q, PQ, and LQ in the M area (Table 12). The estimated BLI for adequate protein intake ranged from 4 to 7 g/day for the C1, C2, C3, C4, AD, and (PQ 1st) groups and from 54 to 206 g/day for PQ 2nd, PQ 3rd, LQ (FI), and LQ (AF) (Table 11).

### 3.3.1 The estimated amount of baobab dried fruit pulp (BFI) as a nutritional intervention

The estimated amounts of daily intake of dried baobab fruit pulp (BFI g/day) from different countries, Kenya (KEN), Senegal (SEN), and Sudan (SUD) to meet the reference values of nutrients for different age groups are summarised in Tables 13 to 18.

Table 12. The baobab dried fruit pulp amount (BFI g/day) for the required potassium and manganese per day

Study Area	C1 (K)	C4 (K)	AD (K)	PQ (K)	LQ (K)	AD (Mn)	PQ (Mn)	LQ (Mn)
KEN	37	163	163	163	186	3	3	3
SEN	46	201	201	201	230	2	2	2
SUD	42	184	184	184	210	2	2	2

Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 13. The baobab dried fruit pulp amount (BFI g/day) for the required calcium per day

Study Area	C1	C2	C3	C4	AD	PQ	LQ
KEN	157	280	280	402	262	262	262
SEN	144	256	256	367	240	240	240

SUD	137	243	243	350	228	228	228
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Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 14. The baobab dried fruit pulp amount (BFI g/day) for the required magnesium per day

Study Area	C1	C2	C3	C4 - B	C4 - G	AD - M	AD - Q	PQ	LQ
KEN	159	214	214	280	233	327	280	280	280
SEN	89	120	120	157	130	183	157	157	157
SUD	97	131	131	171	142	200	171	171	171

Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 15. The baobab dried fruit pulp amount (BFI g/day) for the required sodium per day

Study Area	C1	C2	C3	C4	AD	PQ	LQ
KEN	17	20	30	31	31	31	30
SEN	20	24	32	37	37	37	37
SUD	17	20	27	31	31	31	31

Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 16. The baobab dried fruit pulp amount (BFI g/day) for the required protein per day

Study Area	C1	C2	C3	C4	AD	PQ (1st)	PQ (2nd)	PQ (3rd)	LW (FI)	LQ (AF)
KEN	17	17	17	17	22	26	230	717	487	333
SEN	22	22	23	23	30	34	310	966	655	448
SUD	23	23	23	23	29	34	310	966	655	448

Abbreviations used in this table were explained in sections 3.6 and 4.3.

Table 17. The baobab dried fruit pulp amount (BFI g/day) for the required iron per day

Study Area	C1	C2	C3	C4 - B	C4 - G	AD - M	AD - Q	PQ	LQ
KEN	39	39	61	61	72	61	89	89	89
SEN	144	144	226	226	267	226	329	329	329
SUD	110	110	172	173	204	173	252	252	252

Abbreviations used in this table were explained in sections 3.6 and 4.3.

The amount of BFI required to achieve the recommended daily potassium intake ranged from 37 g/day to 230 g/day in all study areas, KEN and SEN SUD. The highest intake of 230 g/day across all regions was found in SEN, and the lowest intake of 37 g/day was reported in KEN. C1 had the lowest intake requirement. Groups C4, AD, and PQ had a uniform BFI of 201 g/d in the SEN region. On the other hand, dietary recommendations for Mn were limited to the AD, PQ, and LQ age groups, with no major differences between them in all study regions, with BFI ranging from 2 to 3 g/day (Table 13). The amount of BFI required to achieve the daily calcium reference intake for the different groups ranged from 137 g/day to 402 g/day. The lowest intake was observed in BFI from SUD and the highest in KEN. Group C1 required less BFI g/day than groups C2-4, AD, PQ, and LQ (Table 14). The highest and lowest BFI g/day to cover the daily reference intake of magnesium were found in KEN. The AD-M group required the highest BFI value of 327 g/day, whereas C1 had the lowest value of 97 g/day. C4-B required a higher BFI than C4-G in all study areas (157, 171, and 280 g/day versus 130, 142, and 233 g/day), and AD-M required a higher amount than AD-Q (183, 200, and 327 g/day versus 157, 171, and 280 g/day) (Table 15). The highest amount of BFI to meet the recommended daily sodium reference value of 37 g/day was found in the SEN region and was required for the age groups C4, AD, PQ, and QL, whereas the lowest amount of 17 g/day was found in KEN and SUD, especially for C1 (Table 16). To achieve the recommended daily iron intake, the lowest BFI value of 39 g/day was given in the KEN region for the C1 and C2 age groups, and the highest amount of 329 g/day for AD-Q, PQ, and LQ in SEN (Table 18). The estimated BFI for adequate protein intake ranged from 17 to 34 g/day for groups C1, C2, C3 C4, AD, and (PQ 1st) and 310 to 966 g/day for PQ 2nd, PQ 3rd, LQ (FI), and LQ (AF) (Table 17).

