NUTRITIONAL CHARACTERISATION OF BAOBAB (*Adansonia digitata* L.) FRUITS BASED ON AFRICA GEOGRAPHICAL REGIONS

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A thesis submitted to the Graduate School in partial fulfillment for the requirements of the Award of Master of Science Degree in Biochemistry of Egerton University

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DECLARATION AND RECOMMENDATION

DECLARATION

I declare that this thesis is my original work and has not been submitted wholly or in part in this form or any form for a degree in this or any other university.

Signature:…… Date:……

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RECOMMENDATION

We wish to confirm that this research thesis has been prepared and submitted for examination with our approval as University Supervisors.

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DEDICATION

I would like to dedicate this thesis to my dear parents Boniface and Teresia Kinothya whom without their contribution this research and entire MSc programme would not have been possible. I also dedicate this work to my brother Joseph, my sister Ann, and my uncle John Kathae. Thank you for the love and support you accorded me all through my study.

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ABSTRACT

Baobab (*Adansonia digitata* L.) is an indigenous fruit tree occurring in the savannah drylands of sub-Saharan Africa. A vast population of people in this region suffers from hidden hunger and malnutrition. Baobab fruits are a source of micronutrients, and their utilization in local diets has potential to improve health of the rural poor. The present study was conducted to determine the nutritional characteristics of baobab pulp and seeds across Africa geographical regions. Mature baobab fruits were harvested during the ripening stage from provenances established in Kenya, Tanzania, Zambia, Zimbabwe, Malawi, and Mali. The pulp and seed proximate composition was determined using the standard Association of Official Analytical Chemists (AOAC) methods of analyses. Fatty acids (FA) were analysed as fatty acid methyl esters (FAME) using Gas Chromatography-Flame Ionization detector (GC-FID) whereas, pulp vitamin C was quantified using the dichlorophenolindophenol (DCPIP) method. Fruit pulp and seed mineral elements were analysed using inductively coupled plasma-Atomic emission spectrometry (ICP-AES, 9000). Overall, results showed that the nutritive value of baobab varied with the geographical locations. The highest mean pulp vitamin C content was recorded in Taita (4.34 mgg^{-1}) while the lowest was recorded in Malindi (2.31 mgg^{-1}). Pulp crude protein content levels were lower than 3.5 $g100g^{-1}$ dw across all provenances. At country level, mean pulp crude fibre content was highest (8.83 $g100g^{-1}$ dw) in Kenya. The highest mean pulp potassium (22.2 mgg^{-1}) and calcium (4300 $mgkg^{-1}$) levels were recorded in Malawi. Kenya had the highest mean pulp iron (57.4 μgg^{-1}) and manganese (27.2 μgg^{-1}) content while Mali had the lowest iron and manganese at 13.1 μgg^{-1} and 8.6 μgg^{-1}, respectively. Seed proximate content varied significantly ($P < 0.001$) across provenance. At country level the mean seed calcium content was highest (3200 $mgkg^{-1}$) in Malawi and lowest in Kenya (2000 $mgkg^{-1}$). Oleic, linoleic, palmitic, stearic and linolenic were the most abundant fatty acids of baobab seed oil. Generally, the study reveals that baobab fruits are nutrient dense, and their consumption could alleviate hidden hunger and malnutrion among the rural poor. Evidence provided in this study demonstartes the existence of significant variation in the nutrient content of baobab pulp and seeds among the selected regions. The variation offers opportunities for selecting provenances to obtain germplasm from elite mother trees for both *in situ* and *ex situ* conservation, breeding and domestication of baobab.

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LIST OF ABBREVIATIONS AND ACRYONMS

AA	Ascorbic Acid
ALA	α-Linolenic Acid
AOAC	Association of Official Analytical Chemists
CCL_4	Tetra chloromethane
CV	Coefficient of variation
CWR	Crop Wild Relatives
DCPIP	Dichlorophenolindophenol
DW	Dry Weight
EC	European Commission
FAME	Fatty acid methyl esters
FA	Fatty Acids
FDA	Food and Drug Administration
FRC	Forest Research Centre
GC	Gas Chromatography
GC-FID	Gas Chromatography-Flame Ionization Detector
GHI	Global Hunger Index
GIS	Geographical Information Systems
GPS	Global Positioning Systems
HPLC	High Performance Liquid Chromatography
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrometry
ICRAF	International Centre for Research in Agroforestry
IFT	Indigenous fruit trees
IS	Internal standard
LA	Linoleic Acid
MND	Micronutrient Deficiencies
MPA	*meta*-Phosphoric acid
MUFA	Mono-Unsaturated Fatty Acids
NAT	Nucleobase Ascorbate Transporter
NCS	Nitrogen Carbon Soil-elementary analyzer
OA	Oleic Acid
PCA	Principal Component Analysis
PUFA	Polyunsaturated Fatty Acids

RDI	Recommended Daily Intake
ROS	Reactive Oxygen species
RRF	Relative Response Factor
SCA	South Central Asia
SFA	Saturated Fatty Acids
SSA	Sub-Sahara Africa
TE	Trace elements
UNFA	Unsaturated Fatty Acids
VAD	Vitamin A Deficiency

CHAPTER ONE
INTRODUCTION

1.1 Background information

The major global challenge in the food industry currently is the production of adequate, healthy, and safe food that is of significant nutrient content for all populations, and to achieve that in an environmentally stable manner (Capone *et al.*, 2014). Additionally, advances in global food and nutrition security have been affected by climate change, biodiversity stress, population growth and urbanization, social conflict and extreme poverty (McMichael *et al.*, 2015). Therefore, there is dire need to address these challenges and offer key solutions to sustainable food and nutrition security. Despite considerable productivity increases, there is growing evidence that conventional agricultural strategies fall short of eliminating global hunger, result in unbalanced diets due inadequate nutritional diversity, enhance exposure of the most vulnerable groups to volatile food prices, and fail to recognize the long-term ecological consequences of intensified agricultural systems (Sonnino *et al.*, 2014). However, current scientific information suggests that forests and tree-based systems can play an important role in providing adequate and nutritionally diverse diets (Powell *et al.*, 2015).

According to recent global estimates, about 805 million people are chronically undernourished, even though the trend appears to be slowly reversing (Sharma *et al.*, 2016). Majority of these cases have been attributed to lack of adequate minerals and vitamins in the diets. About 168 million children under the age of 5 years particularly living in Sub-Sahara Africa (SSA) and South Central Asia (SCA) are stunted in their growth (De Onis & Branca, 2016). In addition, about one third of preschool children in developing countries suffer from malnutrition causing the death of 5–10 million of these children every year (Tzioumis & Adair, 2014). Out of the 21 high-burden countries with child stunting rates of > 40%, as many as 15 are located in SSA (Keino *et al.*, 2014). Most of those afflicted are dependent on staple food crops such as wheat, rice, and maize for their sustenance (La Frano *et al.*, 2014). The affected population cannot afford the mineral supplements or fortified foods to meet their dietary requirements due to poverty. Thus, exploitation of indigenous fruits and vegetables would be considered a sustainable strategy to combat the problem of health and nutrition security. The consumption of underutilized fruits, nuts, and vegetables plays a significant role in nutrition, especially as sources of vitamins {ascorbic acid (C), carotenoids (A), thiamine (B1), riboflavin (B2), niacin (B3), pyridoxine (B6), and folic acid}, minerals, fat, protein, and dietary fiber (Nandal & Bhardwaj, 2014; Sunil & Pandravada, 2015). Thus, they have the

nutritional capacity to prevent and cure various diseases like kwashiorkor, marasmus, night blindness, anemia, diabetes, cancer, hypertension, and hidden hunger.

It is has been estimated that approximately 1.2 to 1.5 billion people globally are forest dependent (Agrawal *et al.*, 2013). Among them, about 60 million indigenous people are almost solely dependent on forest products (Agrawal *et al.*, 2013). For instance, in Kenya the Ogiek community are the indigenous East Mau forest dwellers and entirely depend on the forest for their food (Langat *et al.*, 2016). Forests and tree based systems supply local populations with wild and cultivated fruits, vegetables, oils, nuts, roots, seeds, fungi, herbs and animal protein, which compliment staple crops from agricultural systems (Vinceti *et al.*, 2013; Vira *et al.*, 2015). These forest products are associated with increased vitamin intake from fruit and vegetable consumption and thus play a vital role in supplementing micronutrients especially during the dry periods. Ultimately, forests contribute to dietary diversity thereby supporting a shift from calorific intake as the primary material for food security towards a broader understanding of nutritionally balanced diets (Ickowitz *et al.*, 2016).

Indigenous fruits are essential for food security, nutrition, economic welfare of local population and are very important during famine and dry periods of the year (Akinnifesi, 2001; Kiptot *et al.*, 2014). This implies that despite the harsh climatic conditions in the tropics, the trees remain a source of food and nutritionally important micronutrients. The fruits are a rich source of sugars, vitamins, proteins and essential minerals and the seeds are a rich source of oils essential for human nutrition and health (Nile & Park, 2014). Interestingly, the nutritional profile of indigenous crops in supplying micronutrients, fat, fibre and protein are better than staple food crops (Chivandi *et al.*, 2015). Since food and phyto-resources are declining globally with rapid human population growth, there is need to find new alternatives for enriching the resource base of our food baskets.

Baobab (*Adansonia digitata* L.) is a distinctive, long-lived tree belonging to the family Malvaceae (Carvalho-Sobrinho *et al.*, 2016). There are two distinct species in the mainland Africa namely; *A. digitata* (tetraploid) and *A. kilima* (diploid) which differ on basis of floral morphology, pollen and chromosome number (Pettigrew *et al.*, 2012). In Africa, *A. digitata* is indigenous to drier areas of West Africa, Sudan, Angola, East Africa, and Southern Africa up to Transvaal covering almost 26 countries (Sidibe & Williams, 2002). In Kenya, baobab trees grow along the coastal regions (Lamu, Malindi, Kilifi, Mombasa, Kwale and Taita) and the populations extend inwards to the Eastern regions (Kibwezi, Tharaka and Meru). The local populations consume the fruit pulp in their households and also sell the

fruits in markets. *Adansonia digitata* is an important multipurpose food tree that grows in the semi-arid and semi-humid regions of SSA, providing both food and non-food products such as fodder and medicine (Sidibe & Williams, 2002). Edible parts of baobab tree are useful for man, with leaves and fruits being the most important for food and nutritional security for local communities (Assogbadjo *et al.*, 2008; De Caluwé *et al.*, 2010a). *A. digitata* has gained the interest of various pharmaceutical companies, cosmetic industries and researchers due to its various traditional uses as food, medicine and cosmetic applications (Kamatou *et al.*, 2011).

Baobab fruit pulp is a good source of vitamin C, micronutrients and soluble fibers with pre- and post-biotic effects thus serving as an intestinal regulator in the case of gastric disorders. The fruit is said to have high vitamin C content four to ten times that of orange, while leaves are high in mineral content and pro-vitamin A. In 2009, baobab pulp was approved by Food and Drug Administration (FDA) as a food ingredient in the United States of America (USA) (Buchmann *et al.*, 2010). In the recent past, the European Commission (EC) authorized the importation of baobab fruit pulp as a novel food (EC, 2008). Some commercial products made of the fruit pulp include; wines, chocolates and sweets and they are available in international markets. Baobab products (seed oil and fruit pulp) are increasingly being commercialized and exported around the world leading to increased pressure on this resource (Sidibe & Williams, 2002; Buchmann *et al.*, 2010). However, despite baobab's potential in providing micronutrients, the wild populations in East African countries remain unexploited due to the lack of significant nutritional information on the fruits. The utilization and commercialization of baobab products in these countries could significantly contribute to its product diversification and market expansion. Moreover, the continued utilization will open opportunities for conservation and domestication of this species in Kenya ultimately leading to improved health, alleviation of micronutrient deficiencies, income generation and enhance rural development which are key goals of the Kenya Vison 2030. Although baobabs are widely known, current scientific knowledge on the biochemical composition and importance of its fruits in human nutrition is scarce particularly in East and Southern Africa. Provision of adequate information concerning the nutritional status of baobab is important to aid mitigate malnutrition and boost health in SSA. Therefore, the present work aims at determining the biochemical composition of baobab fruit pulp and seeds among wild populations in Africa with the goal of widening the nutrition pool and to understand the effect of provenance on nutrient concentration of baobab fruits. This study

will also provide tree-specific information which will be useful in selection of superior trees for domestication and conservation.

1.2 Statement of the problem

The proportion of undernourished people in sub-Sahara Africa (SSA) remains at 13.5%, but progress varies widely at country level. The affected populations face food and nutrient shortage which pose a great challenge to their health and well-being. The vicious cycle of poverty, tropical diseases, and illness aggravates this situation whereas rapid human population growth in these countries endangers nutrient security of staple food crops due to overexploitation. This therefore, creates the need of sourcing nutrients from nutritionally underutilized crops especially the wild plants. However, pre-requisite to adoption and utilization of indigenous forest trees (IFT) is to understand the macro and micro-nutrient contents of the edible parts of the plant (e.g., seed, fruit). In SSA there are many IFT species that contain essential nutrients but their contribution to nutrition and health is not well documented. Many of these IFT remain under researched globally, and critical data on their utilization is limited or fragmented. Baobab (*Adansonia digitata*) trees grow in semi-arid regions and their fruits and leaves are a potential rich source of nutrients including minerals, vitamins, and other nutraceuticals. However, there is lack of comprehensive compositional data regarding the nutrient content of baobab fruit pulp and seeds in the selected regions of Africa. This therefore creates the need to explore the nutritional characteristics of baobab and its products with a goal of using them to alleviate malnutrition, enable value addition of its products and selection of superior trees for domestication.

1.3 Objectives

1.3.1 General objective

To determine the biochemical composition of baobab (*A. digitata* L.) edible parts across geographical regions of Africa.

1.3.2 Specific objectives

1. To determine the proximate composition (moisture, crude protein, crude fiber, crude fat and ash) of baobab fruit pulp and seeds across the six countries in sub –Sahara Africa.
2. To evaluate the concentration of selected micro- and macro-elements (Ca, Mg, Na, K, P, Zn, Fe, Mn and Cu) in baobab fruit pulp and seeds across six countries sub –Sahara Africa.
3. To determine the fatty acid profiles of oils extracted from baobab seeds across six countries in sub –Sahara Africa.

4. To evaluate the Vitamin C content of baobab fruit pulp across six countries in sub – Sahara Africa.

1.4 Null Hypotheses

1. There is no variation in the proximate composition of baobab fruit pulp and seeds across the six countries in sub –Sahara Africa.
2. There is no variation in the selected micro- and macro-elements content of baobab fruit pulp and seeds across the six countries in sub –Sahara Africa.
3. There is no variation in the fatty acid profiles of oils extracted from baobab seeds across the six countries in sub –Sahara Africa.
4. There is no variation in baobab fruit pulp Vitamin C concentration across the six countries in sub –Sahara Africa.

1.5 Justification

Nutrition and health are important for the sustainable development of a population (Johnston *et al.*, 2014). In sub-Sahara Africa (SSA), Micronutrient Deficiencies (MNDs) afflict the rural poor who are dependent on staple food crops such as maize and wheat for their sustenance and cannot afford fortified foods to meet out their mineral requirements. Moreover, the unavailability and high cost of fruits is largely to blame for the widespread vitamin and mineral deficiency especially vitamin A and C in African countries. Therefore, exploitation of Indigenous Forest Trees (IFT) can be considered a sustainable strategy to tackle the problem of vitamin and mineral deficiencies. Several lesser-known wild plants are high in nutrients. For instance, baobab (*A. digitata*) edible parts are rich in micronutrients and their utilization could possibly be used to alleviate malnutrition and improve health in these countries (Kehlenbeck *et al.*, 2013; Chivandi *et al.*, 2015). Baobab tree yields a good harvest even during drought, when staple crops fail, and is a source of food during famine. This is often seen in SSA dry lands where cultivation of exotic fruit species is a challenge. However, prior to utilization, knowledge on the biochemical composition of baobab parts is essential in assessing its contribution to nutrient intake estimations, nutrient digestibility and bioavailability, promote cultivation and expand its usage as strategy to improve nutrition and food security and enhance livelihoods of rural communities in SSA.

CHAPTER TWO

LITERATURE REVIEW

2.1 Food and nutrition security

Food security exists when people at all times have physical and economic access to adequate, safe and nutritious foods to achieve their dietary needs for a productive and healthy life (Pinstrup-Andersen, 2013). The achievement of food security is dependent on four distinct but interrelated processes; first is food availability, which ensures that sufficient quantity and diversity of food is available for consumption (Pinstrup-Andersen, 2013). The second is food access or access to food by households and the third is food utilization, which describes the potential to use and store food appropriately to support healthy diets and its dependent on an individual's health status (Pinstrup-Andersen, 2013). Lastly, food stability and the ability to sustain shocks and vulnerabilities both in the short term as well as long term (Pinstrup-Andersen, 2013).

Food security has been linked to innovations in agricultural production for several decades with the goal of enhancing food availability. For example, plant membrane transporters have been used to enhance yields of stale crops, increase nutrient content and increase resistance to key stresses such as salinity and pathogens (Schroeder *et al.*, 2013). Even though food availability is important in achieving food security, having strategies to effectively access and utilize quality food is key to good nutrition (Negin *et al.*, 2009). Despite advances in agricultural production globally, approximately one billion people are chronically hungry, two billion people regularly experience food insecurity and more than a third of human population is affected by micronutrient deficiencies (Mahamat *et al.*, 2015). Many of the countries with a high prevalence of hunger according to the Global Hunger Index (GHI) scores are in SSA, a region that is a particular target for intervention (von Grebmer *et al.*, 2014). While hunger rates have been declining substantially in many regions of the world, little change has been observed in the rates for micronutrient deficiencies. The burden of double malnutrition (over and under) and micronutrient deficiencies on the well-being of people in low-income countries is immense. Thus there have been calls for greater attention and intervention to nutrition sensitive agriculture and food systems.

Since dietary behavior is shaped by various factors, nutrition-sensitive approaches across disciplines, including human health, education, agriculture and environment is of dire need (Bhutta & Salam, 2012; Pinstrup-Andersen, 2013). The nutrition community agrees on the importance of bio-fortification of staple crops through breeding as well as on the greater

use of a more biodiverse range of nutritious food plants for dietary diversity rather than relying on few staples (Keatinge *et al.*, 2010). The diversity of plants includes locally available and often little-researched and under-researched species, including forests and once-forest taxa (Jamnadass *et al.*, 2011).

2.2 Nutrition challenge in sub-Sahara Africa

Sub-Saharan Africa's effort to alleviate malnutrition lag behind the rest of the world, with 13.5% of population considered under-nourished whereas around one in four people in this region remains undernourished (FAO & WFP, 2014). This region is home to some of the most nutritionally insecure people in the world, with poor infrastructure and scarce resources compounded with tropical diseases, Human immunodeficiency virus (HIV) and inadequate health services contributing to staggering levels of food and nutrition insecurity (Holdsworth *et al.*, 2014). Access to high quality nutritious foods is a challenge for many communities as the commonly available diets consist mainly of cereals or root staple crops, and very little in micronutrient rich vegetables and fruits (Powell *et al.*, 2015). These nutritious foods are either not accessible because of high cost, locally unavailable or are not considered household priorities when incomes are not sufficient to meet the needs of a high quality diet. Moreover, the African continent exhibits environments rich in biodiversity with valuable but often neglected and underutilized resources such as Wild Edible Plants (WEPs) (Boedecker *et al.*, 2014).

The lack of micronutrients especially vitamin A led to poor health outcome for millions of Africans (Saka *et al.*, 2007) mainly associated with the widespread retinol deficiency and thus blindness whereas vitamin C deficiency causes scurvy. The solution to food and nutrition security should be sought through the exploitation of under-exploited native plants, bio-fortification through conventional breeding or genetic modification of staple crops with the aim of widening the narrow food base (Chivenge *et al.*, 2015; Mabhaudhi *et al.*, 2016). The utilization of indigenous fruits and vegetables is important as it allows consumers to take responsibility over their diets.

2.3 Micronutrient deficiency conditions

Micronutrient Deficiency (MND) conditions are widespread among people living in both developing and industrialized countries. These are silent epidemics of vitamin and mineral deficiencies affecting people of all genders and ages, as well as certain risk groups (Tulchinsky, 2010). Micronutrient deficiency is one form of under-nutrition which is invisible unlike the other visible form, and for this reason, MNDs are commonly referred to

as ‘hidden hunger’ (Muthayya *et al.*, 2013; Joy *et al.*, 2014). Such deficiencies are not always clinically apparent or dependent on food supply and consumption patterns but are associated with physiologic effects that can be life threatening or more commonly damaging to optimal health and functioning. The most prevalent nutritional problems exist for vitamin A, folate, iron, iodine and zinc, however, coexistence of multiple MNDs frequently occurs (Bailey *et al.*, 2015). Micronutrient deficiencies mostly affect pregnant women and children under 5 years of age who are the most vulnerable population subgroups (Gernand *et al.*, 2016). In addition, poverty, food insecurity, lack of appropriate infant and child feeding practices, exposure to infectious illnesses, and poor hygiene and sanitation are factors responsible for the high levels of maternal and child undernutrition in developing countries (Bailey *et al.*, 2015). Even though some of these MND disorders can be reversed with provision of the lacking micronutrients, other deficiency disorders result in irreversible lifelong consequences. For example, iron deficiency in infancy is associated to long-lasting neural and behavioral defects (Kennedy *et al.*, 2016). Micronutrient deficiencies occur as a result of insufficient nutrient intake or sufficient intake combined with impaired absorption due to disease or inflammation (Bailey *et al.*, 2015).