## 4 Discussion

### 4.1 The composition of baobab leaves

The study of baobab leaves (BLs) collected from different locations shows the nutritional potential of this plant as a healthy food suitable for several age groups. Baobab leaves are rich in essential nutrients (Asogwa et al., 2021), and their components meet the nutritional requirements of different population groups (Assogbadjo et al., 2021). The parameters analysed are discussed below, and how these results underline their importance.

Previous research has shown that the baobab tree plays an important role in increasing the income of rural populations in Sudan (Adam et al., 2024), and it is a significant source of nutrients with implications for human health (Ogbaga et al., 2017). Baobab leaf extract effectively reduced the cardiotoxicity of doxorubicin owing to its antioxidant compounds (Uhuo et al., 2022). Previous studies have also shown that the mineral content in baobab leaves varies significantly within and between different areas in African countries (Gabaza et al., 2018; Hyacinthe et al., 2015). Similarly, this study also showed remarkable variations in the contents of various nutrients, such as protein, fat, potassium, sodium, magnesium, calcium, manganese, and zinc, emphasizing the dynamic nature of the chemical composition of baobab leaves. This study adds to existing knowledge by examining the effects of habitat and regional factors on the nutrient composition of baobab leaves and provides a new perspective on the variability of nutrient concentrations.

The levels of the essential microelements Ca, K, Mg, and Na found in the BLs in this study were consistent with previous studies (Boukari et al., 2001; Hyacinthe et al., 2015; Kayode et al., 2018), which are important for bone well-being, electrolyte stability, and muscle function (Bennet et al., 2021; Cruz-Jentoft et al., 2020). In particular, the K content of BLs is high, which can support blood pressure regulation (Fadol et al., 2024). A high magnesium and calcium content supports bone development in children and adolescents and helps prevent bone-related situations (Proia et al., 2021). BLs are also rich in Mn and Fe (Hyacinthe et al., 2015; Ogbaga et al., 2017), which is consistent with the results of the present study. Iron supports the prevention of dangerous diseases, such as anemia, especially in children, pregnant women, and people of reproductive age (Mwangi et al., 2021; Stoltzfus, 2011). Mn content is helpful for metabolism, especially in adults and adolescents who engage in regular physical activity (Banach et al., 2020; Martins et al., 2020). Referring to our results and previous research findings, we found that BLs are reliably emphasized

as a nutrient-rich food source. Nonetheless, this study proves that BLs from different areas can show slight variations in nutrient content due to the adaptability of baobabs to ecological factors such as soil type and macroclimate, which can affect the amount of baobab leaves consumed in different locations (Ahmed et al., 2024).

The protein content found in this context was consistent with the results of previous studies (Alba et al., 2020; Dimopoulou et al., 2021; Habte & Krawinkel, 2017). The BLs have a high protein content and are a reputable plant protein source. Protein content is valuable for children and adolescents as it maintains growth and development (Capra et al., 2024). It supports muscle maintenance in adults and the elderly (Carbone & Pasiakos, 2019). Low fat content was consistent with the fat values of baobab leaves, as reported by Abioye et al. (2014) and Chadare et al. (2008). The presence of fatty acids can help all age groups, mainly adults and the elderly, by supporting cardiovascular health (Hirahatake et al., 2020; Klempel et al., 2013). The dry matter and ash contents were consistent with the results reported by (Gbaguidi et al., 2020; Kayode et al., 2018; Ogbaga et al., 2017). The high dry matter content in BLs indicates nutrient density, while the ash content is rich in minerals. Mineral content provides benefits for all age groups and is important for various bodily functions (Dobrowolska-Iwanek et al., 2022; Quintaes & Diez-Garcia, 2015). The pH of BLs was lower than that reported by Assogbadjo et al. (2012), but within the range of many leafy vegetables (Fimbres-Acedo et al., 2023), showing that it is suitable for general consumption without causing acid-related problems.

The evaluation of the antioxidant perspective was considered in this study to demonstrate the potential of (BLs) for human well-being. TPC and TFC in the BLs were investigated to evaluate the antioxidant and well-being perspectives. The results showed that BLs contain considerable amounts of both TPC and TFC. The TPC content in the BLs in the present study was significantly lower than the levels reported in previous studies, but the TFC levels were similar and comparable to those reported by (Mohammed et al., 2024). Phenolic compounds and flavonoids are known for their antioxidant activity, which is essential for scavenging free radicals and reducing oxidative stress in the body (Mutha et al., 2021; Parcheta et al., 2021; Rudrapal et al., 2022).

#### 4.2 The composition of baobab fruits

Our protein content in the DBFP samples ranged from  $2.44 \pm 0.02$  to  $3.06 \pm 0.01$  g/100 g. This amount aligns with the averages reported by (Gebauer et al., 2016; Gurashi et al., 2016; Nour et al., 1980). This protein content, as a source of amino acids in DBFP, contributed significantly to the recommended dietary intake of people in the regions studied.

These amino acids are essential for various functions of the human body (Akhtar et al., 2024; Korhonen et al., 2024; Morishita et al., 2024). The results showed that DBFP is characterized by a low-fat content, typically below 1 g/100 g, which agrees with previous studies (Gurashi et al., 2016; Nour et al., 1980). The fat content in DBFP emphasizes its value as a cardioprotective diet, which is particularly helpful for managing obesity and reducing cardiovascular diseases (Katsi et al., 2022; Patikorn et al., 2021; Rahmawati et al., 2024).

The amount of calcium in DBFP is  $3285 \pm 4.64$  mg/Kg, which makes it an important source for a healthy diet as it is important for muscle contraction and bones. It also supports the immune system and nerve functions. In regions where access to food is scarce, DBFP is an important alternative to dietary calcium (Agrawal et al., 2018; Chaudhary et al., 2024; Dobrowolska-Iwanek et al., 2022; Sarhan et al., 2024). The results also show that the DBFP is rich in potassium, containing  $19074 \pm 7.86$  mg/Kg, which is higher than the average determined by Bilal et al. (2022) and Rocha et al. (2024). It is important for the regulation of fluid balance, nerve transmission, and muscle function (Asogwa et al., 2021; Assogbadjo et al., 2021; Swareldhab et al., 2021). Potassium controls blood pressure and maintains cardiovascular health in humans (Gan et al., 2024). The high K content in DBFP could reduce the prevalence of common health problems, such as hypertension, in Sudan and Senegal. The average magnesium concentration in DBFP was  $1979 \pm 3.98$  mg/Kg, which is consistent with (Bilal et al., 2022; Dimopoulou et al., 2021) but lower than that reported by (Kamanula et al., 2018). Mg is a key element in the regulation of the immune system (Weng et al., 2024). The high Mg content of DBFP could contribute to the overall metabolic health of humans and prevent diseases related to Mg deficiency. The low sodium content of the analysed samples was generally below 10 mg/100 g, which is highlighted in the previously published range (Magaia et al., 2013). This level is useful for maintaining blood health and reducing the risk of cardiovascular diseases (Takano et al., 2024). The low sodium content of DBFP promotes its potential as a preventive healthy diet for heart disease.