Young children and pregnant women experience devastating health consequences as a result of limited resources, cultural influences and biological vulnerabilities (Winett *et al.*, 2016). Under-nutrition and infectious diseases exist in an antagonistic synergy: under-nutrition reduces immunological capacity to defend against diseases and diseases deprive the body of essential nutrients. This further exacerbates poverty through increased health care costs and impaired intellectual development that can significantly reduce earning potential. Moreover, evidence is accumulating that early malnutrition increases the risk of numerous chronic diseases later in life (Kelishadi & Poursafa, 2014). Information provided in Table 1 emphasizes the need for better understanding of nutritional related deficiency disorders.

Table 1: Essential mineral elements, their functions in humans along with symptoms and problems associated with their deficiency.

Mineral	Function	Deficiency
Calcium	Important for healthy bones and teeth, muscle contraction, nerve impulse stimulation, blood clotting, enzyme activation, ion transport (Soetan *et al.*, 2010).	Rickets, osteoporosis
Potassium	Helps in proper functioning of nerve and muscle. Maintains the salt concentration and the acid balance of the body (Pohl *et al.*, 2013).	Low growth, weakness, paralysis and death
Magnesium	Essential for carbohydrate and fat metabolism. Regulation of blood pressure, muscle contraction, blood clotting (Faryadi, 2012).	Paralysis and death convulsions
Phosphorus	Component of proteins, lipids and nucleic acids. Helps to build bones and teeth. Energy metabolism (Soetan *et al.*, 2010).	Rickets, osteomalacia, depraved appetite, stiff joints, muscular weakness, poor fertility, low growth rates.
Iron	Component of hemoglobin. Role in energy metabolism. Iron deficiency causes anemia and disrupts optimal function of both the endocrine and immune systems (Silver *et al.*, 2013).	The most widely recognized symptom is anemia, poor appetite and growth.

Zinc	Involved in cell replication and immune responses, production, storage and secretion of hormones. Component of several enzymes involved in blood clotting. Zinc deficiency increases the levels of lipid peroxidation in mitochondrial and microsomal membranes and the osmotic fragility of erythrocyte membranes (Stefanidou *et al.*, 2006).	Stunted growth, low appetite, reddening of skin which then erupts and forms scabs. Skin lesions and diarrhea.
Manganese	Assists in bone formation and metabolic function (Aschner, 2000).	Retarded growth, skeletal abnormalities, reproductive failure, and loss of coordination in the newborn.
Copper	Involved in hemoglobin formation, iron absorption from the gut. Needed for normal coloring of hair (Soetan *et al.*, 2010)	Anemia, bone disorders, diarrhea, gut disturbances and damage to the brain and spinal cord. Discoloring of hair

2.4 Indigenous fruit trees of sub-Saharan Africa

The diversity of Africa's wild edible fruits indicates high horticultural potential and valuable genetic resources that once domesticated could become the basis for integrating new commercial high-value species and cultivars into existing farming systems. Their utilization and conservation belong to the most valuable tasks for mankind within the international Crop Wild Relatives (CWR) initiative. Across SSA, wild IFT are used across a range of purposes, fulfilling both household and commercial objectives (Jamnadass *et al.*, 2011). The IFT improve nutrition, boost food security, foster rural development and support sustainable landscape management (Kahane *et al.*, 2013; Montagnini & Metzel, 2017). This is often

observed in dry areas where farming of exotic fruit species is a great challenge (Mbow *et al.*, 2014). IFT produce a bounty harvest even during drought, when staple crops fail to produce, and are a source of emergency food during famine and food scarcity (Chivandi *et al.*, 2015). This proves that they are reliable food sources throughout the year despite the harsh climatic conditions provision of energy and nutrients, including vitamins, minerals and proteins. In many areas, IFT are intensively harvested, which sometimes leads to overexploitation of natural stands.

Domestication of IFT species and integration into existing agricultural systems would allow production of a diverse range of horticultural produce on farms to promote food and nutritional security (Leakey, 2012). At the same time, this would reduce the harvesting pressure on natural stands, facilitating conservation of the species' genetic resources (Kehlenbeck *et al.*, 2013). Despite their potential and importance at local scale, IFT are neglected by science and therefore remain underutilized and thus undomesticated due to lack of knowledge and bias of research and development of large-scale agriculture (Jamnadass *et al.*, 2011). Some of the indigenous nutritious fruits consumed in SSA include; *Adansonia digitata* (baobab), *Balanites aegyptica* (desert date), *Sclerocarya birrea* (marula), *Dacryodes edulis* (African pear), *Tamarindus indica* (tamarind), *Vitex doniana* (chocolate berry), *Irvingia gabonensis* (wild mango), *Uapaca kiriakana* (wild loquat), *Syzygium guineense* (water berry) and *Ziziphus mauritana* (jujube). These fruits are a rich source of dietary fiber, vitamins, minerals and fats although a recent review highlighted significant variation in nutrient content among these plants (Stadlmayr *et al.*, 2013).

Recently the growing importance of IFT such as marula (*Sclerocarya birrea* A. Rich.) and the shea butter tree (*Vitellaria paradoxa* C. F. Gaertn.) have exemplarily shown the great potential such species may have for international food and pharmaceutical markets (Hilou *et al.*, 2017). The fruits of *S. birrea* for example are used in South Africa to make the cream liqueur 'Amarula', a major export product that is traded worldwide. Several tropical food trees are widely cultivated globally as commodity crops including; *Theobroma cacao* (cocoa), *Coffea spp*. (coffee) and *Elaeis giuneensis* (oil palm) (Dawson *et al.*, 2014). These trees provide foods rich in sources of vitamins, minerals, proteins, fats and other nutrients, however, the nutritional information of many wild species is either lacking or not reliable. The edible leaves of baobab and tamarind are documented to be rich in calcium and are good sources of protein and iron (De Caluwé *et al.*, 2010b; Gebauer *et al.*, 2016). The iron content of dried seeds of African locust bean (*Parkia biglobosa*) and raw cashew nut (*Anacardium occidentale*) are comparable with that of chicken meat (Aremu *et al.*, 2015). Even though IFT

species are not widely used in global agricultural systems, knowledge on their biochemical components remains an important area of research (Slavin & Lloyd, 2012).

2.5 Retaining nutritional benefits of indigenous fruits

Different IFT species produce fruits at different seasons throughout the year, providing nutrients to complement staple foods such as grains, roots, tubers and pulses (Kehlenbeck *et al.*, 2013). A thorough review of various publications on nutrient content of ten African indigenous fruits documented that the fruits had significant amounts of several macronutrients and micronutrients (Stadlmayr *et al.*, 2013). It was revealed that baobab fruit pulp is high in calcium, vitamin C, iron, magnesium and zinc. However, the reported values were based on data collected from West African baobabs and thus the need to exploit the East and Southern Africa baobabs for comprehensive nutritional information. Black plum (*Vitex doniana*) is rich in iron and tamarind (*Tamarindus indica*) provides calcium, magnesium, phosphorus and potassium (Cemansky, 2015).

The Collaborative Partnership on Forests (CPF) addresses that the potential of forests and trees to improve food and nutritional insecurity needs more attention by policy makers and development agencies. Scientific development programmes are being designed to bring many wild species, both trees and herbs into cultivation and intergrate them into agroforestry systems (Mng'omba *et al.*, 2015). Africa's indigenous fruit tree domestication scientists are working in the region that already has among the highest rates of nutrient deficiencies (Chivenge *et al.*, 2015). The focus is in preserving the nutritional value of 'orphan crops' which are underutilized species whose potential to improve peoples' livelihoods as well as food security is not being fully utilized because of their limited competitiveness with commodity crops mainstream agriculture. These crops are of considerable interest for future adaptation of agriculture to climate change (Padulosi *et al.*, 2011). The species currently under domestication studies include; *Adansonia digitata*, *Barringtonia procera*, *canarium indicum*, *Gnetum africanum*, *Irvingia gabonensis*, *Sclerocarya birrea* and *Vitellaria pardoxa*.

2.6 Biology of Baobab

Baobab (*A. digitata* L., Malvaceae) belongs to the subfamily Bombacoideae (Carvalho-Sobrinho *et al.*, 2016) (fig 1a). The tree is one of the most remarkable trees of the world. It is an important IFT throughout the drylands of Africa and a representative of the wooden ''Big Five'' which also includes *Tamarindus indica*, *Zizyphus mauritiana*, *Sclerocarya birrea*, and *Mangifera indica* (Jama *et al.*, 2008). *Adansonia digitata* is a deciduous tree about 25m tall easily distinguishable by its huge trunk of 3-10 m and the most

succulent plant in the world. The bark of baobab is smooth, folded, reddish-brown or greyish brown and contains a yellow or green inner layer which is composed of thick tough longitudinal fibers. The leaves are compound with 3-9 leaflets, each 5-15 cm in length and the flowers are large, white and solitary in leaf axis (Pettigrew *et al.*, 2012).


(a)

(b)

Figure 1: (a) Baobab (*A. digitata*) tree without leaves. Road to Kariba border, Zambia (b) Globose shaped baobab fruits sampled in Malawi

2.6.1 Origin of the name of the plant

The vernacular name of *A. digitata* is "baobab" and its origin is uncertain though in the past years, several scientists have believed that it is derived from the Arabic name *buhibab*, which means fruit with numerous seeds (Diop *et al.*, 2006). The genus name *Adansonia* was given by Linnaeus in honor of Michel Adanson who had been in Senegal in the eighteenth century and brought seed to Paris in 1754. The species name, *digitata* (hand-like) is used in reference to the shape of the leaves. To date, various names are used to describe baobab tree in different communities and include; "symbol of earth", "magic tree", amongst others (Diop *et al.*, 2006). The local names for baobab include: mbuyu (Swahili), mwamba (Kamba), olimisiera (Maasai), toega (Mooré), Sira (Bambara), mramba (Kipare), isimuhu (Zulu) (Rahul *et al.*, 2015).

2.6.2 Taxonomic and botanical description

The African baobab belongs to the following taxa;

Kingdom: Plantae;

Phylum: Tracheophyta;

Class: Magnoliopsida;

Order: malvales;

Familiy: Malvaceae;

Subfamily: Bombacoideae;

Genus: *Adansonia*;

Species: *digitata*; (Carvalho-Sobrinho *et al.*, 2016)

2.6.3 Flowering and fruitification

Baobab trees produce whitish flowers with a large number of fused purple stamens through which the style protrudes. Tree flowering takes place between the month of October and December in Southern Africa, with fruiting from April to May. In the Sahel, flowering occurs between May and June. Baobab flowers are pollinated by fruit bats and nocturnal moths (Fleming *et al.*, 2009). Flowering season lasts 4–6 weeks with a few flowers opening each night whereas, the period between flowering and fruit ripening is 5–6 months (Venter & Witkowski, 2011). The developing flowers and fruits are a rich source of food, and are eaten and parasitized by a variety of animals including insects, birds, and mammals. The fruit capsules are egg-shaped, covered with velvety hairs, contain numerous seeds, and can reach 12 cm in length.

2.6.4 Distribution and habitat

The genus *Adansonia* comprises of eight species: *A. grandidieri, A. madagascarensis, A. perrieri, A. rubrostipa, A. suarezensis, A. za, A. gregorii* and *A. digitata*. The genus has a disjunct geographical distribution with six species endemic in Madagascar, one in Africa, and one in Australia (Wickens, 2008). The distribution of *A. gregorii* in North Western Australia far from other species is quite unusual. In contrast to the other seven species which are tetraploid, *A. digitata* is the only diploid species and it differs in floral morphology and chromosome number from *A. kilima* (Pettigrew *et al.*, 2012). *Adansonia digitata* is found naturally occurring in the dry climatic zone (above 150–250 mm precipitation) in the North Sudanian zone and is an important species in the dry tropical zone south of the Sahara (Diop *et al.*, 2006). The species is also found in more humid zones (1,400–1,600 mm) for example; Benin (Assogbadjo *et al.*, 2006). The ability of the species to compete with other plants is relatively weak in the humid sites. Baobabs have been introduced in Tropical America and grown successfully (Sidibe, 2002). This remarkable tree is also found on the Arabian Peninsula and has been naturalized in India and south East Asia. Baobabs are located in low altitudes with 4-10 dry months per year with mean annual rainfall of 100-1000 mm and mean annual temperature of 20-30℃ (Rahul *et al.*, 2015).

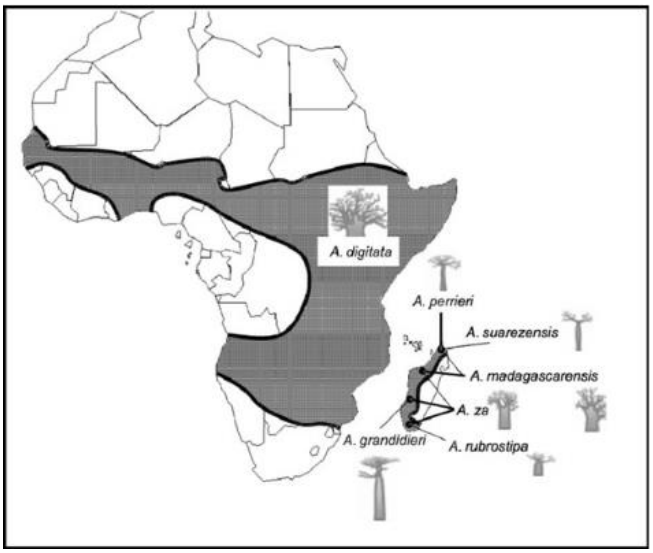

Figure 2: Distribution of Adansonia spp in Africa and Madagascar.

2.7 Phytochemistry of Baobab

A variety of compounds have been isolated and characterized from various parts of baobab (fruit pulp, seed oil, leaves and roots). These classes of compounds include terpenoids, flavonoids, sterols, vitamins, amino acids, carbohydrates and lipids (Shukla *et al.*, 2001). Ten compounds including isopropyl myristate and nonanal have been identified in the fruit pulp using gas chromatography-mass spectroscopy (GC-MS) (Cisse *et al.*, 2009). Column chromatography has been useful in isolating several compounds from baobab pericarp and they include: (-)-epicatechin, epicatechin-(4β → 8)–epicatechin (B2), epicatechin–(4β → 6) – epicatechin (B5), epicatechin (2β →O→ 7, 4β →8)-epicatechin (A2) and epicatechin-(4β →8)-epicatechin-(4β →8)-epicatechin (B1) as represented in figure 3 below (Shahat, 2006).

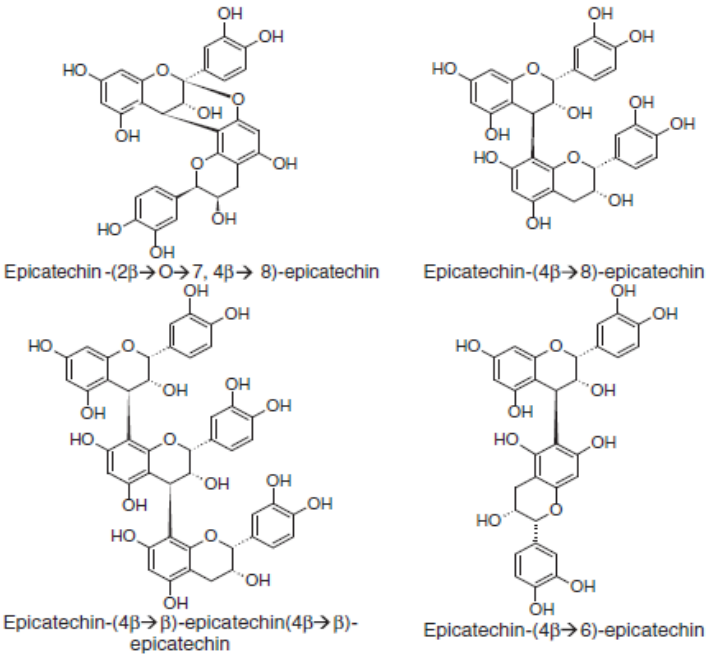

Figure 3: Chemical structures of selected flavonoids isolated from A. digitata.

2.8 Traditional uses of Baobab

Various parts of baobab (leaves, bark, seeds) are used as Panacea, to treat almost any disease such as malaria, tuberculosis, fever, microbial infection, diarrhea, anemia, dysentery, toothache among others as represented in Table 2 (Rahul *et al.*, 2015). In Western Africa, baobab leaves are used as febrifuge as well as an immunostimulant (De Caluwé *et al.*, 2010a). In India, baobab pulp is used externally with buttermilk for the relief of diarrhea and dysentery whereas young leaves are used to treat painful swellings (Sidibe, 2002). Additionally, the leaves are used to treat several conditions including internal pain, otitis, disease of urinary tract, as a tonic for insect bites and Guinea worms (Sidibe, 2002). The leaves can also be used against excessive sweating and as astringent. The oil extracted from seeds is used against diarrhea and hiccough (De Caluwé *et al.*, 2010a). In Ghana baobab bark is used as quinine substitute to relieve fever. In Benin the bark is used to make ropes. In most parts of Africa, people suffering from malaria consume a mash containing dried baobab bark as febrifuge so as to treat the fever associated with the illness (Kamatou *et al.*, 2011).

Table 2: Selected traditional medicinal uses of *A. digitata* tree in Africa.

Therapeutic uses	Plant part(s) used	Country	Preparation
Fever, diarrhea	seeds	South Africa	Mixed with water
Dysentery, fever	Seeds, fruits	Cameroon	Decoction
Anemia	bark	Nigeria	Aqueous extract
Malaria	Bark, leaves	Nigeria	Powdered ark mixed with porridge
Wound healing	Stem, bark	Mali	Decoction
Dysentery, hemoptysis	Fruits, seeds	Tanzania	Decoction
Kidney and bladder diseases	leaves	South Africa	Decoction

2.9 Nutritional value of baobab

Baobab is an important food tree of SSA including countries in Western Africa (e.g. Senegal, Mali, Niger, Benin), Southern Africa (e.g. Namibia, South Africa, Mozambique, Zambia, Malawi) and Eastern Africa (e.g. Sudan, Ethiopia, Kenya, Tanzania) (Sidibe & Williams, 2002). The baobab is a multi-purpose tree with products having numerous food uses and medicinal properties, and a fibrous bark that is used for various applications (Buchmann *et al.*, 2010; Assogbadjo *et al.*, 2012). The fruit pulp, the seeds, and the leaves are all utilized and are essentially wild gathered foods which are consumed as part of the daily meal by rural populations in Africa and are also commercialized (Assogbadjo *et al.*, 2008). The tuberous taproot of seedlings and young saplings are also eaten, especially in times of famine. Baobab products (leaves, fruits, craft products, and bark) are sold on local, informal markets where middlemen operate and trade in the larger urban markets (Sidibe & Williams, 2002). Baobab products are for home consumption, though raw products are sold by local communities.

Previous studies on baobab parts biochemical analyses revealed that the pulp, leaves, and seeds are rich in nutrients (Kamatou *et al.*, 2011; Assogbadjo *et al.*, 2012; Simbo *et al.*, 2013). Micronutrients (iron, vitamins A, C, E and F) in baobab are high when compared to the daily recommended dose for human (Chadare *et al.*, 2010). It is worth noting that there is a huge variation in the previously reported values for a given chemical element in the species.

Despite the high nutritional composition of baobab fruits, leaves, and seeds, the tree is not well adopted in East African countries as a source of micronutrients.

2.9.1 Nutrient content of baobab leaves

The young tender leaves of *A. digitata* are staple food for many people in SSA especially the central region of the continent (Gebauer *et al.*, 2002). In the Western Sahel, the leaves are used in making sauces used with thick gruels of grain. The preparation is usually mixed with onions, pepper, ginger and fish. Baobab leaves are rich in carbohydrate (60-70%), protein (13-15%), fat (4-10%) and around 11% fibre and 16 % ash (De Caluwé *et al.*, 2010a). The energy value is of 1180-1900kJ/100g of which 80% is metabolized energy. Baobab leaves also contain provitamins A and C of which the highest level of provitamin A has been identified in young leaves (Diop *et al.*, 2006; Assogbadjo *et al.*, 2012). The level of pro-vitamin A is about one-third of the content in *Amaranthus* dried leaves. The content of B-group vitamins (B1 and B2) in the leaves is of moderate level as revealed by a study in East and West Africa (Hyacinthe *et al.*, 2015). Additionally, baobab leaves are a rich source of calcium, iron, potassium, magnesium, molybdenum, phosphorus and zinc (Assogbadjo *et al.*, 2012; Stadlmayr *et al.*, 2013).

2.9.2 Nutrient value of baobab fruit pulp

The dry baobab fruit pulp is cream or white in color and can either be eaten fresh or used to add to gruels on cooling after cooking (Buchmann *et al.*, 2010). The dry pulp has a slightly tart, refreshing taste and it's very nutritious, particularly, high values for carbohydrates, calcium, potassium, thiamine, nicotinic acid and vitamin C (De Caluwé *et al.*, 2010a). Baobab fruit pulp has very high vitamin C content varying from 162.3 mg/100 g in one tree to 499.1 mg/ 100 g in another (Assogbadjo *et al.*, 2012; Simbo *et al.*, 2013; Stadlmayr *et al.*, 2013). The fruit pulp is the most important part of the tree with the highest commercial value in the international market because of its nutritive value (Buchmann *et al.*, 2010). The authorization of baobab fruit pulp trade in international food markets (both the EU and US) has increased the world's interest in the species (Sanchez *et al.*, 2011). The natural fruit powder has been packed by different companies and it's available in both the local and international markets.

In some coastal towns of Kenya and its capital Nairobi, the pulp is a popular ingredient in ice products. From the baobab fruit pulp, local communities produce sweets, snacks and juice (Gebauer *et al.*, 2016). Chunks of dried baobab pulp with the seeds embedded are coloured with food ingredients and sugar-coated then sold as 'mabuyu' (figure

4.d) sweets in many shops and supermarkets. The liquid made from the pulp can be used as a drink, a sauce for food, a fermenting agent in local brewing, or as a substitute for cream of tartar in baking (Sidibe & Williams, 2002). The fruit pulp has been documented to contain a high pectin content in, which makes it suitable for jam production (Ndabikunze *et al.*, 2011). The Kenya Forestry Research Institute (KEFRI) recently produced baobab jam for testing its market potential. In Sudan, commercial production and processing of baobab pulp powder and seed oil are done by e.g. the Kordofal Taste Factory for Fruit Trees Extraction in El Obeid for the local market (Gebauer *et al.*, 2016). Despite these advances, there is no data detailing that baobab fruit pulp is exported from East Africa whereas, some countries in West Africa such as Senegal are well integrated into the baobab export business to Europe.

The fruit is a rich source of bio-accessible polyphenols and it has the potential for reducing the Glycemic Response (GR) to carbohydrate-rich foods *in vivo* and *in vitro* (Coe *et al.*, 2013). Fruit pulp also contributes to the recommended daily intake (RDI) for energy, carbohydrate and protein for children and pregnant women (Chadare *et al.*, 2010). The pulp is said to be rich in amino acids such as valine, glycine methionine, proline, arginine, tryptophan, phenylalanine and tyrosine, but there are variations in amino acid profile despite the usage of similar methods for determination (Chadare *et al.*, 2010). Baobab fruit pulp is of high nutritional interest and it could be a significant contributor to the daily intake of important nutrients.

2.9.3 Nutrient value of baobab seeds

Baobab seeds are kidney-shaped (figure 4a & 4c) and have a hard testa, which is not readily separated from the kernel. The endosperm has a pleasant almond-like taste and is rich in oil (Kamatou *et al.*, 2011). Seeds can be eaten fresh, dried or roasted and edible oil for cooking and cosmetic use can be pressed from them. Additionally, the baobab seeds are also used as thickening agents in soups. The seeds can be fermented and used as flavoring agents or roasted and eaten as snacks. The seeds can be classified as both protein and oil rich (Vermaak *et al.*, 2011). The fermentation of baobab seeds is said to decrease protein and carbohydrate content but increase fat levels (De Caluwé *et al.*, 2010a). Proximate analyses have shown protein (21.75/100g), ash (5.01/100g) and fiber (6.71/100g), and crude lipid content (12.12/100g) (Nkafamiya *et al.*, 2007). The seeds contain a relatively high amount of essential amino acids such as lysine which can be used to improve cereal protein quality (Osman, 2004). The major mineral contents present in the seed include phosphorus, calcium

and potassium, suggesting that baobab seed could contribute to the overall daily intake of these elements (Nkafamiya *et al.*, 2007).


(**a**)

(**b**)

(**c**)


(**d**)

Figure 4: (4a and 4c.) A descriptive representation of the size and physical appearance of baobab seeds. (4b). Baobab seeds embedded in dry fruit pulp. (4d). Baobab seeds coated with coloured pulp and sold as 'mabuyu.'

Baobab seed oil is semi-fluid, gently scented and golden-yellow and is extremely stable though with a highly variable shelf life estimated to be between 2 to 5 years. Among the class of pytosterols present in baobab oil (Figure 5), β-Sitosterol (≈80% of the total sterols) is one of the major sterol constituents. The other sterols include campesterol (8.3%) and stigmasterol (2.9%) (Kamatou *et al.*, 2011).

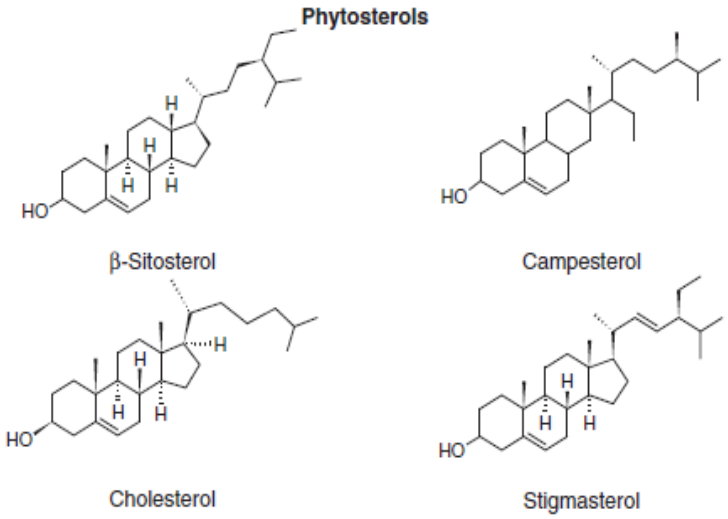

Figure 5: Chemical structures of selected phytosterols isolated from A. digitata seed oil.

Linoleic and oleic acids are the major fatty acids in seed oil although lesser amounts of linolenic, palmitic, stearic and arachidic acids are also present (Sidibe, 2002). The polyunsaturated fatty acids play an essential role in modulating human metabolism. Therefore the high linoleic acid is of nutritive value because of the ability of some unsaturated vegetable oils to reduce cholesterol levels. This high content of mono and polyunsaturated fatty acids suggest that baobab seed oil would be useful as food oil (Osman, 2004). The saponification value of the seed oil is high suggesting that baobab oil may be used for making soap (Nkafamiya *et al.*, 2007). Despite studies showing the possible utilization of baobab seed oil in human health, there is need to exploit the species to probe in the existence of variation in the seed oil content and fatty acids profile.

2.10 Medicinal properties of baobab

Adansonia digitata has been used for treatment of various ailments among local populations mostly in Africa and in Asia. All parts of the tree are reputed to have medicinal properties and have been used to treat various ailments. The antipyretic activity of *A. digitata* extract was evaluated on twenty hyperthermic rats and its activity resembled that normally induced by standard dose of administered acetylsalicylic acid (Khan *et al.*, 2006). The analgesic and antipyretic activities were mentioned by the United Nations (UN) in 2005 probably due to the presence of sterols, saponins and triterpenes in the fruit pulp (Masola *et al.*, 2009). The leaves are applied locally for a variety of inflammatory conditions, insect bites and Guinea worm sores (Shukla *et al.*, 2001). In Ghana the bark is used as a substitute for quinine in curing fever (Wickens, 2008). In Congo Brazaville, a bark decoction is used to

bathe rickety children and in Tanzania it is used as a mouthwash for toothache (Masola *et al.*, 2009).

Baobab parts have been applied in traditional medicine to treat microbial infections both in humans and animals. The roots and bark extracts exhibit antibacterial and antifungal activity which is ascribed to the presence of various potentially bioactive ingredients including triterpenoids, flavonoids and phenolic compounds (Chadare *et al.*, 2010). Additionally, baobab root extracts eliminate the motility in *Trypanosoma congolense* within 60 minutes and drastically reduce motility in T. brucei (Atawodi *et al.*, 2003). Four other different extracts (petroleum ether, chloroform, water, and methanol) obtained from leaves and bark haave been shown to reduce the motility of trypanosomes.

2.11 Factors affecting nutritional composition of tropical trees

Tropical fruit trees are a rich source of nutrients mainly for the local population. Despite the wide repertoire of nutritionally essential micronutrients, there exists a nutritional variation among trees, within species and across regions. The nutritional status of these trees is governed both by chemical and spatial nutrient availability to plant roots (Hobbie, 2015). Spatial nutrient availability is dependent on the exploitation of soil by roots or mycorrhizal hyphae and the mobility of the respective nutrient in soil (Soudzilovskaia *et al.*, 2015). The trace element (TE) content in most foods varies significantly depending on the TE availability in the soil in which the plant is grown (Antoniadis *et al.*, 2017). There is a great variation in reported values of baobab tissue nutrient content. The causes of these variations are not well described in science, however they are assumed to be associated with quality of the sample, provenance of the sample, age of the sample, treatment before analysis, storage conditions, processing methods, probable genetic variation, soil structure and its chemical conditions (Chadare *et al.*, 2010). The micronutrients e.g. vitamins and minerals present are biologically active and they are known to interact with other nutrients and change in their bioavailability (De Caluwé *et al.*, 2010a). Studies in Benin have shown that nutritional composition of baobab parts does not vary with genetic or ecological provenance; rather, physio-chemical properties of the soil have an influence on the nutritive value of baobab organs (Assogbadjo *et al.*, 2012).

2.12 Conservation of baobab populations

The baobab tree (*Adansonia digitata* L.) has been identified as one of the most important edible savanna trees to be conserved and domesticated in Africa because of it’s

nutritional and medicinal uses, and commercial value in European Union and United States of America (Sanchez *et al.*, 2010). A decline in baobab populations due to overexploitation and/or changes in climate could have a significant negative effect on African livelihoods. Although the baobab tree is not yet considered to be an endangered species, there are threats to local populations such as elephant damage, commercial exploitation or land clearance for mining, dams and construction. Due to the many benefits of this 'tree of life,' conservation of its germplasm through breeding should be done with the aim of promoting its cultivation in other tropical regions. Even though baobab takes almost 30 years to produce first fruits, breeding techniques combined with biotechnology have the potential to shorten this period. Grafting of baobab seedlings has been achieved successfully and this would lead to developing a hybrid species with a relatively short maturation period (Anjarwalla *et al.*, 2017). It is important for local communities and government to develop policies that ensure conservation of baobab trees because many of the trees grow in the wild and prone to damage.

Despite the high nutritional composition of baobab parts, the tree remains underutilized in East African countries. There is substantial uncertainty about the regional variation of nutrient contents in baobab leaves, fruit pulp and seeds from East Africa and whether the variation would be genetic or environmental. This study will move us from the realm of hypothesis to specific knowledge on the nutritional composition of baobab parts within the East African and Southern Africa regions. Moreover, this study aims at generating nutritional information that can be adapted for clinicl nutrition related projects in SSA and also elucidate on the biochemical composition of edible parts of *Adansonia* species. In addition, the results of this work could be used for the selection of superior trees and identification of traits to consider for domestication and germplasm conservation.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

Baobab used in this study was obtained from populations established in 17 provenances across six African countries as tabulated in Table 3 below.

Table 3: Study site (provenances) selected from Eastern, Western, and Southern Africa.

Country	Region	Provenance	Latitude	Longitude	Altitude (m)	Annual Temperature (℃)	Annual Rainfall (mm)
Kenya	East Africa	Kibwezi	2° 24′ S	37° 40′ E	885	23.0	626
		TaitaTaveta	3° 23′ S	37° 40′ E	760	23.3	616
		Malindi	3° 13′ S	40° 07′ E	8	26.3	1094
Tanzania	East Africa	Moshi Rural	3° 27′ S	37° 31′ E	730	23.5	916
		Kongwe	6° 12′ S	36° 27′ E	1114	22.7	579
		Kilolo	7° 28′ S	36° 30′ E	535	19.1	661
		Mwanga	3° 26′ S	37° 31′ E	740	23.1	553
Mali	West Africa	Mopti	14° 11′ N	3° 35′ W	321	28.4	463
		Kayes	14° 32′ N	11° 26′ W	80	29.3	632
		Seguo	13° 05′ N	6° 31′ W	300	28.0	611
		Sikasso	11° 30′ N	5° 47′ W	393	26.9	1125
Zambia	Southern	Chirundu	16° 01′ S	28° 35′ E	458	25.2	656

	Africa	Siavonga	16° 26′ S	28° 41′E	525	25.5	712
		Mambwe	13° 11′-19′ S	31° 49′ E	555	25.1	768
Zimbabwe	Southern	Hwange	18° 45′ S	26° 34′ E	330	24.0	576
	Africa	FRC	19° 48′ S	32° 52′ E	400	18.4	831
Malawi	Southern Africa	Mangochi	14° 14′ S	35° 04′ E	470	24.3	841

3.2 Study design and sample collection

Mature, unblemished baobab fruits used in this study were obtained from populations established in 17 provenances (Table 3) across six African countries (Kenya, Tanzania, Zambia, Zimbabwe, Malawi, and Mali). Sampling was done randomly without consideration of tree fruit density, fruit size, leaf canopy, or tree height to identify 2–7 trees in each provenance because genetic differentiation was found to exist between baobab populations from different climatic zones/provenances (Assogbadjo *et al.*, 2006). A composite bulk sample (both for pulp and seed) comprised 2–5 fruits from the same tree. In this study, a baobab population was defined as a group of baobab trees randomly and naturally distributed in an agroforestry system. The location (latitude and longitude) of sampled trees from the baobab populations was recorded with the aid of a geographical positioning system (GPS).
The samples were packed into polythene bags, labeled with unique population codes and tree numbers and transported to the Tree Diversity, Domestication and Delivery Unit at ICRAF-Nairobi.

3.3 Fruit pulp and seed extraction

Baobab fruits were cracked open using a hammer, the fruit pulp detached from the seeds by the use of a mortar and pestle and then separated from fibers and seeds by passing them through a 2 mm sieve. The baobab powder was weighed in grams (Kern, ACJ-320-4M, Germany), transferred to labelled zip-lock bags then wrapped with aluminium foil before storing them in a refrigerator at 4℃. Seeds from the composite bulk of each tree were soaked in water for almost 1 hr and then washed by hand to remove the remaining pulp and fibers. The seeds were spread on labeled drying trays covered with an adsorbent (paper towels) and left overnight on the laboratory bench to lose moisture acquired during the washing step. When felt dry, they were packed in cotton bags and stored in a room at 15% relative humidity and 15°C for almost 7 days before milling them into powder using a laboratory mill (Thermo Scientific™, USA). The hopper, rotor, blades, and sieve of the mill were cleaned by blowing with air at high velocity and then wiping the parts with 70% ethanol to avoid sample cross contamination.

3.4 Vitamin C analysis

Baobab fruit pulp vitamin C content was determined using the oxidation-reduction indicator dye titration method (A.O.A.C, 1984). The principle of the method lies in the reduction of 2, 6-dichlorophenolindophenol (DCPIP) to a colorless solution by ascorbic acid. After oxidation of ascorbic acid to dehydroascorbic acid, the excess dye remains pink in acid

solution. At titration end point, excess dye is rose pink in acid solution. Vitamin C was extracted and titration performed in the presence of HPO_3-CH_3COOH-H_2SO_4 (metaphosphoric acid-acetic acid-sulfuric acid solution) to maintain proper acidity for the reaction and to avoid autoxidation of ascorbic acid at high pH.

Ascorbic acid standard solution was prepared by accurately weighing 50 mg of USP ascorbic acid reference standard into 50 ml volumetric flask and diluted to final volume of 50 ml with metaphosphoric acid. The DCPIP standard solution was prepared by dissolving 50 mg of 2, 6-dichlorophenolindophenol sodium salt hydrate and 42 mg of sodium hydrogen carbonate into 50 ml of distilled water. The DCPIP solution was stirred, filtered through Whatman #1004 125 (12.5 cm) filter paper and diluted to 200 ml with distilled water. The extracting solution (Metaphosphoric acid-acetic acid-sulfuric acid) was prepared by dissolving 15 g of HPO_3 sticks into 40 ml of CH_3COOH and 200 ml of 0.15 N H_2SO_4. The solution was diluted to 500 ml in a volumetric flask. The 0.15 N H_2SO_4 was prepared by pipetting 4.2 ml of concentrated H_2SO_4 into 200 ml of distilled water and then diluted to 1 L. All the reagents used were of analytical grade.

The DCIP solution was standardized by pipetting in triplicate 2 ml aliquots of Ascorbic acid (AA) standard solution to a 50 ml Erlenmeyer flask each containing 5 ml metaphosphoric acid solution. This was titrated rapidly with indophenol solution from a 50 ml burette until the solution turned light rose pink in color. The volumes of the DCPIP used for each titration were recorded and used to obtain the mean titre. For the blank test, 7 ml HPO_3-CH_3COOH-H_2SO_4 were pipetted in triplicate into 50 ml Erlenmeyer flasks and titrated with indophenol solution until a rose pink color persisted for $\geq$ 5 seconds. The volumes of DCIP used were recorded and used to get the mean. To determine vitamin C content, 250 mg of fruit pulp were dissolved into 50 ml of HPO_3-CH_3COOH-H_2SO_4 solution. Three aliquots each of 5 ml were pipetted into 50 ml Erlenmeyer flasks and titrated with indophenol solution until a rose pink color appeared. The volumes of DCPIP used for titration were recorded. The calculations for pulp vitamin C content were expressed as presented in formula (i) below.

Calculation for mg ascorbic acid per ml indophenol solution

$$\text{(i) mg/ml Ascorbic acid standard} = \frac{\text{weight ascorbic acid standard}}{\text{total dilution volume}}$$

$$\text{Factor} = \frac{2\text{ ml} \times \text{mg/ml ascorbic standard}}{(\text{mean vol (ml)indophenol standard} - \text{mean vol (ml)blank})}$$

Calculation for mg ascorbic acid per 100 g sample

mg/100 g vitamin C

$$= \frac{(\text{vol indophenol solution -blank}) \times \text{factor} \times \text{total volume} \times \text{Dilution factor} \times 100}{\text{sample weight} \times \text{aliquot}}$$

The value of the indophenol reagent for the determination of ascorbic acid is limited by the presence of reducing substances in foods such as ferrous iron, stannous tin, cuprous copper, sulphur dioxide, sulphite, or thiosulphate. Another limitation of the method arises when the sample to be analysed gives a highly intense coloured solution, such as the reddish-purplish colours of certain fruits. Ascorbic acid is a highly unstable vitamin; it is sensitive to alkalis and to oxidation. The sampling and extraction of the sample material was therefore carried out with minimum delay and analyses conducted in the presence of stabilizing acids mentioned above. These acids are able to retard the oxidation of ascorbic acid by inactivating the catalytic effects of ascorbic acid oxidase, copper and iron. They also aid in maintaining proper acidity for the reaction with the indophenol dye.

3.5 Moisture Content (MC) determination

The Moisture Content (MC), usually expressed in g per 100 g of the test sample, was quantitatively estimated for both the baobab fruit pulp and seed test samples. The method used is based on the drying of the test sample under controlled pressure and temperature until a constant weight is obtained (A.O.A.C, 1984). Moisture content is required to express the nutrient content on a dry weight basis and is a quality indicator in some foods. Dry homogenous baobab fruit pulp and seed powder (2 g) were used in this analysis. Clean drying containers were place in a drying oven (WTC binder, Tuttlingen-Germany) at 100 ℃ for approximately 1 to 2 h, until a constant weight was attained. They were cooled in a desiccator for 30 min and weighed (W1). One gram of sample was weighed in triplicate into separate pre-weighed drying containers (W2) and placed in the preheated oven at 105 ℃ for 12 hours after which they were allowed to cool in a desiccator for 30 min before being weighed (W3). The MC content of the test samples was the calculated as using formulae (ii) below.

$$\text{(ii) Moisture (g/100 g)} = \frac{(W2 - W3) \times 100}{W2 - W1}$$

Where; W1 is the weight of a clean, dry, empty container (g)

W2 is the weight of container + test sample before drying (g)

W2-W1 is the weight of the test sample (g)

W3 is the weight of container + test sample after drying (g)

W2 – W3 is the loss in sample weight (g)

3.6 Element content determination by ICP-AES

Element content determination was performed as described by (A.O.A.C, 1984). Approximately 0.5 g of each test sample (pulp and seed powder) was weighed into a separate, clean and dry specimen tube and ashed in a muffle furnace (Gallenkamp, England) at 460 ℃ for four and half hours. The ashed test samples were allowed to cool prior to digestion. The ashes of the test samples were then digested using an acid-peroxide mixture prepared as described herein; Acid solutions A and B were prepared in the ratio 1:1 HNO_3 to water and 1:1 HCl to water respectively. A mixed acid solution (C) was prepared by mixing equal volumes of solutions A and B, two parts of which were mixed with three parts of 20 volumes of H_2O_2 {(200 ml of 30 % H_2O_2 (100 volumes H_2O_2)} made to 1 L with distilled water to give an acid-peroxide mixture (D). To each ashed test sample, 1 ml of D was added and the specimen tubes heated indirectly, that is, on a metallic tray placed on an electric hot plate (HEATRAE, England), to near dryness. To each test sample, 25 ml of 0.05 N HCl was added and the specimen tubes stoppered with corks, shaken thoroughly and left to stand overnight prior to analysis. The 0.05 N HCl was prepared from a stock solution of concentrated HCl as follows; the normality of concentrated HCl was determined by the relation

Formulae (iii):

$$\frac{1000}{36.46} \times \frac{37}{100} \times 1.18$$

Where; 1000 is a liter with respect to molarity (moles per liter),

36.46 is the relative molecular mass (R.M.M) of HCl,

37/100 is the percentage of concentrated HCl,

1.18 is the specific gravity of concentrated HCl,

Thus normality of concentrated HCl; $\frac{1000}{36.46} \times \frac{37}{100} \times 1.18 = 11.9748$ N

Then by using the relation $N_1V1=N_2V_2$ the volume of concentrated HCl required to prepare a 500 ml stock solution of 2 N HCl was calculated as;

$$11.9748 \text{ N} \times V_1 = 2 \text{ N} \times 500 \text{ ml}$$

$$\text{Thus, } V_1 = \frac{2 \times 500 \text{ ml}}{11.9748}$$

$$V_1 = 83.5 \text{ ml.}$$

Therefore, to prepare 500 ml of 2 N HCl, 83.5 ml of concentrated HCl were pipetted into a 500 ml volumetric flask containing 200 ml of distilled water and the solution topped up to the 500 ml mark with distilled water. The volume of this stock solution required to prepare 2000 ml of 0.05 N HCl was determined using the relation;

$$N_1V_1 = N_2V_2$$

$$0.05 \text{ N} \times 2000 \text{ ml} = 2 \text{ N} \times V_2$$

$$\text{Thus, } V_2 = \frac{0.05 \times 2000 \text{ ml}}{2} = 50 \text{ ml.}$$ Thus, 2000 ml of 0.05 N HCl was prepared by adding 50 ml of the 2 N HCl stock solution were into 500 ml of distilled water in a 2000 ml volumetric flask and the volume topped up to the mark with distilled water.