The concentrations of Zn, Mn, and Cu are consistent with those reported by Abioye et al. (2014) and Chadare et al. (2008). Mn is crucial for bone formation (Kang et al., 2016), Cu is an essential component of the nervous system (Gale & Aizenman, 2024), and Zn strengthens immune functions (Zahran et al., 2024). The daily requirement of these elements in the diet is relatively important for the growth of children and is useful for pregnant women. Their presence in DBFP can ensure and contribute to the overall necessary mineral intake for the maintenance of various physiological processes. Even though the average iron content of  $65.22 \pm 4.14$  mg/10 g determined in this study is lower than the average reported by (Kayode et al., 2018; Turck et al., 2019), DBPF remains an important plant source of this essential mineral. Iron is necessary for the production (Alzahrani et al., 2017). This iron content can help prevent iron deficiency and anemia, which are prevalent in many parts of Sudan, Kenya, and Senegal.

#### 4.3 The estimated amount of dried baobab leaves and fruit pulp to be consumed

The nutritional and medicinal properties of baobab leaves and fruit pulp have been widely recognized in previous studies, highlighting their potential as food ingredients. However, an important gap remains: the lack of studies quantifying the specific amounts of baobab products required to fulfil the recommended daily nutrient intake for different age groups. In addition, previous studies have not sufficiently considered the differences in nutrient composition resulting from the different geographical origins or distributions of baobab trees.

In the current study, the nutritional value of baobabs was thoroughly evaluated, taking these deviations into account. By establishing appropriate consumption levels based on standardized dietary guidelines, our research focused on closing this knowledge gap and providing science-based recommendations for the optimal use of baobab products in the diet. This work not only contributes to a deeper understanding of baobab's potential but also supports its use in addressing nutritional deficiencies and promoting health in diverse populations.

## 5 Conclusion

This study highlights the essential health policies that will reduce hunger and food insecurity by including certainly available, nutritious substitutes like the baobab dried fruit pulp and leaves. Policy-makers internationally must reflect and consider the feedback of this proposed protocol highlighted in this study into public health food programs, precisely in local and rural areas with a lack of foodstuffs, to improve the nutrient deficiencies and their significance for health problems, such as undernourishment, anemia, and hypertension. Contribution to food security and rural improvement creativity will diminish gaps due to low health expenditure and economic hurdles. In the context of interventional practice, the study points out the potential for combining nutrient-dense plant-based selections into dietary rules. Showing programs for susceptible populations must be important, and the adoption of nutritional counseling to include locally available food keys.

Further research should be conducted to improve the availability of Fe and to increase its absorption in different age groups. Here, research strategies are suggested: (i) fermentation of BLs and fruits can reduce antinutrients that affect iron absorption (Hendek Ertop & Bektaş, 2018; Jeyakumar & Lawrence, 2021; Mongwaketse et al., 2022); (ii) exploring baobab-based products by adding bioavailable iron constituents such as ferrous gluconate and ferrous sulphate to improve iron content to ensure recommended intake (Hurrell, 2021; Man et al., 2022); (iii) developing concentrated baobab extracts with high iron concentrations, especially for children, to meet their needs; (iv) introducing new processing techniques to improve bioavailability; and (v) investigating different cooking methods for the leaves, such as boiling and steaming, which could influence the anti-nutritional factors. Each of these findings could help improve iron absorption from BLs while managing intake levels. Further studies are needed to confirm their efficacy and practical application.

## 6 New scientific results

We conducted this research and discovered a significant difference in the nutrient composition of baobab leaves and fruits across different regions and habitats. The findings highlight the importance of geographic factors in determining the nutritional value of baobab products and estimating nutrient reference intakes used for nutritional intervention for various age groups accordingly. The new scientific results have been emphasized as follows:

1. The nutritional profile of baobab leaves has been affected by different regions and habitats:
  - A. The highest calcium ( $2903 \pm 187$  mg/100 g) was found in mountains (M), making it an excellent source of this essential mineral.
  - B. Potassium ( $1654 \pm 34$  mg/100 g) and sodium ( $7.7 \pm 1.2$  mg/100 g) were highest in the wetland (W) site.
  - C. Magnesium ( $529 \pm 101$  mg/100 g) was highest in the plain land (P) site, where sodium levels of (6.9 to 7.7 mg/100 g) were comparatively lower.
  - D. The highest iron content ( $15 \pm 4$  mg/100 g) and protein content ( $16.6 \pm 0.3$  g/100 g) were also found in the plain land (P) site.
  - E. Fat content was low across all study sites (wetland, mountain, and plain land), ranging from 1.9 to 2.0 g/100 g, and sodium values were consistently low (6.9 to 7.7 mg/100 g).
2. The nutritional profile of dried Baobab fruit pulp (DBFP) has been affected by different regions (Kenya, Senegal, and Sudan).
  - A. The highest protein content ( $3.9 \pm 0.8$  g/100 g dw), iron ( $18 \pm 9.7$  mg/100 g), potassium ( $2145 \pm 635$  mg/100 g), and sodium ( $6.6 \pm 4.2$  mg/100 g) were reported in Kenya (KEN).
  - B. The highest magnesium content ( $191 \pm 10$  mg/100 g) was found in Senegal (SEN).
  - C. The highest calcium content ( $329 \pm 0.5$  mg/100 g) was found in Sudan (SEN).
3. The daily estimated amount of baobab leaves to be consumed for nutritional intervention by referring to the recommended daily intake for each age group and the total nutrient

concentration is identified by the habitat of origin as follows: The age group abbreviations used in the following term were explained in sections 3.6 and 4.3 above.

- a) The estimated daily intake of baobab leaves to meet calcium requirements for different children age groups (C1, C2, C3, C4) is 16 g/day, 29 g/day, 28 g/day, and 40 g/day, respectively, with site mountain (M) being the most suitable source.
  - b) To meet potassium requirements for electrolyte balance, the recommended intake of baobab leaves ranges from 32 g/day to 297 g/day, with the wetland (W) site as the best source.
  - c) For magnesium intake, which supports muscle function, the estimated consumption ranges from 32 g/day to 66 g/day, with the plain land (P) site being the preferred source.
  - d) The estimated amount of baobab leaves that can be added to soups and sauces commonly consumed by local communities as an alternative to other leafy vegetables, according to my new scientific protocol in Figure 11.
2. The estimated amount of baobab fruit pulp to be consumed for nutritional intervention is identified by the region of origin as described below. The target age groups and their abbreviations were explained in sections 3.6, 4.3, and 4.3.1 above.
- a. The recommended amount of dried baobab fruit pulp powder varies by location:
    - i. The estimated amount of dried baobab fruit pulp obtained from Kenya ranges from 37 g/day to 186 g/day for potassium, 17 g/day to 487 g/day for protein, and 39 g/day to 89 g/day for iron, suitable for different age groups, see section 4.3.1.
    - ii. The estimated amount of dried baobab fruit pulp obtained from Sudan ranges from 137 g/day to 350 g/day for calcium and 97 g/day to 200 g/day for magnesium, suitable for different age groups, see section 4.3.1.
    - iii. The estimated amount of dried baobab fruit pulp obtained from all study areas (Kenya, Senegal, and Sudan) ranges from 2 g/day to 3 g/day and is suitable for manganese intake.
  - b. The estimated amount of dried baobab fruit pulp can be suspended in water and consumed as a juice or paste, providing a nutrient-rich dietary supplement.

These findings underscore the potential of baobab leaves and fruit pulp as nutrient-dense food sources that vary in composition based on geographic location.

## 7 Practical utilization of the new scientific results

Baobab products (BP) can be incorporated into daily diets to enhance overall health across different target age groups in this study. Their high mineral content, respectable protein levels, and low fat and sodium content make them ideal for supporting nutritional needs. Based on my new scientific results, the following practical applications are proposed:

1. Geographic considerations for dietary recommendations:

- a) Nutrient composition varies based on region and habitat, and dietary guidelines should consider these differences to address specific deficiencies in different populations.
- b) Incorporating baobab products into daily diets can be an effective solution for combating malnutrition, especially in regions with nutrient deficiencies in countries such as Sudan, Kenya, and Senegal.

2. Public health and policy implications:

- a) Health policies in Sudan, Kenya, and Senegal should integrate naturally available, nutrient-dense foods such as baobab leaves and fruit pulp to combat malnutrition and food insecurity.
- b) Policymakers should consider these findings, especially the new scientific protocol described below, when developing nutrition intervention programs for underserved and rural communities, addressing issues such as anemia, malnutrition, and hypertension.