3.6.1 ICP-AES calibration

Approximately 0, 1, 3, 5, 10, 15 and 20 ml of a 100 ppm multi-element standard solution (prepared by diluting 20 ml of the 1000 ppm commercial multi-element standard stock solution stock solution to 200 ml with distilled water) were diluted into 100 ml in separate 100 ml volumetric flasks giving standard solutions containing 0, 1, 3, 5, 10, 15 and 20 ppm of each element. A mixed phosphorus (P) and Sulphur (S) standard stock solution of 1000 ppm was prepared from potassium sulfate and potassium phosphate salts (purity, > 99%; Sigma, Aldrich chemicals respectively, 20 ml of which was diluted to 200 ml with distilled water to make a working solution of 100 ppm. Further working concentrations of 0, 2, 5,10, 25 and 50 ppm were prepared from the 100 ppm working solution. The ICP-AES operating parameters are presented in Table 4.

Table 4: Operating conditions for the ICPE-9000 spectrometer.

Operating Parameter	Description of parameter
Spectrometer/Spectrometer temp	Charged coupled device (CCD) detector/-15℃
Radio Frequency power	1.20 kW
Output power	1.2 kW
Argon flow	Pressure of pure Argon: 450±10 KPa
	Cooling gas: 10 L/min
	Auxillary: 0.6 L/min
	Carrier gas: 0.7 L/min
Nebulizer	Pneumatic (coaxial nebulizer)
Vacuum pressure	>10 Pa
Plasma viewing	Axial
Replicates for each analysis	2
Sample exposure time	30 s
External coolant temperature	20 ± 2°C

The spectrometer was programmed to generate three calibration curves at different wavelengths for each element in the standard solution and the curve with both the highest R^2 value (5 sf) and line of best fit plotted from the least concentration was chosen as the working calibration curve. The selected wavelength and limits of detection (LOD) for each element of interest are shown in table 5. Only a single optimal measurement result was shown, regardless of the number of wavelengths registered. All elements included in the sample were monitored, and interference from the various wavelengths of the measured elements was automatically evaluated. The optimal wavelength for measurement was automatically selected, thereby obtaining accurate measurement result. The results expressed in ppm and percentages were read from the monitor connected to the spectrometer.

Table 5: Element wavelengths and the limits of detection for ICPE-9000 spectrometer.

Element	Wavelength (nm)	Limit of detection (ppm)
Ca	315.887	100 ppb
K	769.896	100 ppb
Na	588.995	100 ppb
P	213.618	100 ppb
Mg	383.826	100 ppb
S	182.037	100 ppb
Fe	233.280	10 ppb
Zn	213.856	10 ppb
Cu	324.754	10 ppb
Co	238.616	10 ppb
Mn	260.569	10 ppb

3.6.2 Sample analysis

Approximately, 2 ml of each digested sample was pipetted into a 25 ml volumetric flask followed by addition a 5 ml of distilled water. 2.5 ml of 5 % strontium chloride {prepared by accurately weighing and dissolving (304 g of strontium chloride salt into 1000 ml of distilled water) in 2000 ml of distilled water} was added and the solution topped up to the 25 ml mark with distilled water. The volumetric flasks were stoppered, shaken thoroughly and the solution was transferred into clean and dry test tubes placed in a rack. The test tubes were transferred to the auto sampler chamber of the spectrometer. With the aid of the ICPE-9000 software, blanks, standard solutions and test samples were analysed and quantified taking into account the total dilution factor (TDF) which is usually given by formulae (iv) below;

$$\text{(iv) T. D. F} = (\text{W. F} \times \text{D. F}) \text{ ppm}$$

Where; W. F is the weight factor; and D. F is the dilution factor

3.7 Determination of crude protein content

The apparatus for the experiment included; a KJELDATHERM® block digestion unit (KBL40S-Nominal voltage 230 V Ac; Frequency 50-60 Hz; Nominal wattage 2360 W; Maximum temperature 430℃; Heating places 40) coupled to a TZ control unit (WTZ) and TURBOSOG (TUR/K) unit, 100 ml micro digestion tubes (Gerhardt Systems-Germany),

Markham distillation unit, 25 ml burette, 100 ml conical flasks, concentrated sulfuric acid (analar), copper-selenium catalyst, Conway indicator, hydrochloric acid (analar), boric acid (analar), borax and sodium hydroxide. All chemical and reagents were obtained from SIGMA-ALDRICH and of analytical grade.

The catalyst contained 12.5 g of cupric sulfate ($CuSO_4.5H_2O$), 0.5 g of selenium and 250 g of anhydrous sodium sulfate. The Conway indicator was prepared by mixing 6ml of methyl red solution (0.16% in 95% absolute ethanol), 12 ml of bromocresol green (0.04% in distilled water) and 6 ml of 95% ethanol. 0.03 N HCl was prepared by pipetting 6.4 ml of concentrated sulfuric acid and diluting to 2 L with distilled water then standardized. Boric acid solution (2%) was prepared by dissolving 20 g of analar boric acid in distilled water then diluted to 1 L. Borax solution (0.6%) reference solution was prepared by dissolving 0.3 g of analar borax (sodium borate) in distilled water then diluting to 50 ml. Sodium hydroxide solution (40%) was prepared by dissolving 400 g of sodium hydroxide pellets in distilled water and diluting to 1 L.

3.7.1 Wet digestion

Approximately 0.1 g of ground baobab seeds and 0.2 g of fruit pulp were weighed separately into clean and dry 100 ml Kjedahl digestion flasks. 0.06 g of powdered selenium catalyst was added to the sample prior to addition of 1 ml of concentrated H_2SO_4. The mixture in the flask was transferred to an insert rack made of aluminium with an integrated heat shield then connected to the exhaust manifold and mounted onto the KJELDATHERM digestion block using the KJELDALIFT unit. The TZ temperature-time controller unit was programmed to achieve seven stages of digestion (table 6) and then the Gerhardt digestion system switched on. A TURBOSOG centrifugal scrubber was fitted with two condensate bottles each containing 10 % NaOH solution and connected to water for lubrication of its compressor, condensed and neutralized aggressive acid fumes. This TURBOSOG unit worked in two steps, separating and washing out acid fumes. After the digestion was complete, the digester was switched off and the flasks allowed to cool at room temperature. The blank test solution was prepared by dissolving the catalyst in 1 ml of concentrated sulfuric acid and heated until the catalyst dissolved. The flask was cooled and 2 ml of distilled water were added.

3.7.2 Sample distillation

Sample distillation was done using the Markham Still apparatus (Markham, 1942). The apparatus was steamed out before operation and the digest was washed into the apparatus quantitatively with 2 ml of distilled water through a funnel fitted with a ground-in stopper. The stopper was replaced and 10 ml of 40% sodium hydroxide was poured into the funnel. The strong base was allowed to run into the still by slowly lifting up the stopper. The funnel was rinsed with 2 ml of distilled water and raising the stopper to allow the washing into the still then replacing the stopper to avoid ammonia gas from escaping. Ammonia was distilled into conical flasks containing a mixture of 5 ml of 2 % boric acid solution, 2 drops of indicator and 10 ml of distilled water. Distillation proceeded preferably at a rate of 8-10 ml/min. When approximately 35 ml of the distillate had been collected, the conical flasks were lowered and the outside of the condenser tube was rinsed into the flask. When distillation was complete for each sample, the apparatus was flushed with distilled water to avoid sample cross contamination.

Table 6: KJELDATHERM digestion parameters using TZ Controller program 1 with seven (7) steps.

Step	Rising temperature time (s)	Temperature (℃)	Running time (min)
1	10	150	30
2	5	200	30
3	5	250	30
4	5	300	80
5	5	350	90
6	0	350	30
7	10	200	20
Cooling			30

3.7.3 Titration and quantitation

The standardization of HCl was done as follows; approximately 0.3 g of analar borax were weighed then dissolved in distilled water and diluted to 50 ml. 10 ml of the borax solution were pipetted into a conical flask into which 1 drop of the Conway indicator was added then titrated with 0.03 N HCl.

Formulae (v): Normality of HCl $= \frac{200 \times \text{Weight of borax}}{190.72 \times (\text{Ml of HCl})}$

The N content in the test samples was evaluated as follows;

1 ml of 0.03 N HCl = 0.0005g N if:

N= Normality of HCl (calculated above)

W= Weight of digested sample

V= Volume of HCl used in titrating the sample distillate less that used for the blank distillate

Then % N= $\frac{V \times N \times 14}{10 \times Wt}$

The % N content was multiplied with 6.25 to convert the result to sample crude protein content.

3.8 Determination of crude lipids

The method used for the determination of the crude lipid involved the chemical extraction of the crude lipids from the ground seed samples using *n*-hexane as the solvent and evaluated as a percentage of the sample weight (A.O.A.C, 1984). The chemical used included; *n*-hexane (99.5 %), Soxhlet extraction apparatus, hot air oven, extraction thimbles, cotton wool, 250 ml round bottomed flasks, rotor evaporator, analytical balance, condenser units and a dryer.

About 5 g (W1) of milled baobab seeds were weighed into a clean extraction thimble and stoppered with cotton wool. The stoppered thimble was placed a butt tube and connected to a pre-weighed (W2) clean dry extraction flask containing hexane. The ratio of the sample to solvent was 1:20. Thus, 100 ml of *n*-hexane were used to extract oil from 5 g of sample. Soxhlet apparatus were assembled and water was allowed to run through the apparatus before the electro mantle (Electromantle ME, Britain) was switched on. Extraction was allowed to run for 6 h at normal atmospheric pressure and a temperature of 60℃ with about 10 reflexes per hour before switching off the mantle. The thimbles were removed from the butt tube after extraction. The hexane extract was concentrated using a rotary evaporator (Rotavapor® R-3000, BUCHI Switzerland). The flasks were cooled in a dryer and weighed (W3). The defatted samples were kept in labelled zip-lock bags for use in crude fibre determination. The extracted oil was transferred to glass vials, labelled and stored refrigerated at 4℃.

The crude lipid content was evaluated by the formulae vi below;

(vi) Crude lipid content (g/100g) = $\frac{W3-W2}{W1} \times 100\ \%$

Where; W1 is the weight of sample

W2 is the weight of dried flask before fat extraction

W3 is the weight of dried flask after fat extraction

3.9 Determination of the crude fibre content

The determination was done according to (A.O.A.C, 1984) methods. The analytical reagents used were; 1.25% sulphuric acid, Amyl alcohol, Petroleum ether, 1% hydrochloric acid, 100 ml round bottomed flask, condensation unit, Whatman N0.541, porcelain crucible, heating mantle.

3.9.1 Analysis and quantitation

Approximately 2 g (W1) of the sample was weighed into a 1000 ml round bottomed flask followed by addition of 200 ml of boiling 1.25% sulphuric acid. The flask was then mounted onto a heated mantle attached to a condenser unit and the contents refluxed for 30 minutes. The flask was unmounted and the contents filtered using a funnel and a nylon cloth into a 500 ml conical flask. The residue on the nylon cloth was washed three times with hot distilled water then transferred to the flask using a retort containing 200 ml of boiling 1.25% sodium hydroxide solution. 1 ml of amyl alcohol was added as an antifoam and boiling was done under reflux for a further 30 minutes. Thereafter, filtration was done using a funnel fitted with filter paper (Whatman No. 541). The residue was rinsed twice with hot distilled water then with 1% hydrochloric acid. Further rinsing was done with boiling water to wash off the acid traces from the residue. Finally, the residue was washed with petroleum ether.

The sample was then washed into a clean porcelain dish and dried in an air oven at 105℃ for 5 hours to a constant weight, weighed and recorded (W2). The dry sample was then ashed in a muffle furnace at 550℃ for 3 hours. The dish was allowed to cool and the final weight (W3) was taken and recorded. The crude fibre content in each test sample was then calculated as shown in formulae vii below;

(vii) $$\% \text{ Crude fibre} = \frac{W2-W3}{W1} \times 100\ \%$$

Where; W1 is the weight of acid and alkali digested sample

W2 is the weight of incinerated sample after acid alkali digestion

W3 is the initial weight of sample

3.10 Determination of total ash content

Approximately 1 g of the sample was placed in a clean and dry, previously weighed porcelain crucible and placed in a muffle furnace set at 550℃ for 12 h (A.O.A.C, 1984).

After ashing time had elapsed the furnace was allowed to cool and the crucibles were transferred to a dryer. The crucibles with ash were weighed and their weights recorded. All analyses were done in triplicate and the ash content in in each test sample was evaluated as shown in formulae viii below;

$$\text{(viii) Ash content \%} = \frac{\text{A-B}}{\text{C}} \times 100$$

Where; A is the weight of crucible with sample (g)

B is the weight of crucible with ash (g)

C is the weight of sample (g)

3.11 Estimation of carbohydrate content

The carbohydrate content was estimated for the seed samples only using the difference method as illustrated in formulae ix below;

(ix): % carbohydrate = 100 – (% protein + % fat + % ash + % moisture)

3.12 Fatty acid analysis

. The fatty acid profiles of the crude oils were determined as Fatty Acid Methyl Esters (FAME) by Gas Chromatography (GC). Approximately, 0.5 mg of the sample oil and 0.0150 g of the internal standard were weighed into a clean and dry 250 mL round bottomed flask fitted with a reflux condenser. To the sample oil, 10.0 mL of 0.5 M methanolic sodium hydroxide was added and the mixture refluxed for 10 min until the lipids dissolved. 12 ml of BF_3 methanol complex (about 14% BF_3) was added through the top of the condenser and refluxing done for a further 2 min. Subsequently, 10.0 mL of *n*-hexane was then added via the condenser to the mixture and boiled under reflux for a further 2 minutes. The heating mantle was then switched off after which 10.0 mL of saturated sodium chloride solution was added to the mixture and shaken thoroughly. The organic layer was separated using a separating funnel and dried with anhydrous sodium sulfate. About 1.5 mL of the *n*-hexane layer was transferred into a clean GC vial. The sample (1 μL) was injected by using a microliter syringe of 10 μL. In all derivatizations, a constant amount of the internal standard (i.e 0.0150 g) was added to the sample.

The chromatographic system used to quantitatively estimate the FAME derived from the authentic commercial fatty acids' standards and crude sample oils constituted of a Varian 3300 gas chromatograph equipped with a Flame Ionization Detector (FID) and fitted with a column (30 m × 0.32 × 0.25 μm i.d.) packed with chromosorb WAW 60 - 80 mesh

(percolated with 15% diethyl glycol succinate) and a Varian integrator (Varian 4290) as the read out. The column (DB-wax column) was first conditioned by passing nitrogen gas through at 180˚C ± 0.5˚C for 3 hours. The chromatographic operating conditions used were; the nitrogen and hydrogen flow rates were both 40.0 mL·min^{-1}, the air flow rate was 30.0 mL·min^{-1}, the injection volume was 1.0 µL and the injector, column and detector temperatures were 230˚C ± 0.5˚C, 180˚C ± 0.5˚C and 240˚C ± 0.5˚C respectively.

The fatty acids were identified based on their retention times compared with those of the FAMEs derived from the authentic commercial fatty acids' standards. *viz.*, lauric acid (dodecanoic acid), myristic acid (tetradecanoic acid), oleic acid (*cis*-9-Octadecenoic acid), linoleic acid (*cis*-9,*cis*-12-Octadecadienoic acid), linolenic acid (*cis*,*cis*,*cis*-9,12,15-Octadecatrienoic acid), palmitic acid (Hexadecanoic acid), and stearic acid (Octadecanoic acid) all of highly purified form (≥ 98.5%) purchased from Sigma Aldrich, Germany. Heptadecanoic acid (99.8%) was used as the internal standard.

3.12.1 Determination of relative retention times of the fatty acid standards

Approximately 0.015 g of each of the commercial authentic fatty acid standards was measured into a round-bottomed flask. To each flask was added 0.015 g of the IS and the samples derivatized as outlined in section 3.13.3 below. A volume of 1 μL was injected to the GC column under the same conditions as for sample analysis. The experiment was done in triplicate for each sample. The duration each standard and the internal standard took to pass through the GLC column was recorded (Table 7) as a mean of the three replicates.

Table 7: GLC retention times (minutes) of pure fatty acid standards and internal standard; temperature programme: Column 180℃, injector 230℃, detector 240℃.

Pure fatty acid standards	GLC retention time (min)	
	F.A.S	I.S
Lauric acid	6.58	10.01
Myristic acid	7.45	9.99
Palmitic acid	8.80	10.03
Stearic acid	11.50	10.01
Oleic acid	11.70	9.97
Linoleic acid	12.40	10.00
Linolenic acid	13.81	10.04

F.A.S is Fatty Acid Standard, I.S is Internal Standard

3.12.2 Quantitative GLC analysis of samples

The approach adopted to determine the amount of fatty acids in each seed oil sample was based on the following assumptions; a) the areas under the peak signal monitored by the hydrogen flame ionization detector were proportional to the concentration of respective components in the samples and b) the detector responded in the same way for each fatty acid component as it did for the internal standard. Under such conditions the detector Relative Response Factor (RFF) for sample and internal standard would be unity. The RFF is defined as the ratio:

$$\frac{A\,x \times W\,i.s}{A\,i.s \times W\,x}$$

Where; A x is area under the peak for pure sample

A i.s is peak area for internal standard

W x is mass of pure sample

W i.s is mass of internal standard

In practice the determination of a response factor for any compound in a mixture under investigation is determined by plotting a curve for area under the peak against increasing amounts of standard. A similar plot is made for the internal standard. The ratio of the slope for the sample against that of internal standard is the response factor. Therefore pure samples are necessary to determine the RRF for each compound in a mixture of unknown composition. Since the internal standard is chosen as a compound structurally similar to the samples, the slope of the calibration curve for the internal standard could, if incorporated the RRF for unknown sample, be used to determine the concentration of each component in a mixture analyzed in GLC column. This of course assumed that the areas under the peaks were proportional to concentration of samples. The GC-FID RRF for the standard fatty acids was determined in triplicate under the same analytical conditions described above and the mean used in sample fatty acid profile quantitation. The percent composition of each fatty acid in the sample was calculated using formulae x presented below;

$$\text{(x) \% composition} = \frac{PA(compo) \times RRF \times Wt(is) \times DF}{PA(is) \times Wt(sample)} \times 100\ \%$$

Where; PA (compo) is the peak area of component (fatty acid) of interest

RRF is the response factor for the component (fatty acid) of interest

Wt (is) is the weight of the internal standard used in sample derivatization

DF is the dilution factor used prior to sample injection

PA (is) is the peak area of the internal standard

Wt (sample) is the weight of the sample used in derivatization.

3.13 Data Analysis

All determinations were conducted in triplicate, and the data were subjected to analysis of variance (ANOVA) using the nested model. In the model, trees were nested in provenances, while provenances were considered as nested factors within countries. For each country, the biochemical concentration of the fruit pulp and seeds for trees from different provenances (inter-provenance) and for trees within the same provenance (Intra-provenance) were compared. In Zimbabwe where we had two provenances, comparisons were made using an unpaired two-sample t-test with the provenances as group factor. Data analysis were conducted using Genstat Software version 15.1 to describe the nutritive value of baobab parts across the countries and within countries. Principal Component Analysis (PCA) was performed on the correlation matrix of the elemental concentration of each of the baobab parts to describe the relationship among them and between them and the countries. PCA and hierarchical cluster analysis was also conducted for the baoab seed oil fatty acids. Tukey's test was conducted to identify significant differences at $\alpha = 0.05$ level. Data is presented as mean ± standard error of the mean (SEM).

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Biochemical concentration of baobab fruit pulp and seeds in Kenya

4.1.1 Proximate composition of baobab fruit pulp and seeds across the Kenyan provenances

The macronutrients of baobab fruit pulp were compared among investigated trees in Malindi, Taita and Kibwezi (Appendix 1a). In Malindi, there were no significant differences ($P < 0.05$) for the crude protein, crude fibre and moisture content at tree level but the ash content varied significantly at $P < 0.05$. In Kibwezi provenance, the trees varied significantly ($P < 0.001$) in mean crude protein, ash and moisture content. The crude fibre content did not seem to vary significantly, $P < 0.05$ at tree level. In Taita provenance, trees did not vary significantly ($P < 0.05$) in crude fibre, ash and moisture but in the crude protein content as shown in Appendix 1a. The three Kenyan provenances were further compared for the mean proximate composition (Table 8). The three provenances varied significantly ($P < 0.01$) in the mean moisture, crude protein and ash levels. However, they did not vary significantly ($P < 0.05$) in the mean crude fibre content. Kibwezi and Taita provenances did not show any significant variation in the mean moisture, crude protein and fibre content. Similarly, Malindi and Taita did not vary significantly in their means for the previously mentioned parameters. For the three provenances, moisture and ash content showed the lowest variation (CV=0.3 & 2.4% respectively) while crude protein and crude fibre had relatively high variation (CV=10 & 29%).

Table 8: Baobab fruit pulp proximate composition according to three provenances in Kenya.

Provenance	Moisture (g/100 g)	Crude protein (g $100g^{-1}$ dw)	Crude fibre (g $100g^{-1}$ dw)	Ash (g $100g^{-1}$ dw)
Kibwezi	9.79 ± 0.026^{b}	2.42 ± 0.051^{a}	8.44 ± 1.937^{a}	4.23 ± 0.099^{c}
Taita	9.82 ± 0.032^{ab}	2.08 ± 0.195^{ab}	7.82 ± 0.828^{a}	4.66 ± 0.090^{a}
Malindi	9.85 ± 0.027^{a}	2.04 ± 0.313^{b}	9.61 ± 3.428^{a}	4.48 ± 0.122^{b}
P-value	< 0.01	< 0.01	NS	< 0.001
CV (%)	0.3	10.0	29.0	2.4

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

Seed macronutrients were analysed for the three provenances in Kenya to establish intra-provenance variation. The ANOVA results for intra-provenance variation are presented

in Appendix 1b. In Kibwezi provenance, there were statistical significant differences ($P < 0.05$) among the trees in their seed moisture, crude protein, crude fat, carbohydrates and crude fibre content. However the ash content did not show any statistical significant differences ($P < 0.05$) at tree level. The ANOVA results revealed the existence of statistical significant differences ($P < 0.05$) among trees in Malindi for seed moisture, proteins, fat, carbohydrates and ash content but the individual trees did not vary significantly ($P < 0.05$) for seed fibre content. In Taita provenance, statistical significant differences ($P < 0.05$) among the trees were recorded for crude fat and moisture content. For crude protein, crude fibre, carbohydrates and ash, there were no statistical significant differences between the trees as presented in Appendix 1b.

The three provenances were also compared (inter-provenance variation) for the mean seed proximate composition (Table 9). The provenances differed significantly for crude protein, crude fat and carbohydrate content but did not show any significant differences ($P < 0.05$) in the mean moisture, crude fibre and ash content. The mean crude protein concentration varied from 13.26 g $100g^{-1}$ dw in Malindi to 15.93 g $100g^{-1}$ dw in Taita. According to Table 9, the seed proximate components occurred in the order; carbohydrates > crude fibre > crude protein > crude fat > moisture > ash. There was low variation (CV < 5%) for most of the proximate components except for crude fibre which showed a slightly higher variation (CV=12.2%).

Table 9: Seed proximate composition according to the three provenances in Kenya.

Provena-nce	Moisture (g/100 g)	Protein (g/100g dw)	Fibre (g/100g dw)	Fat (g/100g dw)	Carbohydrate (g100g/dw)	Ash (g100g/dw)
Kibwezi	6.97±0.04[a]	14.99±0.47[b]	22.47±1.31[a]	12.62±0.33[b]	61.11±0.86[b]	4.01±0.290[a]
Taita	7.01±0.05[a]	15.93±0.3[a]	20.93±3.36[a]	13.49±0.35[a]	59.50±0.57[c]	3.78±0.051[a]
Malindi	7.04±0.08[a]	13.26±0.26[c]	25.11±3.62[a]	11.77±0.68[c]	63.74±0.56[a]	3.89±0.062[a]
P-value	NS	< 0.001	NS	< 0.001	< 0.001	NS
cv	1.0	2.5	12.2	4.1	1.1	4.9

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.1.2 Concentration of selected macro and micro elements of baobab fruit pulp and seeds

The macro and micro-elements of baobab fruit pulp were compared among trees sampled within Kibwezi, Malindi and Taita provenances. The results showing intra-provenance variation for pulp element content are presented in Appendix 1c. In Malindi provenance, the investigated trees varied significantly ($P < 0.01$) for pulp elemental concentration except for sodium. In Kibwezi provenance, the trees varied significantly ($P < 0.001$) in the mean element content though with the exception of sodium and zinc. Different observations were recorded in Taita provenance, the trees differed significantly ($P < 0.01$) in calcium, potassium, phosphorus and copper content but did not vary significantly in mean magnesium, sodium, zinc, iron and manganese content. The concentration of selected macro and micro elements of baobab fruit pulp were compared among the three study provenances (Table 10). The three provenances varied significantly ($P < 0.001$) in the mean pulp macro and micro element concentration. Taita provenance recorded the lowest mean pulp calcium (2400 $mgkg^{-1}$) and manganese (23.8 μgg^{-1}) content but also the highest content of magnesium, phosphorus and copper while the highest iron content (61.5 μgg^{-1}**)** was recorded in Kibwezi provenance. Malindi had the highest level of pulp potassium, sodium and manganese. According to Table 10, the elements occurred in the order; K > Ca > Mg > P > Na > Zn > Fe > Cu > Mn. For both macro and micro elements concentration in the pulp, the variability among the provenances was very low (CV=1.8-3.6%) but with the exception of sodium which showed relatively high variation (35.1%).

Table 10: Concentration of selected macro and micro elements in baobab fruit pulp according to three provenances in Kenya.

Provenance	Ca	K (mgg^{-1})	Mg	Na	P	Cu	Fe	Mn	Zn
Kibw	2800±100[a]	18.5±0.05[b]	1300±50[b]	300±100[b]	600±20[b]	47.1±0.801[b]	61.5±2.143[a]	26.3±0.486[b]	81.3±2.492[a]
Taita	2400±80[b]	17.6±0.62[b]	1600±50[a]	300±70[b]	800±30[a]	49.1±0.860[a]	58.0±2.236[b]	23.8±0.430[c]	79.1±2.081[a]
Malindi	2900±100[a]	25.3±0.89[a]	1200±40[c]	700±230[a]	600±20[b]	42.3±0.754[c]	53.1±1.845[c]	29.5±0.565[a]	58.9±2.100[b]
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	3.6	3.6	3.6	35.1	3.6	1.8	3.6	1.9	3.2

For the same column, Values (means ± S.E.M) followed by the same letter are not significantly different. Kibw: Kibwezi. Units: Ca, Mg, Na, P ($mgkg^{-1}$); Cu, Fe, Mn, Zn (μgg^{-1})

The elemental concentrations of baobab seeds were compared among the sampled trees in each of the three provenances. The statistical significance levels are presented in Appendix 1d. In Kibwezi provenance there were no statistical significant differences ($P < 0.05$) among the trees for mean magnesium and sodium content. However, there were statistical significant differences ($P < 0.01$) in seed calcium, potassium, phosphorus, copper, iron, zinc and manganese concentrations among the trees. In Malindi provenance, the trees differed significantly ($P < 0.01$) for calcium, magnesium, phosphorus, copper, iron, zinc and manganese levels but did not show significant differences ($P < 0.05$) for sodium and potassium content. However, potassium and sodium content did not vary significantly among trees within the provenance. The trees in Taita provenance did not significantly ($P < 0.05$) in the seed macro element (Ca, K, Mg, Na, P) concentration. However, they revealed statistical significant differences ($P < 0.05$) in the micro element (Cu, Fe, Mn, Zn) concentration.

To establish inter-provenance variation, the three provenances were compared for the mean concentrations of selected macro and micro elements (Table 11). The provenances differed significantly ($P < 0.01$) for most of the macro and micro elements concentration

though with the exception of sodium. Malindi had the highest mean calcium and manganese content while Taita had the highest mean for potassium, magnesium, copper and zinc content. According to table 11, the order of seed elements was K > P > Mg > Ca > Na > Fe > Cu > Zn > Mn. Across the provenances, the variation was very low (CV=2 - 4%) in both macro and micro elements except for sodium (CV=29.7%).

Table 11: Concentration of selected macro and micro elements in baobab seeds according to three provenances in Kenya.

Provenance	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Kibw	1900±60^{b}	9.1±0.29^{b}	3300±120^{b}	200±50^{a}	5.6±0.19^{b}	28.2±0.775^{b}	70.0±2.598^{a}	19.3±0.734^{b}	23.2±0.811^{b}
Taita	1800±60^{b}	9.7±0.34^{a}	3600±130^{a}	200±60^{a}	6.2±0.21^{a}	30.3±0.533^{a}	67.3±2.397^{a}	15.2±0.275^{c}	36.1±1.392^{a}
MLD	2300±80^{a}	8.9±0.31^{b}	3200±110^{b}	200±60^{a}	6.5±0.23^{a}	25.7±0.452^{c}	56.0±2.003^{b}	23.1±0.434^{a}	14.6±0.284^{c}
P-value	< 0.001	< 0.01	< 0.01	NS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
cv	3.4	3.4	3.5	29.7	3.5	2.2	3.7	2.8	3.6

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. Kibw: Kibwezi. Units for Cu, Zn, Mn, Fe ((μgg^{-1}); Ca, Mg, Na (mg/kg); K and P (mg/g)

4.1.3 Baobab seed oil fatty acid profiles

Baobab seed oil fatty acids were expressed as a percentage of total fatty acid methyl esters (FAMES). The GC-FID analyses revealed the presence of five major fatty acids namely; palmitic, stearic, oleic, linoleic and linolenic. The concentrations of these fatty acids were further compared statistically among trees in each study provenance (Appendix 1e). In Kibwezi provenance, there existed statistical significant differences ($P < 0.05$) among the trees for palmitic, oleic and linolenic acids but no significant differences were recorded for stearic and linoleic acids at $P < 0.05$. For three in Malindi, they differed significantly ($P < 0.05$) in palmitic acid content but there were no statistical significant differences ($P < 0.05$) for seed oil stearic, oleic, linoleic and linolenic acids. In Taita provenance the investigated trees did not show statistical significant differences ($P < 0.05$) for any of the fatty acids identified. The seed oil fatty acid concentration was further compared among the study

provenances (Table 12). Among the three provenances, there were statistical significant differences ($P > 0.05$) in palmitic, oleic, linoleic and linolenic acids concentrations but no significant differences at $P < 0.05$ were recorded for stearic acid. Malindi provenance had the lowest levels of palmitic and linoleic acids but recorded the highest linolenic acid content. According to table 12, the seed oil fatty acids in Kenyan provenances were in the order: Oleic > linoleic > palmitic > stearic > linolenic.

Table 12: Fatty acid profile of baobab seed oil from Kenyan provenances.

Provenance	Palmitic acid (%)	Stearic acid (%)	Oleic acid (%)	Linoleic acid (%)	Linolenic acid (%)
Kibwezi	18.44±0.503[a]	1.54±0.140[a]	33.94±0.571[b]	25.81±3.955[a]	0.84±0.074[b]
Taita	19.04±0.961[a]	1.59±0.129[a]	34.43±0.725[b]	27.89±0.577[a]	0.75±0.092[b]
Malindi	17.47±0.554[b]	1.43±0.140[a]	39.06±1.855[a]	19.62±1.507[b]	1.33±0.416[a]
P-value	< 0.01	NS	< 0.001	< 0.001	< 0.01
CV (%)	3.4	9.2	3.6	11.6	26.7

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.1.4 Vitamin C concentration of baobab fruit pulp in Kenya

Baobab fruit pulp vitamin C content was compared among the sampled trees within each provenance. The ANOVA results are presented in Appendix 1f. The analyses reveled that in Kibwezi and Malindi provenances the trees varied significantly ($P < 0.001$) for pulp vitamin C concentration. However, no significant differences ($P < 0.05$) among the trees were observed in Taita for vitamin C as shown in Appendix 1f. Results in Table 13 below showed that there were statistical significant differences ($P < 0.001$) between the provenances for pulp vitamin C concentration. Taita provenance had the highest mean pulp vitamin C concentration, almost twofold that of either Kibwezi or Malindi. But Kibwezi and Malindi did not differ significantly for mean vitamin C. The variability (CV) between the provenances was 11.3%.

Table 13: Baobab fruit pulp vitamin C concentration according to three provenances in Kenya.

Provenance	Vitamin C (mgg^{-1})
Kibwezi	2.34 ± 0.268^{b}
Taita	4.34 ± 0.278^{a}
Malindi	2.31 ± 0.203^{b}
CV (%)	11.3%

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.2 Biochemical composition of baobab fruit pulp and seeds in Zambia

4.2.1 Proximate composition of baobab fruit pulp and seeds according to three provenances in Zambia

The proximate composition of baobab fruit pulp was compared among the trees within each provenance. The ANOVA results are presented in Appendix 2a. In Chirundu and Mambwe provenances, there were statistical significant differences ($P < 0.01$) in the crude protein, ash and moisture content among the investigated trees. In Siavonga provenance, the trees differed significantly ($P < 0.05$) in pulp moisture, crude fibre, crude protein and ash content.

Baobab fruit pulp proximate composition was further compared among the provenances in Zambia (Table 14). The three provenances differed significantly ($P < 0.001$) for pulp moisture, crude protein, crude fibre and ash content. Siavonga provenance showed the highest concentration for crude protein (2.65 g $100g^{-1}$ dw) and ash (4.68 g $100g^{-1}$ dw) and content. Mambwe and Chirundu provenances did not show any significant differences ($P < 0.05$) in crude protein and crude fibre content. Among the three provenances, moisture content showed the least variability (CV= 0.7) while high variation (CV=10.2) was recorded for crude fibre.

Table 14: Proximate composition of baobab fruit pulp according to three provenances in Zambia.

Provenance	Moisture (g/100g)	Crude protein (g $100g^{-1}$ dw)	Crude fibre (g $100g^{-1}$ dw)	Ash (g $100g^{-1}$ dw)
Chirundu	8.82 ± 0.063^{c}	2.06 ± 0.158^{b}	7.10 ± 0.823^{ab}	4.51 ± 0.130^{b}
Siavonga	8.95 ± 0.063^{a}	2.65 ± 0.059^{a}	7.75 ± 0.048^{a}	4.68 ± 0.084^{a}
Mambwe	8.89 ± 0.054^{a}	2.02 ± 0.111^{b}	6.42 ± 0.943^{b}	3.82 ± 0.085^{c}
P-value	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	0.7	5.2	10.2	2.3

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

Seed macronutrient content was investigated among trees within each provenance in Zambia. The results showing the level of significance in variation are presented in Appendix 2b. In Chirundu provenance, the trees varied significantly ($P < 0.05$) in crude fibre, crude fat, carbohydrates, moisture and ash content but there were no statistical significant differences at $P < 0.05$ in crude protein content. In Siavonga provenance, statistical significant differences ($P < 0.05$) were noted for seed crude fibre, ash and moisture content among trees. However, within Siavonga there were no statistical significant differences at $P < 0.05$ for crude protein, crude fat and carbohydrate content. For trees growing in Mambwe provenance, there were statistical significant differences ($P < 0.05$) in the seeds macronutrient content (crude protein, crude fibre, crude fat and carbohydrates).

Further, the three provenances were compared for seed proximate composition (Table 15). It was noted that for the seeds there were statistical significant differences ($P < 0.001$) between the provenances for crude fibre, crude fat, carbohydrates, moisture and ash. But no statistical significant differences at $P < 0.05$ were noted among the provenances for crude protein. According to Table 15, the seed proximate components were present in the order: Carbohydrates > Crude fibers > Crude protein > crude fat > moisture > ash. Low variability among the provenances was recorded for moisture, crude fibre, carbohydrates and ash (CV= < 2.5) whereas crude protein and crude fat showed relatively moderate variation (CV= 6.5 - 8.8).

Table 15: Baobab seed proximate composition according to three provenances in Zambia.

Provenance	Moisture (g $100g^{-1}$)	C.protein (g $100g^{-1}$ dw)	C. fibre (g $100g^{-1}$ dw)	Crude fat (g $100g^{-1}$ dw)	Carbohydrates (g $100g^{-1}$ dw)	Ash (g $100g^{-1}$ dw)
Chirundu	6.31± 0.145[b]	13.46± 1.045[a]	22.90± 0.447[b]	11.21± 0.713[b]	64.91± 1.304[a]	4.10± 0.080[a]
Siavonga	6.50± 0.156[a]	13.85± 0.535[a]	23.58± 0.273[a]	10.35± 1.354[b]	65.16± 1.426[a]	4.14± 0.087[a]
Mambwe	6.20± 0.104[b]	14.00± 1.000[a]	22.32± 0.139[c]	12.53± 0.805[a]	63.43± 1.495[b]	3.83± 0.108[b]
P-value	< 0.001	NS	< 0.001	< 0.001	< 0.01	< 0.001
CV (%)	2.2	6.5	1.4	8.8	2.2	2.3

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.2.2 Concentration of selected macro and micro elements in baobab fruit pulp and seeds

The concentration of selected macro and micro elements in fruit pulp were compared among the trees for the three provenances (Appendix 2c). In Chirundu and Mambwe provenances the trees varied significantly ($P < 0.001$) in both pulp macro and micro element content but with the exception of sodium levels. The order in mineral element composition of fruit pulp was: K > Ca > Mg > P > Na > Cu > Fe > Zn > Mn. In Siavonga provenance, there were statistical significant differences ($P < 0.01$) among the trees for both macro and micro elements.

The ANOVA results presented in Table 16 revealed statistical significant differences ($P < 0.001$) among the Zambian provenances for both macro and micro elements concentration in the fruit pulp. Chirundu had the highest mean sodium, phosphorus and copper content while Siavonga had the highest mean calcium, magnesium and zinc content. Potassium and iron levels were highest in Mambwe compared to the other provenances. According to Table 16, the concentration of these elements in fruit pulp was in the following order: K > Ca > Mg > P > Na > Fe > Cu > Zn > Mn. Low variability (CV= < 3.8%) was present among the provenances for most elements except for sodium that showed high (CV=33.7%) variability.

Table 16: Concentration of selected macro and micro-elements in baobab fruit pulp according to three provenances in Zambia.

Provenance	Ca	K (mgg^{-1})	Mg	Na	P	Cu (µg/g)	Fe (µg/g)	Mn (µg/g)	Zn (µg/g)
Chiru	3000±110^{b}	21.1±0.74^{b}	1700±60^{b}	700±210^{a}	900±30^{a}	45.1±0.823^{a}	40.7±1.448^{c}	11.3±0.206^{b}	16.6±0.569^{c}
Siav	3600±130^{a}	17.2±0.61^{c}	1900±70^{a}	200±80^{b}	700±30^{c}	43.8±0.768^{b}	45.7±1.299^{b}	23.6±0.975^{a}	66.2±3.379^{a}
Mamb	2900±100^{b}	21.9±0.77^{a}	1200±40^{c}	400±110^{b}	800±30^{b}	39.9±0.836^{c}	58.5±2.051^{a}	23.4±0.427^{a}	41.2±1.504^{b}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	3.6	3.5	3.7	33.7	3.6	1.9	3.4	3.2	5.2

For the same column, Values (means ± S.E.M) followed by the same letter are not significantly different. Chiru: Chirundu, Siav: Siavonga, Mamb: Mambwe. Units: Ca, Mg, Na, P ($mgkg^{-1}$)

Intra-provenance variation in seed elemental concentration was investigated for the provenances in Zambia (Appendix 2d). Within Chirundu and Mambwe provenances there were statistical significant differences ($P < 0.001$) among the trees for macro and micro element concentration though with the exception of sodium as shown in Appendix 2d. In Siavonga provenance there were statistical significant differences ($P < 0.001$) among the trees for the macro and micro elements except for magnesium and sodium. In all provenances, the order of element accumulation within the seed tissue was: K > P > Mg > Ca > Na > Fe > Cu > Zn > Mn.

The ANOVA results (Table 17) reveal that there were statistical significant differences ($P < 0.001$) among the provenances for the seed macro and micro elements though with the exception of sodium. Siavonga provenance had the highest concentration of magnesium, phosphorus, manganese and zinc while Mambwe provenance had the highest seed iron content. According to Table 17, the order of selected elements based on their concentration in the seed was K > P > Mg > Ca > Na > Fe > Cu > Zn > Mn. Among the

provenances, low variation (CV= 1.9 – 6.1%) was noted for both macro and micro elements while a relatively higher variation (CV= 30.3%) was noticed for sodium.

Table 17: Concentration of selected macro and micro elements of baobab seeds according to three provenances in Zambia.