3. New scientific protocol:

The protocol for implementing nutritional intervention based on baobab products aims to improve nutritional status and combat malnutrition. This protocol applies to rural and urban individuals. The assessment step involves collecting baseline data on dietary needs and health status for target populations. The intervention utilises dried baobab leaves (BLI) and fruit pulp powder (BPI). The BLI powder should be added to the cooked sauce or soup (i.e., onion, tomato, salt, etc.) as an alternative leafy vegetable, while the BPI should be suspended in water and taken as paste or juice. Distribution networks will be set up using age as a category to ensure that baobab products can be easily introduced to the target age groups. The estimated amount of BLI/BPI (g/day) will be integrated into existing dietary programs for each age group. Expected outcomes include avoiding nutrient deficiency, preventing malnutrition among the population, and enhancing food security.

## 8 Summary

Baobab (*Adansonia digitata* L.) is an underutilized species, and its edible parts (fruits, leaves, and seeds) contribute to food security and human health in tropical regions. Although the fruits have attracted considerable research interest and have recently been authorized for consumption in EU countries, the leaves are traditionally consumed; however, no study has investigated them from an interventional perspective. The main objective of this research was to discover a new plant resource with an appropriate and healthy composition, such as the African baobab, to improve food security and contribute to nutritional intervention in rural and urban communities (different age groups in Sudan, Kenya, and Senegal). We then propose a protocol for nutritional intervention using dried baobab leaves and fruit pulp powder to achieve the daily recommended reference values for proteins and minerals (K, Ca, Mg, Na, Fe, and Mn) for different target groups. A mixture of young and old fresh leaves was collected in Sudan to cover two regions: the Blue Nile and the North Kordofan. Dried baobab fruits were collected from different markets in Sudan, Kenya, and the Hungarian market for fruits from Senegal. Dry matter, crude fat, protein and ash content, mineral content (Na, Mg, K, Ca, Fe, Mn), and total phenol and flavonoid content were determined in the laboratory of the Food Institute of the University of Debrecen, Hungary. Time series data (2013-2023) from the DataBank Health, Nutrition and Population Statistics database were used to assess the health and nutritional status of these countries. The reference values for nutrients recommended by the European Food Safety Authority were used to estimate the amount of baobab leaf and fruit pulp intake (g/day). For each nutrient, the study area with the lowest number of BLs consumed is recommended. For K and Na, leaves from site W are recommended at 48 and 14 g/day, respectively, which is particularly beneficial for children aged 1–3 years. Leaves from site M were suitable for Ca intake, with approximately 16–40 g/day required for all age groups. Leaves from site P (32–66 g/day, 44–101 g/day, and 4–168 g/day) were optimal for meeting the daily requirements of magnesium, iron, and protein, in that order. The leaves from all locations (0.5-0.6 g/day) were suitable for Mn intake. The amount of baobab pulp powder (BPI) from the study areas KEN, SEN, and SUD (17-37 g/day) is suitable for Na intake. BPI from KEN (37-186 g/day, 17-487 g/day and 39–89 g/day) is recommended for nutrients K, protein, and Fe, respectively. In contrast, the BPI of SUD (137-350 g/day and 97-200 g/day) is recommended for Ca and Mg, respectively. For Mn intake, BPI from all study areas (2-3 g/day) was recommended.

Systematic inclusion of baobab products in the diet can positively support the nutritional status of various population groups. In addition, the results of this study provide a basis for public health and nutrition policymakers on how to combat malnutrition and food insecurity worldwide by incorporating naturally available foods and nutritious alternatives. Further research should focus on assessing the nutritional composition factors that could influence the absorption of nutrients, such as phytates and oxalates, as well as investigating the in vitro bioavailability of these elements.

**Keywords:** Baobab leaves, baobab fruit, food insecurity, dietary intervention, human health

## 9 Certified Publications



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Doctoral School: Doctoral School of Nutrition and Food Sciences  
MTMT ID: 10083295

### List of publications related to the dissertation

#### Foreign language scientific articles in Hungarian journals (1)

1. **Ahmed, A. E. M.**, Mozzon, M., Shaikh, A. M., Kovács, B.: Baobab (*Adansonia digitata* L.) as a remedy to human livelihood challenges: a review.  
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