Provenance	Ca mg/kg	K mgg^{-1}	Mg mg/kg	Na mg/kg	P mgg^{-1}	Cu µg/g	Fe µg/g	Mn µg/g	Zn µg/g
Chiru	2300 ±80^{b}	10.4± 0.36^{ab}	3600± 138^{b}	200± 60^{a}	7.5±0. 27^{b}	41.9±0. 75^{c}	48.1±1. 67^{c}	23.1±0. 44^{b}	28.7±0. 98^{c}
Siav	2600 ±100^{a}	10.7± 0.37^{a}	3900± 340^{a}	200± 70^{a}	8.2±0. 32^{a}	49.7±0. 87^{b}	51.6±1. 78^{b}	24.2±0. 45^{a}	36.1±1. 23^{a}
Mamb	2500 ±90^{a}	10.3± 0.36^{b}	3400± 120^{b}	200± 70^{a}	7.6±0. 26^{b}	47.4±0. 84^{b}	53.5±1. 86^{a}	19.9±0. 36^{c}	30.9±1. 08^{b}
P-value	< 0.001	<0.05	< 0.001	NS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	3.7	3.5	6.1	30.3	3.7	1.8	3.5	1.9	3.4

For the same column, Values (means ± S.E.M) followed by the same letter are not significantly different. Chiru: Chirundu, Siav: Siavonga, Mamb: Mambwe

4.2.3 Fatty acid profile of baobab seed oil from Zambia

Intra-provenance variation in seed oil fatty acid content was investigated for Zambian provenances. The results are presented in Appendix 2e. In Chirundu provenance trees varied significantly ($P < 0.05$) for palmitic and stearic acids but did not show statistical significant differences ($P < 0.05$) in oleic, linoleic and linolenic acid content. In Mambwe provenance, the trees varied significantly ($P < 0.05$) in palmitic, oleic and linoleic acids. However no statistical significant differences at $P < 0.05$ were noted for stearic and linolenic acid content in Mambwe. In Siavonga provenance the investigated trees showed statistical significant differences ($P < 0.05$) for seed oil palmitic, stearic, oleic and linoleic acids but did not vary significantly at $P < 0.05$ for linolenic acid content. The provenances were further compared for seed oil fatty acid content. Results presented in Table 18 below revealed the existence statistical significant differences ($P < 0.05$) among the provenances for palmitic, oleic and linoleic acids but, there were no statistical significant differences at $P < 0.05$ among the three provenances for stearic and linolenic acids. Oleic acid was highest in Siavonga provenance. According to Table 18, the fatty acid profile was in the order: Oleic > linoleic > palmitic >

stearic > linolenic. The variability in the mean seed oil fatty acid content was low (CV = 3–8%) for palmitic, oleic and linoleic but relatively high (CV= 10 - 20%) for stearic and linolenic acid.

Table 18: Fatty acid profile of baobab seed oil according to three provenances in Zambia.

Provenance	Palmitic (%)	Stearic (%)	Oleic (%)	Linoleic (%)	Linolenic (%)
Chirundu	21.09± 0.715[a]	1.19± 0.082[a]	35.83± 1.151[b]	27.12± 3.300[a]	0.85± 0.104[a]
Siavonga	20.50± 0.830[ab]	1.27± 0.125[a]	37.08± 1.208[a]	28.08± 1.031[a]	0.85± 0.177[a]
Mambwe	20.13± 0.599[b]	1.19± 0.162[a]	34.49± 0.843[c]	24.39± 1.147[b]	0.88± 0.215[a]
P-value	< 0.01	NS	< 0.001	< 0.001	NS
CV (%)	3.5	10.4	3.0	7.9	20.0

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.2.4 Vitamin C concentration of baobab fruit pulp in Zambia

Baobab fruit pulp vitamin C concentration was compared among trees within each study provenance in Zambia. The results (Appendix 2f) revealed the existence of statistical significant differences ($P < 0.001$) among the trees for fruit pulp vitamin C content. The provenances were compared for the mean vitamin C content to establish inter-provenance variation. Results (Table 19) revealed that there were statistical significant differences ($P < 0.05$) among the provenances for pulp vitamin C concentration. The variability among the provenances was moderate (CV=10.3%).

Table 19: Vitamin C concentration of baobab fruit pulp according to three provenances in Zambia

Provenance	Vitamin C (mg/g)
Chirundu	3.17 ± 0.28^{b}
Siavonga	3.23 ± 0.34^{ab}
Mambwe	3.37 ± 0.33^{a}
CV (%)	10.3%

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.3 Biochemical composition of baobab fruit pulp and seeds in Tanzania

4.3.1 Proximate composition of baobab fruit pulp and seeds according to four provenances in Tanzania

Intra-provenance variation in pulp proximate composition was investigated within each Tanzanian provenance. Results presented in Appendix 3a show the level of significance in variation for the macronutrients within each provenance. In Kilolo provenance, the trees varied significantly in pulp moisture, crude protein and ash content but there were no statistical significant differences ($P < 0.05$) among the trees for pulp crude protein content. Trees in Kongwe provenance varied significantly ($P < 0.05$) for moisture and ash content but no significant variation at $P < 0.05$ was noted for crude protein and fibre content. However, trees in Moshi Rural and Mwanga provenances showed statistical significant differences ($P < 0.05$) in pulp moisture, protein, fibre and ash content. The ANOVA results (Table 20) revealed the existence of statistical significant differences ($P < 0.05$) among the provenances (inter-provenance variation) for pulp moisture, crude protein, crude fibre and ash. Kilolo provenance had the highest mean pulp moisture and crude protein while Kongwe had the lowest ash and crude fibre content. Moisture, crude protein and ash showed low variation (CV= 3 - 7%) while crude fibre had a relatively high variation (CV= 10.6%).

Table 20: Fruit pulp proximate composition according to four provenances in Tanzania.

Provenance	Moisture (g/100 g)	Crude protein (g 100 g^{-1} dw)	Crude fibre (g 100 g^{-1} dw)	Ash (g 100 g^{-1} dw)
Kilolo	9.77 ± 0.436^{a}	2.44 ± 0.138^{a}	6.80 ± 0.945^{ab}	4.40 ± 0.130^{b}
Kongwe	9.24 ± 0.267^{b}	1.58 ± 0.135^{d}	6.84 ± 1.090^{ab}	3.98 ± 0.155^{c}
Moshi rural	8.98 ± 0.224^{b}	1.82 ± 0.027^{c}	6.54 ± 0.083^{b}	4.54 ± 0.088^{a}
Mwanga	8.97 ± 0.063^{b}	2.15 ± 0.179^{b}	7.51 ± 0.291^{a}	4.59 ± 0.118^{a}
P-value	< 0.001	< 0.001	< 0.05	< 0.001
CV (%)	3.0	6.6	10.6	2.9

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

Seed macronutrient content were compared among trees in each provenance in Tanzania. Data presented in Appendix 3b revealed that the trees in Kilolo varied significantly ($P < 0.05$) for moisture, fibre, ash, fat and carbohydrate but no significant differences ($P < 0.05$) were noted for seed protein content. Trees in Kongwe, Moshi Rural and Mwanga provenances showed statistical significant differences ($P < 0.05$) for seed moisture, protein, fibre, fat, ash and carbohydrate content. The macronutrients, moisture and ash content of baobab seeds were compared among the four provenances of Tanzania (Table 21). There were statistical significant differences ($P < 0.001$) among the provenances for all seed macronutrients. Kilolo provenance had the highest ash content while Moshi had the highest fibre and carbohydrate content. There was low variability (CV= 1.5–5.3%) among the provenances for the seed proximate composition.

Table 21: Baobab seed proximate composition according to four provenances in Tanzania.

Provenance	Moisture (g/100g)	Protein (g 100 g^{-1} dw)	Fibre (g 100 g^{-1} dw)	Fat (g 100 g^{-1} dw)	Carbohydrates (g 100 g^{-1} dw)	Ash (g 100 g^{-1} dw)
Kilolo	6.61± 0.175^{b}	16.02± 0.895^{a}	23.29± 0.175^{b}	13.04± 0.264^{a}	60.03± 0.935^{c}	4.31± 0.082^{a}
Kongwe	6.95± 0.175^{a}	15.10± 0.568^{b}	22.31± 0.513^{c}	13.35± 0.209^{a}	60.50± 0.647^{c}	4.09± 0.108^{b}
Moshi	6.81± 0.090^{a}	13.17± 0.733^{c}	26.25± 0.960^{a}	11.93± 0.354^{b}	64.23± 0.649^{a}	3.86± 0.163^{c}
Mwanga	6.26± 0.076^{c}	15.38± 0.681^{ab}	23.47± 0.386^{b}	12.08± 1.249^{b}	62.22± 1.282^{b}	4.06± 0.234^{b}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	2.1	4.9	2.5	5.3	1.5	3.9

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.3.2 Concentration of selected macro and micro-elements of baobab fruit pulp and seeds

The concentration of selected macro and micro-elements of baobab fruit pulp were compared among trees within each of the four provenances. According to ANOVA results presented in Appendix 3c there were statistical significant differences ($P < 0.05$) among trees in Kilolo for calcium, potassium, magnesium, copper, iron and zinc but no significant differences were noted in sodium, phosphorus and manganese content. In Kongwe provenance trees varied significantly at $P < 0.05$ for macronutrient content though with the exception of sodium. However, trees in Kongwe did not vary significantly for in the microelement content as shown in Appendix 3c. Trees growing in Moshi Rural varied significantly ($P < 0.05$) for both pulp macro and micro element concentration. For Mwanga provenance, statistical significant differences ($P < 0.05$) existed among the trees for pulp elemental concentration but with the exception of sodium content. The pulp elemental concentration was further compared among the four provenances in Tanzania (Table 22). Results revealed the existence of statistical significant differences ($P < 0.001$) among the provenances for both micro and macro element concentration. Kilolo provenance had the

highest calcium content while Kongwe provenance had the highest sodium concentration. Moshi provenance showed the highest recorded magnesium and copper content. Even though Mwanga provenance had the highest mean for potassium, zinc, iron and manganese it also had the lowest mean in pulp calcium, sodium, phosphorus and copper. Among the provenances, variability was low (CV= 3.1 – 6.3%) for macro elements but with the exception of sodium (11.8%) while for micro elements it ranged between 4.3 – 10.0%.

Table 22: Concentration of selected macro and micro elements of baobab fruit pulp according to four provenances in Tanzania.

Provenance	Ca	K (mgg^{-1})	Mg	Na	P	Cu (µg/g)	Fe (µg/g)	Mn (µg/g)	Zn (µg/g)
Kilolo	3600±100^{a}	19.3±0.55^{c}	1200±40^{c}	700±80^{b}	800±50^{ab}	46.8±2.74^{b}	16.5±0.96^{c}	3.7±0.53^{d}	26.0±1.46^{c}
Kongwe	3500±130^{b}	18.7±0.54^{c}	1800±60^{b}	800±80^{a}	700±50^{b}	49.1±3.66^{b}	17.6±1.22^{c}	5.0±1.56^{c}	26.0±7.09^{c}
Moshi	3500±90^{b}	20.3±0.46^{b}	1900±180^{a}	600±40^{c}	800±50^{a}	53.6±1.46^{a}	38.0±1.07^{b}	13.8±0.70^{b}	39.2±1.67^{b}
Mwanga	2200±80^{c}	23.1±0.82^{a}	1300±50^{c}	200±70^{d}	600±20^{c}	41.5±0.73^{c}	64.1±2.23^{a}	25.2±0.46^{a}	63.1±2.17^{a}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	3.1	3.0	6.3	11.8	6.3	5.1	4.3	7.8	10.0

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. Units: Ca, Mg, Na, P (mg/kg).

Seed elemental composition was investigated among the trees within each provenance (intra-provenance). Trees in Kilolo and Kongwe provenances varied significantly ($P < 0.05$) for both seed macro and micro element concentration as shown in Appendix 3d. In Moshi provenance, trees varied significantly at $P < 0.05$ for all investigated macro elements and manganese but did not show any significant differences in copper, iron and zinc content. In Mwanga provenance, statistical significant differences existed among the trees for seed elemental concentration except for sodium content. All the results for intra-provenance variation in seed elemental composition are presented in appendix 3d. The ANOVA results from inter-provenance comparison (Table 23) revealed that there were statistical significant

differences ($P < 0.001$) among the provenances for all the investigated elements. Kongwe provenance had the highest magnesium, sodium and zinc content while Moshi had the highest potassium content. Even though Mwanga provenance had the lowest calcium, potassium, magnesium, sodium and zinc level it had the highest coper, iron and manganese levels. The seed elements occurred in the order: K > P > Mg > Ca > Na > Fe > Zn > Cu > Mn. The variability among the provenances for macro elements was low (2.9 – 6.4%) except for sodium (9.5%) while relatively high variability (5.8 – 8.3%) was recorded for the micro elements.

Table 23: Concentration of selected macro and micro elements of baobab seeds according to four provenances in Tanzania.

Provenance	Ca	K (mgg^{-1})	Mg	Na	P mgg^{-1}	Cu (µg/g)	Fe (µg/g)	Mn (µg/g)	Zn (µg/g)
Kilolo	3500±100[a]	13.4±0.36[b]	4200±120[b]	400±10[b]	6.8±0.19[a]	24.5±2.07[c]	36.6±3.06[c]	7.4±0.65[b]	28.1±2.45[b]
kongwe	3500±100[a]	11.6±0.33[c]	4700±130[a]	500±20[a]	6.6±0.74[a]	32.1±2.82[b]	47.7±4.08[b]	7.8±0.65[b]	33.0±2.87[a]
Moshi	2900±80[b]	14.0±0.39[a]	4000±110[c]	400±10[b]	6.1±0.18[b]	22.9±1.94[c]	32.3±2.74[d]	7.6±0.70[b]	26.8±2.45[b]
mwanga	2000±70[c]	0.90±0.31[d]	3400±120[d]	200±80[c]	5.7±0.20[b]	35.7±0.65[a]	60.0±2.27[a]	19.3±0.35[a]	19.9±0.45[c]
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	3.0	2.9	2.9	9.5	6.4	7.0	7.0	5.8	8.3

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. Units: Ca, Mg, Na (mg/kg)

4.3.3 Fatty acid profile of baobab seed oil according to the four provenances in Tanzania

The concentrations of individual fatty acids of baobab seed oil were compared among trees in each provenance. The ANOVA results from the intra-provenance variation are presented in Appendix 3e. Trees in Kilolo provenance varied significantly ($P < 0.05$) for palmitic, oleic, linoleic and linolenic acids but did not show any significant differences at $P < 0.05$ in stearic acid content. In Kongwe provenance trees varied significantly for seed oil stearic and linolenic acids only while in Moshi provenance statistical significant differences

were noted for linolenic acid only. It is worth noting that trees in Mwanga provenance varied significantly at $P < 0.05$ for linolenic acid only as shown in Appendix 3e. Results from the comparative assessment of baobab seed oil fatty acids profile are shown in Table 24. There were statistical significant differences ($P < 0.01$) among the provenances for palmitic, stearic, oleic and linoleic acids. However, there were no significant differences at $P < 0.05$ for seed oil linolenic acid concentration. The results further revealed that Mwanga provenance had the highest concentration of the seed oil palmitic, oleic and linolenic acid concentration. Among the fatty acids identified, oleic acid was the highest (32-37%) while linolenic acid was the least in concentration (0.87 – 1.00%). The order of fatty acid abundance in the seed oil was: Oleic > linoleic > palmitic > stearic > linolenic. Relatively low variability (CV = 5.4 – 11.2%) was recorded for oleic, linoleic and palmitic acids while a high variation (20.8 – 21.7%) was observed for stearic and linolenic acids. According to data on Table 24, the concentration of seed oil fatty acids was in the order: Oleic > linoleic > palmitic > stearic > linolenic.

Table 24: Fatty acid profile of baobab seed oil according to four provenances in Tanzania.

Provenance	Palmitic (%)	Stearic (%)	Oleic (%)	Linoleic (%)	Linolenic (%)
Kilolo	16.44±0.874^{b}	1.31±0.202^{ab}	32.13±1.733^{b}	21.09±1.066^{b}	0.99±0.161^{a}
Kongwe	15.36±0.952^{c}	1.05±0.210^{b}	32.08±1.324^{b}	21.93±0.733^{b}	0.87±0.184^{a}
Moshi	14.95±0.849^{c}	1.30±0.111^{ab}	32.62±3.578^{b}	21.99±2.802^{b}	0.99±0.197^{a}
Mwanga	19.30±0.859^{a}	1.55±0.472^{a}	37.78±4.405^{a}	26.25±4.069^{a}	1.01±0.249^{a}
P-value	< 0.001	< 0.01	< 0.001	< 0.001	NS
CV (%)	5.4	21.7	9.0	11.2	20.8

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.3.4 Vitamin C concentration of baobab fruit pulp in Tanzania

Vitamin C concentration was investigated for trees sampled within each provenance. The results (Appendix 3f) revealed the existence of statistical significant differences ($P < 0.001$) among trees for vitamin C content within each provenance. Reported values for vitamin C ranged from 1.86 mg/g (lowest) in a tree at Kilolo to 5.33 mg/g (highest) in another at Moshi rural provenance. Further analyses conducted on fruits from the same tree in Mwanga provenance showed that vitamin C content did not vary significantly ($P < 0.05$) within a tree. Results presented in Table 25 for inter-provenance comparison revealed

statistical significant differences ($P < 0.001$) between the provenances for vitamin C concentration. Moshi rural provenance had the highest mean pulp vitamin C content while the least was recorded in Kilolo provenance.

Table 25: Vitamin C concentration of baobab fruit pulp according to four provenances in Tanzania.

Provenance	Vitamin C (mg/g)
Kilolo	3.14 ± 0.26^{c}
Kongwe	3.71 ± 0.25^{b}
Moshi rural	3.91 ± 0.23^{a}
Mwanga	3.59 ± 0.31^{b}
P-value	< 0.001
CV (%)	8.7

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.4 Biochemical composition of baobab fruit pulp and seeds in Mali

4.4.1 Proximate composition of baobab fruit pulp and seeds according to four provenances in Mali

In each of the study provenances in Mali, comparisons were conducted among the sampled trees for pulp macronutrient content. The ANOVA results from the intra-provenance investigations were presented in Appendix 4a. Results revealed that in Mopti, Sikasso and Kayes provenances, there were statistical significant differences ($P < 0.05$) among the trees for pulp moisture and crude protein content but no significant differences at were observed for ash and crude fibre. In Seguo provenance, there were statistical significant differences ($P < 0.05$) among the trees for pulp moisture, crude protein and ash content but significant differences were not recorded for crude fibre. From the ANOVA results (Table 26), it was noted that there were statistical significant differences ($P < 0.05$) between the provenances for moisture, crude protein, crude fibre and ash content. It was noticed that Mopti had the highest crude protein and the lowest mean moisture content. Pulp moisture and crude protein had low (CV=0.5 – 4.1%) variability while crude fibre and ash had the highest (CV=10.6 – 13.8%) variation.

Table 26: Fruit pulp proximate composition according to four provenances in Mali.

Provenance	Moisture (g/100 g dw)	Crude protein (g 100 g^{-1} dw)	Crude fibre (g 100 g^{-1} dw)	Ash (g 100 g^{-1} dw)
Mopti	9.57 ± 0.070^{b}	1.97 ± 0.053^{a}	6.35 ± 0.940^{b}	3.40 ± 0.586^{b}
Sikasso	9.89 ± 0.016^{a}	1.86 ± 0.033^{b}	6.63 ± 0.451^{ab}	3.97 ± 0.765^{a}
Kayes	9.94 ± 0.038^{a}	1.73 ± 0.090^{c}	6.52 ± 0.482^{ab}	3.86 ± 0.383^{ab}
Seguo	9.88 ± 0.057^{a}	1.87 ± 0.108^{b}	7.25 ± 0.799^{a}	4.21 ± 0.181^{a}
P-value	< 0.001	< 0.001	< 0.05	< 0.01
CV (%)	0.5	4.1	10.6	13.8

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

Seed proximate composition was compared for trees within each study provenance in Mali. Trees within Sikasso and Mopti provenances varied significantly ($P < 0.05$) in seed moisture, ash, protein, fibre, fat and carbohydrate concentration as shown in Appendix 4b. In Kayes provenance trees varied significantly ($P < 0.05$) in pulp macronutrients but with the exception of crude protein. Trees in Seguo provenance varied significantly in seed macronutrients though with the exception of fat content.

From the results of ANOVA performed (Table 27), it was noted that there were statistical significant differences ($P < 0.05$) among the provenances for all the seed proximate components. It is worth noting that among the provenances, Sikasso had the highest mean seed moisture and ash content while Seguo had the highest mean fibre and carbohydrate content. At provenance level, the mean seed moisture content varied from 5.50 g 100 g^{-1} (Mopti) to 5.86 g 100 g^{-1} (Sikasso). According to Table 27, the seed proximate components were present in the order: Carbohydrates > fibers > proteins > fat > moisture > ash. There was low variation (Table 27) between the provenances for the investigated parameters.

Table 27: Baobab seed proximate composition according to four provenances in Mali.

Provenance	Moisture (g/100g)	Crude protein g/100g dw	Crude fibre g/100g dw	Crude fat g/100g dw	Carbohydrate g/100g dw	Ash g/100g dw
Mopti	5.51±0.15^{c}	13.09±0.34^{a}	23.99±0.23^{b}	11.43±0.30^{b}	65.82±0.55^{b}	4.14±0.12^{b}
Sikasso	5.86±0.06^{a}	12.93±0.67^{a}	23.20±0.21^{c}	11.98±0.4^{ab}	64.83±0.68^{bc}	4.39±0.14^{a}
Kayes	5.58±0.08^{c}	13.66±1.03^{a}	23.05±0.31^{c}	12.36±0.52^{a}	64.50±0.89^{c}	3.89±0.20^{c}
Seguo	5.71±0.04^{b}	11.21±0.97^{b}	24.63±0.35^{a}	11.45±1.35^{b}	67.44±1.49^{a}	4.19±0.17^{b}
P-value	< 0.001	< 0.001	< 0.001	< 0.05	< 0.001	< 0.001
CV (%)	1.6	6.2	1.2	6.4	1.5	3.8

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different.

4.4.2 Concentration of selected macro and micro elements of baobab fruit pulp and seeds

The concentration of selected macro and micro elements of baobab fruit pulp were investigated within each provenance. Results were presented in Appendix 4c. Trees in Mopti provenance exhibited statistical significant differences ($P < 0.05$) in the pulp elemental concentration but with the exception of sodium. In Sikasso provenance, statistical significant differences were noted for the pulp elements but no significant differences were noted for sodium and copper content. In Kayes provenance, the trees significantly ($P < 0.05$) varied in pulp calcium, potassium and magnesium levels but there were no significant differences at $P < 0.05$ for pulp sodium, phosphorus and the microelements concentration. Trees in Seguo provenance showed statistical significant differences in most of the elements but they did not vary significantly for pulp phosphorus content.

Results on selected macro and micro elements of fruit pulp (Table 28) showed that there were statistical significant differences ($P < 0.01$) among the provenances for most of the elements except iron. Pulp calcium levels ranged from 1800 $mgkg^{-1}$ in Mopti to 2900 $mgkg^{-1}$ in Kayes. Kayes provenance had the highest mean magnesium and zinc content while Seguo provenance had the highest mean potassium content. Mopti provenance had the lowest recorded values for mean pulp calcium, potassium and magnesium content. According to Table 28, the concentration of the selected elements was in the order: K > Ca > Mg > P > Na > Cu > Zn > Fe > Mn. For the pulp macro elements, there existed low to moderate variation

between the provenances (CV= 5.8 – 13.5%) but a relatively high variation (CV= 9.6 – 25.4%) was noted for the micro elements.

Table 28: Concentration of selected macro and micro elements of baobab fruit pulp according to four provenances in Mali.

Provenance	Ca $mgkg^{-1}$	K mgg^{-1}	Mg $mgkg^{-1}$	Na mg/kg	P mg/kg	Cu (µg/g)	Fe (µg/g)	Mn (µg/g)	Zn (µg/g)
Mopti	1800±70^{c}	13.8±0.40^{b}	1200±30^{d}	400±80^{b}	800±40^{a}	56.5±3.32^{a}	12.8±0.84^{a}	4.4±0.38^{b}	23.5±1.33^{c}
Sikasso	2500±80^{b}	13.3±0.40^{b}	1500±50^{c}	600±80^{a}	800±30^{a}	44.8±2.64^{b}	13.1±0.84^{a}	3.8±0.53^{b}	22.3±1.31^{c}
Kayes	3000±360^{a}	13.7±1.53^{b}	1900±100^{a}	600±90^{a}	700±90^{b}	58.7±9.71^{a}	14.7±6.92^{a}	14.0±3.84^{a}	35.5±7.24^{a}
Seguo	2900±90^{a}	15.6±0.50^{a}	1700±70^{b}	600±20^{a}	800±40^{a}	53.3±1.53^{a}	12.0±0.56^{a}	13.0±0.56^{a}	30.0±0.84^{b}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.01	< 0.001	NS	< 0.001	< 0.001
CV (%)	7.4	5.8	4.1	13.5	6.4	9.6	25.4	21.5	13.0

For the same column, means followed by the same letter are not significantly different. cv: coefficient of variation

Comparative assessment of macro and micro element concentration of baobab seeds was conducted within the provenances in Mali (Appendix 4d). The trees in Mopti, Sikasso and Kayes provenances varied significantly at $P < 0.05$ for seed element concentration though they did not show significant differences in copper and manganese levels. In Seguo provenance, there were statistical significant differences ($P < 0.05$) among the trees for macro and micro element concentration. However, the trees in Seguo did not vary significantly for seed potassium content as shown in Appendix 4d.

Our results for the seed element concentration (Table 29) showed that there existed statistical significant differences among the provenances for both macro and micro elements. Seed calcium levels varied from 2400 $mgkg^{-1}$ in Mopti to 2700 $mgkg^{-1}$ in Sikasso Kayes. Among the four provenances, Sikasso had the highest mean phosphorus level while Kayes had the lowest sodium content. The highest mean Iron, copper and zinc concentrations were recorded in Seguo provenance. According to Table 29, the order of seed macro and micro

elements was: K > P > Mg > Ca > Na > Cu > Zn > Mn > Fe. Among the provenances, there existed very low variation (CV=3.0 – 5.5) for the elements except for potassium (CV=26.8%).

Table 29: Concentration of selected macro and micro elements of baobab seeds according to four provenances in Mali.

Provenance	Ca (mgkg^{-1})	K (mgg^{-1})	Mg (mgkg^{-1})	Na (mgkg^{-1})	P (mgg^{-1})	Cu (µg/g)	Fe (µg/g)	Mn (µg/g)	Zn (µg/g)
Mopti	2400±70^{c}	10.9±0.32^{a}	3800±110^{ab}	300±10^{b}	5.9±0.17^{c}	37.0±2.07^{bc}	24.4±1.60^{b}	23.0±1.41^{b}	26.2±1.53^{c}
Sikasso	2700±80^{a}	9.4±0.27^{a}	4000±330^{a}	300±10^{b}	6.8±0.20^{a}	35.4±2.03^{c}	24.2±1.71^{b}	24.6±1.33^{a}	26.0±1.39^{c}
Kayes	2700±80^{a}	9.6±0.27^{a}	3700±110^{b}	400±10^{a}	5.5±0.16^{d}	38.5±2.25^{b}	17.9±0.86^{c}	23.5±1.29^{ab}	30.1±1.68^{b}
Seguo	2600±80^{b}	6.5±4.76^{b}	3500±100^{c}	200±10^{c}	6.1±0.20^{b}	52.7±1.94^{a}	35.7±1.25^{a}	24.0±0.92^{ab}	42.6±1.58^{a}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.05	< 0.001
CV (%)	3.0	26.8	5.1	3.0	3.0	5.1	5.5	5.3	4.9

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. cv: coefficient of variation

4.4.3 Fatty acid profile of baobab seed oil across four provenances in Mali

The fatty acid content of baobab seed oil was compared among trees within each study provenance (Appendix 4e). In Mopti provenance trees varied significantly at $P < 0.05$ for seed oil palmitic and oleic acids but did not show significant differences in stearic, linoleic and linolenic acid content. Trees in Sikasso showed significant differences only for palmitic and linolenic acids while in Kayes statistical significant differences ($P < 0.05$) existed among the trees for mean palmitic, linoleic and linolenic acid concentration as shown in Appendix 4e. In Seguo provenance, baobab trees varied significantly for palmitic, oleic, linoleic and linolenic acid concentrations only. Results (Table 30) of the inter-provenance comparison on fatty acids concentration of baobab seed oils from Mali showed that there were no statistical significant differences ($P < 0.05$) among the provenances for palmitic, linoleic and linolenic. However there were significant differences ($P < 0.05$) among the provenances for seed oil stearic oleic acid content. The fatty acids were present in the order: Oleic > linoleic > palmitic > stearic > linolenic. There was low to high variation (CV=3.7 – 15.4%) among the provenances for seed oil fatty acid content.

Table 30: Baobab seed oil fatty acid profile according to four provenances in Mali.

Provenance	Palmitic (%)	Stearic (%)	Oleic (%)	Linoleic (%)	Linolenic (%)
Mopti	17.70 ± 0.920^{a}	1.37 ± 0.175^{b}	33.93 ± 1.156^{a}	21.80 ± 2.813^{a}	0.88 ± 0.145^{a}
Sikasso	17.90 ± 1.749^{a}	1.55 ± 0.087^{a}	32.09 ± 1.462^{b}	21.56 ± 1.183^{a}	0.89 ± 0.187^{a}
Kayes	17.08 ± 2.084^{a}	1.49 ± 0.166^{ab}	32.38 ± 1.067^{b}	22.23 ± 2.202^{a}	0.96 ± 0.131^{a}
Seguo	17.74 ± 0.413^{a}	1.52 ± 0.155^{ab}	33.14 ± 1.183^{ab}	22.74 ± 0.970^{a}	0.87 ± 0.064^{a}
P-value	NS	< 0.05	< 0.01	NS	NS
cv	8.1	10.1	3.7	8.8	15.4

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different.

4.4.4 Vitamin C concentration of baobab fruit pulp from Mali

The vitamin C concentration of baobab fruits from sampled trees was compared among trees within each provenance. Results presented in Appendix 4f revealed the existence of significant variation among trees of the same provenances for Vitamin C concentration. Trees

within each provenance varied significantly ($P < 0.05$) in the mean vitamin C level. At tree level, vitamin C ranged from 1.71 mgg^{-1} (Kayes) to 5.81 mgg^{-1} (Mopti). Further analyses conducted showed that fruits from the same tree (intra-tree) did not vary significantly ($P < 0.05$) in the mean vitamin C content. Fruit pulp vitamin C concentration was compared among the four provenances (inter-provenance) in Mali. Results (Table 31) revealed that there existed statistical significant differences ($P < 0.001$) among the provenances for vitamin C concentration. Mopti provenance had the highest mean vitamin C level. Variability between the provenances was high (CV=18.8%) for vitamin C concentration.

Table 31: Baobab fruit pulp vitamin C concentration according to four provenances in Mali.

Provenance	Vitamin C (mg/g)
Mopti	4.02 ± 0.556^{a}
Sikasso	3.13 ± 0.485^{b}
Kayes	2.98 ± 0.577^{b}
Seguo	2.73 ± 0.394^{b}
P-value	< 0.001
CV (%)	18.8

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different

4.5. Biochemical composition of baobab seeds from Zimbabwe

4.5.1 Proximate composition of baobab seeds from Zimbabwe

The concentrations of seed macronutrient content were compared among the trees within each provenance. In FRC, there were statistical significant differences ($P < 0.05$) among the trees for crude protein, crude fibre, carbohydrates, ash and moisture content as shown in Appendix 5a. However, the crude fat content did not vary significantly among the trees. In Hwange provenance, trees varied significantly in crude fibre, carbohydrates ash and moisture content but there were no statistical significant differences ($P < 0.05$) in crude protein and crude fat content.

Results (Table 32) of proximate composition of baobab seeds showed that there were statistical significant differences ($P < 0.05$) between the two provenances for crude fat, carbohydrates and ash. However, there were no statistical significant differences between the

provenances for moisture, crude protein and crude fibre. According to Table 32, the seed macronutrients were in the order: carbohydrates > fibers > proteins > fat.

Table 32: Proximate composition of baobab seeds according to two provenances in Zimbabwe.

Provenance	Moisture (g/100g)	Protein g/100g dw	Fibre g/100g dw	Fat g/100g dw)	Carbohydrates g/100g dw	Ash g/100g dw
FRC	5.92±0.144	14.98±0.423	22.55±0.598	12.88±0.236	62.26±0.596	3.96±0.21
Hwange	5.85±0.140	13.92±0.469	21.81±0.385	11.48± .510	65.76±0.929	3.00±0.16
P - summary	ns	ns	ns	*	**	***

Values are means ± S.E.M. *P* -summary within column; $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$, ns; Not significant.

4.5.2 Concentration of selected macro and micro elements in baobab seeds from Zimbabwe

Seed macro and micro element composition was compared among trees in both FRC and Hwange provenances. Within each provenance, there were statistical significant differences ($P < 0.05$) among the trees for seed calcium, potassium, magnesium, phosphorus, copper, iron, manganese and zinc concentrations. However, there were no statistical significant differences among the trees for sodium concentration.T-test results (Table 33) showed that there were statistical significant differences ($P > 0.05$) between the two provenances for magnesium and phosphorus. But there were no significant differences between the provenances at $P < 0.05$ for calcium, potassium, sodium, copper, manganese and zinc. According to their concentrations (Table 33), the seed elements were in the order: K > P > Mg > Ca > Na > Fe > Cu > Zn > Mn.

Table 33: Concentration of selected macro and micro elements in baobab seeds according to two provenances in Zimbabwe.

Provenance	Ca ($mgkg^{-1}$)	K (mgg^{-1})	Mg ($mgkg^{-1}$)	Na ($mgkg^{-1}$)	P (mgg^{-1})	Cu (µg/g)	Fe (µg/g)	Mn (µg/g)	Zn (µg/g)
FRC	2500 ± 100	9.0 ± 0.17	3300 ± 70	200 ± 10	6.1 ± 0.2	33.9 ± 2.79	56.4 ± 1.80	19.2 ± 0.585	22.6 ± 3.64
Hwange	2200 ± 120	8.6 ± 0.14	2900 ± 60	200 ± 10	5.0 ± 0.1	31.1 ± 1.44	60.3 ± 4.63	20.5 ± 0.618	15.2 ± 1.05
p-summary	ns	ns	***	ns	**	ns	ns	ns	ns

Values are means ± S.E.M. *P* -summary within column; *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001, ns; Not significant.

4.5.3 Fatty acid profile of baobab seeds from Zimbabwe

Baobab seed oil fatty acid content was compared among the trees in each provenance. Baobab trees in both provenances showed statistical significant differences (*P* < 0.05) for palmitic and oleic acid content as shown in Appendix 5c. However, in both provenances there were no significant differences among the trees for stearic, linoleic and linolenic acids. The fatty acid concentrations were also compared between two provenances in Zimbabwe (Table 34). It was noted that there were no statistical significant differences (*P* < 0.05) between the two provenances for all the identified fatty acids. According to their concentrations as shown in Table 34, the order was oleic > linoleic > palmitic > stearic > linolenic.

Table 34: Baobab seed fatty acid profile according to two provenances of Zimbabwe.

Provenance	Palmitic acid (%)	Stearic acid (%)	Oleic acid (%)	Linoleic acid (%)	Linolenic acid (%)
FRC	21.82± 0.561	1.42 ± 0.092	34.13 ± 0.884	23.67 ± 0.664	0.87 ± 0.067
Hwange	22.87± 0.944	1.50 ± 0.082	33.29 ± 1.492	25.06 ± 0.987	0.86 ± 0.053
P - summary	ns	ns	ns	ns	ns

Values are means ± S.E.M *P*-summary; *, *P* < 0.05; **, *P* < 0.01; ***, *P* < 0.001, ns: Not significant.

4.6 Biochemical composition of baobab fruit pulp and seeds in Malawi

4.6.1 Proximate composition of fruit pulp and seeds

In the Mangochi provenance, there were statistical significant differences (*P* < 0.001) among the trees for pulp moisture, crude protein, crude fibre and ash content as shown in Appendix 6a. The pulp moisture content ranged between 8.17 g/100 g in one tree to 9.42 g/100g in another tree. Crude protein varied almost twice from 1.28 g 100 g^{-1} dw to 3.02 g 100 g^{-1} dw. For crude fibre content, the lowest recorded value was 6.16 g 100 g^{-1} dw while the highest value was 8.43 g 100 g^{-1} dw. Pulp ash content ranged between 3.42 g 100 g^{-1} dw to 5.22 g 100 g^{-1} dw. The range in values for the proximate composition are shown in Table 35.The variation among these trees was very low (CV=0.8 – 2.0%) for the proximate components.

Regarding seed proximate composition, there were statistical significant differences ($P < 0.01$) among the trees for moisture, crude protein, crude fibre, crude fat and ash content as shown in Appendix 6a. However, there were no significant differences among the trees for seed carbohydrate. The seed moisture and ash content varied from 5.18 g 100 g^{-1} dw to 6.28 g 100 g^{-1} dw and 3.77 g 100 g^{-1} dw to 4.73 g 100 g^{-1} dw respectively. Seed fat levels ranged from 11.05 g 100 g^{-1} dw to 14.04 g 100 g^{-1} dw while the crude protein content varied from 13.46 g 100 g^{-1} dw to 16.19 g 100 g^{-1} dw as shown in Table 35. The proximate components were present in the following order: Carbohydrates > fibre > protein > fat > moisture > ash. There was very low variation (CV=0.6- 2.6%) among the trees for the seed proximate composition.

Table 35: Range in values (lowest-highest) of the proximate composition among the sampled trees in Mangochi provenance.

Baobab part	Moisture (g 100 g^{-1} fw)	Crude protein*	Crude fibre*	Crude fat*	Ash*	CHO*	Vitamin C (mgg^{-1})
Pulp	8.17-9.42	1.28-3.02	6.16-8.43	NA	3.42-5.22	NA	1.89-4.30
Seed	5.18-6.28	13.46-16.19	22.08-24-83	11.05-14.05	3.77-4.73	60.73-63.49	NA

*: g 100 g^{-1} dw, CHO: Carbohydrate

Table 36: Range in values (lowest-highest) of the elemental composition among the sampled trees in Mangochi provenance.

Baobab part	Ca ($mgkg^{-1}$)	K (mgg^{-1})	Mg ($mgkg^{-1}$)	Na ($mgkg^{-1}$)	P ($mgkg^{-1}$)	Cu (μgg^{-1})	Fe (μgg^{-1})	Mn (μgg^{-1})	Zn (μgg^{-1})
Pulp	3500-4900	19.8-24.3	1800-2700	830-1060	950-1300	26-33	25-30	16-19	20-30
Seeds	2600-3900	9.3-11.8	4000-4400	560-690	5200-6800	28-34	41-54	6-11	27-38

Table 37: Range in values (lowest-highest) of the elemental composition among the sampled trees in Mangochi provenance.

Baobab part	Palmitic (%)	Stearic (%)	Oleic (%)	Linoleic (%)	Linolenic (%)
Seed	17.94-22.32	1.03-1.94	25.30-41.76	20.17-29.13	0.60-0.89

4.6.2 Concentration of selected macro and micro elements of the fruit pulp and seeds

In Mangochi, there were statistical significant differences ($P < 0.001$) among the trees for pulp calcium, potassium, magnesium, sodium, phosphorus and zinc concentration. However, there were no significant differences among the trees for copper, iron and manganese concentration as shown in Appendix 6b. The order of element accumulation was: K > Ca > Mg > P > Na > Cu > Fe > Zn > Mn. Pulp calcium levels ranged between 3500 $mgkg^{-1}$ to 4900 $mgkg^{-1}$ while the potassium content varied from 19.8 mgg^{-1} to 24.3 mgg^{-1} as shown in Table 36. Pulp zinc concentration ranged between 20 μgg^{-1} and 30 μgg^{-1}. Zinc concentration was the lowest in the pulp and varied from 15 μgg^{-1} to 18 μgg^{-1}. There was minimal variation (CV= 2.8 -2.9%) among the trees for the macro elements but a slightly high variation (CV=4.9 – 9.2%) was noted for the micro elements.

For the seeds, there were significant differences ($P < 0.05$) among the trees for calcium, potassium, phosphorus, manganese, iron and zinc as presented in Appendix 6b. However, there were no significant differences among the trees for magnesium, sodium and copper concentration in the seed. Seed phosphorus concentrations ranged between 5.1 mgg^{-1} and 6.2 mgg^{-1} while the potassium concentrations varied from 7.1 mgg^{-1} to 9.8 mgg^{-1}. The lowest levels were of manganese and they ranged between 6.5 μgg^{-1} and 10.5 μgg^{-1}. The range of values for the mineral content are presented in Table 36. Low variation (CV=2.5-2.8%) was noted among the trees for the macro elements while a relatively high variation (CV=7.9-10.5%) was recorded for the micro-elements.

4.6.3 Vitamin C concentration of baobab fruits

About two or three fruits within each tree were investigated for vitamin C to establish intra-tree variation. The results revealed that there were no statistical significant differences ($P < 0.05$) between fruits of the same tree for vitamin C concentration. However, there were statistical significant differences ($P < 0.001$) between trees in Mangochi provenance for vitamin C

concentration (Appendix 6c). Vitamin C levels ranged from 1.89 mgg^{-1} to 4.30 mgg^{-1} among trees within the provenance as shown above in Table 35. The variability among the trees for pulp vitamin C was moderate (CV=10.5%).

4.6.4 Fatty acid profile of baobab seed oil

Within Mangochi provenance, there were statistical significant differences ($P < 0.05$) among the trees for palmitic, stearic and oleic acids as shown in Appendix 6d. However, there were no significant differences among the trees for linoleic and linolenic acid concentration. For palmitic, stearic, oleic, linoleic and linolenic acid the concentrations ranged between 17.94-22.32; 1.03-1.94; 25.20-41.76; 20.17-29.13 and 0.60-0.89% respectively as presented in Table 37. The order of fatty acid accumulation was: Oleic > linoleic > palmitic > stearic > linolenic.

4.7 Biochemical composition of baobab fruit pulp and seeds according to selected countries

4.7.1 Baobab fruit pulp proximate composition

The content of crude protein, moisture, crude fibre and ash from the study countries was reported in Table 38. There were statistical significant differences ($P < 0.001$) among the countries for pulp moisture, crude protein, crude fibre and ash content. Baobab fruit pulp from Kenya and Mali had the highest moisture content at 9.82 g and 9.81 $g100^{-1}$ g respectively whilst that from Zambia and Malawi (though not significantly different from each other) had the lowest content of 8.89 g and 8.94 $g100^{-1}$ g respectively. For crude fibre, the highest content of 8.83 g 100 g^{-1} dw was found in pulp from Kenya. At provenance level (Appendix 7), Siavonga had the highest (2.65 $g100^{-1}$ g) mean crude protein content while Kayes and Kongwe had the lowest content at 1.73 g and 1.57 $g100^{-1}$ g respectively. The pulp moisture content was high in East and West African provenances but significantly lower in Southern Africa provenances as presented in Appendix 7. Mopti in Mali had the lowest ash content while Malindi, Kibwezi and Taita had the highest pulp fibre content. The variability among the countries was extremely low for moisture (CV=1.7%) but relatively high for crude protein, crude fibre and ash content (CV=6-15%).

Table 38: Baobab fruit pulp proximate composition according to five countries in Africa.

Country	Moisture (g 100 g^{-1})	Crude protein (g 100 g^{-1} dw)	Crude fibre (g 100 g^{-1} dw)	Ash (g 100 g^{-1} dw)
Tanzania	9.24 ± 0.281^{b}	1.99 ± 0.132^{b}	6.92 ± 0.737^{b}	4.38 ± 0.125^{a}
Zambia	8.89 ± 0.061^{c}	2.24 ± 0.116^{a}	7.09 ± 0.723^{b}	4.34 ± 0.102^{a}
Kenya	9.82 ± 0.028^{a}	2.20 ± 0.220^{a}	8.83 ± 2.564^{a}	4.41 ± 0.108^{a}
Malawi	8.94 ± 0.071^{c}	1.91 ± 0.039^{bc}	7.27 ± 0.083^{b}	4.40 ± 0.054^{a}
Mali	9.81 ± 0.050^{a}	1.86 ± 0.077^{c}	6.69 ± 0.706^{b}	3.86 ± 0.531^{b}
P-value	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	1.7	6.2	15.6	7.1

Values (means ± S.E.M) followed by the same letter are not significantly different.

A comparative assessment was conducted for baobab seeds proximate composition across six African countries. The results (Table 39) revealed that there were statistical significant differences ($P < 0.001$) among the six countries for the seed proximate composition. Kenya had the highest (7.00 g 100^{-1} g) seed moisture content whereas Mali had the lowest mean (5.66 g 100^{-1} g) seed moisture content. The mean crude protein content was lowest (12.69 g 100 g^{-1} dw) in Mali while Zimbabwe had the lowest seed fibre content. At provenance level, Malindi had the highest (7.04 g 100^{-1} g) seed moisture content though it was not significantly ($P < 0.05$) different from Taita, Kibwezi, Kongwe, Moshi and Kilolo (Appendix 8). Mean crude protein content ranged between 11.21 g (Seguo) to 16.02 g 100^{-1} g (Kilolo). However, Kilolo provenance was not significantly different from Taita, Mwanga, Mangochi, Kongwe, Kibwezi and FRC. For crude fibre content, there was no specific regional trend across the provenances. According to Table 39, the seed moisture, ash and macronutrients were present in the following order: Carbohydrates > crude fibers > crude protein > crude fat > moisture > ash. Among the countries, variability was low (CV=1.8-6.6%) for all investigated macromolecules.

Table 39: Baobab seed proximate composition according to six African Countries.

Country	Moisture (g 100 g^{-1})	Protein*	Fibre*	Fat*	CHO*	Ash*
Zimbabwe	5.88±0.20^{d}	14.45±0.63^{a}	22.18±0.71^{c}	12.18±0.56^{ab}	64.01±1.10^{b}	3.48±0.26^{e}
Tanzania	6.65±0.14^{b}	14.92±0.73^{a}	23.83±0.58^{a}	12.60±0.67^{a}	61.75±0.91^{c}	4.08±0.16^{ac}
Malawi	5.90±0.12^{d}	15.18±0.39^{a}	23.56±0.13^{ab}	12.66±0.51^{a}	62.08±0.81^{c}	4.18±0.11^{a}
Zambia	6.34±0.14^{c}	13.77±0.89^{b}	22.93±0.31^{b}	11.37±0.99^{c}	64.50±1.41^{b}	4.03±0.09^{cd}
Kenya	7.01±0.06^{a}	14.43±0.36^{a}	23.31±2.84^{ab}	12.41±0.50^{a}	61.94±0.70^{c}	3.92±0.19^{d}
Mali	5.67±0.09^{e}	12.69±0.79^{c}	23.74±0.28^{a}	11.79±0.76^{bc}	65.69±0.97^{a}	4.17±0.16^{ab}
P-values	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	1.8	5.5	4.3	6.6	3.7	1.8

Values (means ± S.E.M) followed by the same letter are not significantly different. *: g/100 g dw

4.7.2 Concentration of macro and micro elements of baobab fruit pulp and seeds in selected African countries

The five countries were compared for the mean fruit pulp macro and micro elements concentration (Table 40). ANOVA results (Appendix 12) showed that there were statistical significant differences countries ($P < 0.001$) among the five countries for the concentration of all investigated elements. At country level, the mean pulp calcium levels ranged from 2500 $mgkg^{-1}$ in Mali to 4300 $mgkg^{-1}$ in Malawi. The mean pulp potassium levels varied from 14.1 mgg^{-1} in Mali to 22.2 mgg^{-1} in Malawi. Among the five countries, Kenya had the highest iron, manganese and zinc concentrations while Mali had the lowest recorded calcium, potassium, iron and manganese levels. At provenance level (Appendix 9), the mean pulp calcium levels ranged from 1800 $mgkg^{-1}$ in Mopti (Mali) to 4300 $mgkg^{-1}$ in Mangochi (Malawi). The highest pulp potassium content (25.3 mgg^{-1}) was recorded in Malindi (Kenya) while the lowest level was recorded in three provenances in Mali (Kayes (13.6 μgg^{-1}), Sikasso (13.3 μgg^{-1}) and Mopti (13.8 μgg^{-1}). Pulp iron was highest in Mwanga and Kibwezi at 64.15 μgg^{-1} and 61.50 μgg^{-1}respectively, being almost fivefold the content reported in any of the Malian provenances which ranged between 12.07 $\mu gg^{-1}$and 14.75 μgg^{-1}. According to Table 40, and with reference to most of the countries, the elements occurred in the order: K > Ca > Mg > P > Na > Cu > Fe > Zn > Mn although this pattern was challenged in some countries due to variation in micronutrient levels. There was low

variability (CV=3-8%) among the countries for the macro and micro element concentration but with the exception of sodium (CV=19.1%).

Table 40: Concentration of macro and micro elements in baobab fruit pulp according to five African countries

Count	Ca ($mgkg^{-1}$)	K (mgg^{-1})	Mg ($mgkg^{-1}$)	Na ($mgkg^{-1}$)	P ($mgkg^{-1}$)	Cu (μgg^{-1})	Fe (μgg^{-1})	Mn (μgg^{-1})	Zn (μgg^{-1})
Tanzania	3200±100^{b}	20.3±0.61^{c}	1600±100^{b}	600±70^{b}	700±50^{d}	47.7±2.4^{b}	34.0±1.5^{c}	11.9±0.9^{d}	38.6±3.9^{c}
Zamb	3200±110^{b}	20.0±0.71^{c}	1600±60^{b}	400±150^{c}	800±30^{c}	42.9±0.8^{d}	48.3±1.6^{b}	19.4±0.6^{b}	41.3±2.2^{b}
Kenya	2700±100^{c}	21.2±0.76^{b}	1300±50^{c}	500±170^{b}	600±20^{e}	45.4±0.8^{c}	57.4±2.0^{a}	27.2±0.5^{a}	71.6±2.3^{a}
Malaw	4300±120^{a}	22.2±0.64^{a}	2300±60^{a}	1000±30^{a}	1100±30^{a}	28.9±2.4^{e}	26.7±2.2^{d}	16.3±0.8^{c}	22.5±2.0^{e}
Mali	2500±190^{d}	14.1±0.81^{d}	1600±70^{b}	500±70^{b}	820±50^{b}	53.1±5.1^{a}	13.1±3.3^{e}	8.6±1.9^{e}	27.5±3.6^{d}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	4.4	3.8	4.6	19.1	5.3	6.7	6.8	8.0	8.1

For the same column, Values (means ± S.E.M) followed by the same letter are not significantly different. CV: Coefficient of variation. Count: Country, Zamb: Zambia, Malaw: Malawi.

The countries were also compared for the mean macro and micro element concentration of the seeds. The results (Appendix 13 and Table 41) showed that there were statistical significant differences ($P < 0.001$) among the six countries for all the investigated elements. Seed calcium levels ranged from 2000 $mgkg^{-1}$ in Kenya to 3200 $mgkg^{-1}$ in Malawi. Malawi had the highest calcium, magnesium and sodium content while Zimbabwe had the lowest mean magnesium, phosphorus and zinc content. Zambia had the highest seed phosphorus and copper concentration while Kenya had the lowest seed copper content. Seed iron levels were highest in Kenya (63.7 μg^{-1} g) but lowest in Mali (25.8 μg^{-1} g). At provenance level, the highest seed

potassium content was at Moshi (14.0 mgg^{-1}) and Kilolo (13.4 mgg^{-1}), being insignificantly ($P < 0.05$) different while Seguo had the lowest mean content at 6.47 mgg^{-1} (Appendix 10). Seed copper content was very low in East African provenances but high in Southern and Western Africa provenances as shown in Appendix 10.The data on Table 41 shows that the macro and micro elements accumulation at country level was: K > P > Mg > Ca > Na > Fe > Cu > Zn > Mn. The countries did not show large variability (CV=3-5%) for most of the selected macro and micro elements except for potassium and sodium, 12.3 and 14.6 % respectively.

Table 41: Concentration of macro and micro elements in baobab seeds according to six African countries.

Countr	Ca ($mgkg^{-1}$)	K (mgg^{-1})	Mg ($mgkg^{-1}$)	Na ($mgkg^{-1}$)	P (mgg^{-1})	Cu (µg/g)	Fe (µg/g)	Mn (µg/g)	Zn (µg/g)
Zimba	2300±160^{e}	8.8±0.2^{c}	3100±100^{f}	200±20^{d}	5.5±0.3^{d}	32.5±3.2^{c}	58.3±4.9^{b}	19.9±0.9^{c}	18.9±3.8^{e}
Tanzania	2900±90^{b}	12.0±0.35^{a}	4000±120^{b}	400±40^{b}	6.3±0.4^{b}	28.8±2.0^{d}	44.2±3.1^{e}	10.5±0.6^{d}	26.9±2.2^{c}
Malawi	3200±90^{a}	10.6±0.28^{b}	4200±120^{a}	600±20^{a}	5.9±0.2^{c}	30.0±3.1^{d}	46.5±3.8^{d}	8.9±0.8^{e}	33.3±2.6^{a}
Zambi	2400±90^{d}	10.4±0.36^{b}	3600±220^{d}	200±60^{d}	7.7±0.3^{a}	46.3±0.8^{a}	51.0±1.8^{c}	22.4±0.4^{b}	31.9±1.1^{ab}
Kenya	2000±70^{f}	9.1±0.31^{c}	3300±120^{e}	190±60^{e}	6.0±0.2^{c}	27.5±0.6^{e}	63.7±2.3^{a}	20.1±0.6^{c}	21.8±0.8^{d}
Mali	2600±80^{c}	9.0±0.24^{c}	3800±190^{c}	300±10^{c}	6.1±0.2^{c}	41.0±2.1^{b}	25.8±1.4^{f}	23.8±1.3^{a}	31.3±1.5^{b}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	3.2	12.3	4.4	14.6	4.4	4.8	5.2	4.3	5.9

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. Countr: Country, Zimba: Zimbabwe, Malaw: Malawi, Zambi: Zambia

4.7.3 Principal Component Analyses

A principal component analysis was performed on the correlation matrix to describe the elemental characteristics of each baobab tissue among the study countries and the relationships between the elements. Table 42 presents the relationships between the elements for the fruit pulp.

Table 42: Correlation matrix (Pearson (n)) for the elemental composition of fruit pulp.

Variables	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Ca	1	0.667	0.907	0.853	0.768	-0.940	-0.101	-0.001	-0.492
K	0.667	1	0.300	0.322	0.067	-0.741	0.629	0.637	0.303
Mg	0.907	0.300	1	0.919	0.963	-0.820	-0.453	-0.298	-0.773
Na	0.853	0.322	0.919	1	0.845	-0.799	-0.487	-0.248	-0.652
P	0.768	0.067	0.963	0.845	1	-0.692	-0.573	-0.399	-0.850
Cu	-0.940	-0.741	-0.820	-0.799	-0.692	1	-0.093	-0.284	0.273
Fe	-0.101	0.629	-0.453	-0.487	-0.573	-0.093	1	0.909	0.855
Mn	-0.001	0.637	-0.298	-0.248	-0.399	-0.284	0.909	1	0.819
Zn	-0.492	0.303	-0.773	-0.652	-0.850	0.273	0.855	0.819	1

The results revealed that the macro elements (Ca, K, Mg, Na and P) were positively correlated with each other but negatively correlated with the micro elements (Cu, Fe, Mn and Zn). For the micro elements, only zinc was positively correlated to copper, iron and manganese. The first two components extracted from the PCA conducted on the fruit pulp explained 94.81% of the general information of the elemental concentration. Table 43 presents the eigenvalues from the PCA from which we retained factor 1 and 2 which showed high eigenvalues and accounted for over 94% of the variability.

Table 43: Eigenvalues and cumulative variability for the principal components.

	F1	F2	F3	F4
Eigenvalue	5.316	3.217	0.259	0.208
Variability (%)	59.064	35.742	2.879	2.315
Cumulative %	59.064	94.806	97.685	100.000

Table 44 presents the correlations between the principal components and the fruit pulp elements and also between them and the countries. On the first axis all the macro elements (Ca,

K, Mg, Na, P) showed positive correlations whereas the micro elements (Cu, Fe, Mn, Zn) showed negative correlations with the axis. These two groups of elements revealed opposite trends and such results could be explained by the fact that the pulp elemental concentration may be affected by environmental factors and soil characteristics, thus opposite sensitivity to those factors. It is evident that calcium, magnesium, sodium and phosphorus were highly positively correlated with axis 1/factor 1 whereas potassium, iron and manganese were highly positively correlated with axis 2/factor 2. Correlation between factor 1 (Axis 1) and the countries helped to link the elemental concentration of baobab fruit pulp to the countries. We noticed from Table 44 that Malawi was positively correlated with axis 1 and axis 2. Therefore, Malawi and the pulp macro elements were positively correlated with axis 1. The other countries showed negative correlations with the first axis. Links between the countries and elemental concentration of baobab fruit pulp were described by projecting the different elements and countries in the axis system defined by the two principal components. Figure 6 indicated that baobab fruit pulp from Malawi exhibited relatively higher potassium, calcium, sodium and magnesium than baobabs in other countries whereas pulp from Kenya exhibited significantly higher iron, manganese and zinc content than the other countries. The biplot further demonstrated that pulp from Mali contained significantly high copper content which is similar to the results from Table 40.

Table 44: Correlations between the principal components related to the elemental characteristics of baobab fruit pulp and the countries

Parameters	Axis 1	Axis 2
Ca	0.870	0.462
K	0.220	0.935
Mg	0.990	0.104
Na	0.938	0.127
P	0.959	-0.084
Cu	-0.757	-0.646
Fe	-0.558	0.804
Mn	-0.403	0.865
Zn	-0.827	0.533
Correlations between the two axes and the countries		
Kenya	-2.977	1.912

Tanzania	-0.403	-0.486
Zambia	-0.476	0.636
Malawi	4.152	1.167
Mali	-0.295	-3.229

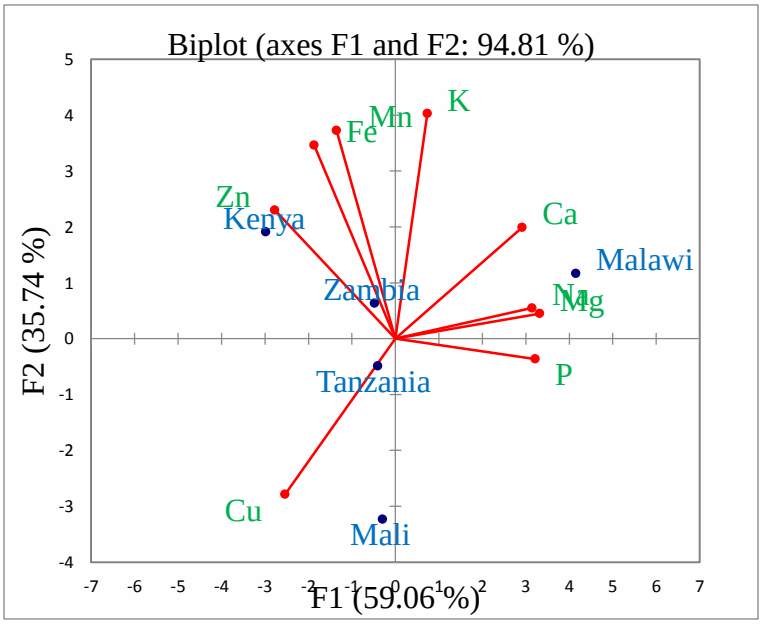

Figure 6: Biplot showing the relationship between the fruit pulp elements and the countries.

PCA was also conducted on the elemental concentration of baobab seeds to establish the relationships between them and to link them to the study countries. Table 45 presents the correlation matrix of baobab elemental composition.

Table 45: Correlation matrix (Pearson (n)) of the elemental concentration of baobab seeds across the study countries

Variables	Ca	K	Mg	Na	P	Cu	Fe	M	Zn
Ca	1	0.724	0.912	0.983	-0.067	-0.122	-0.508	-0.770	0.658
K	0.724	1	0.811	0.619	0.368	-0.028	-0.411	-0.635	0.564
Mg	0.912	0.811	1	0.883	0.145	-0.033	-0.592	-0.661	0.817
Na	0.983	0.619	0.883	1	-0.177	-0.221	-0.424	-0.803	0.614
P	-0.067	0.368	0.145	-0.177	1	0.720	-0.080	0.266	0.520
Cu	-0.122	-0.028	-0.033	-0.221	0.720	1	-0.431	0.646	0.496
Fe	-0.508	-0.411	-0.592	-0.424	-0.080	-0.431	1	-0.070	-0.642
Mn	-0.770	-0.635	-0.661	-0.803	0.266	0.646	-0.070	1	-0.191
Zn	0.658	0.564	0.817	0.614	0.520	0.496	-0.642	-0.191	1

Data presented on Table 45 indicated that the macro elements of baobab seeds were positively correlated with each other but phosphorus showed negative correlations with calcium and sodium. Further, the macro elements were negatively correlated with the micro elements except for zinc which exhibited positive correlation with Ca, K, Mg, Na & P. For the seed micro elements only iron showed negative correlations with copper, manganese and zinc. The first two principal components of the PCA which was conducted on the correlation matrix accounted for 83.22% of the variability. Table 46 presents the eigenvalues and cumulative variability generated by the PCA on the seeds elements. From the analysis we retained factor 1 (F1) and factor 2 (F2) which had the highest eigenvalues.

Table 46: Eigenvalues and cumulative variability expressed by the principal components.

	F1	F2	F3	F4	F5
Eigenvalue	4.896	2.593	0.957	0.394	0.159
Variability (%)	54.403	28.812	10.635	4.380	1.770
Cumulative %	54.403	83.215	93.850	98.230	100.000

Table 47 presents the correlations between the principal components related to the variables and the countries. According to the table, it is evident that the seed macro elements were positively correlated with axis 1/factor 1. Calcium, potassium, magnesium, sodium and zinc were strongly positively correlated with axis 1 whereas iron and manganese were strongly negatively correlated with the same axis. Phosphorus, copper and manganese were strongly positively correlated with axis 2. For the countries, Malawi and Tanzania were strongly positively correlated with axis 1 whereas Kenya and Zimbabwe were strongly negatively correlated with the same axis. Figure 7 presents the biplot showing the relationships between the elements of baobab seeds and the study countries. From figure 7, it can be deduced that elements and countries that fell in the same quadrant were strongly correlated. For instance, copper and manganese were highest in Zambia whereas iron was significantly high in Kenya and Zimbabwe. The relationships between countries and the elements were further revealed. For this case, countries and elements that fell in opposite quadrants indicated that such countries had low concentration of the elements. For instance, Mali and iron fell in opposite quadrants which meant that seeds from Mali contained very low concentration of iron. Such information is similar to the data presented on Table 41.

Table 47: Correlations between the principal components related to the elemental characteristics of baobab seeds and the countries.

Parameters	F1 (Axis 1)	F2 (Axis 2)
Ca	0.964	-0.156
K	0.831	0.069
Mg	0.983	0.037
Na	0.926	-0.263
P	0.118	0.799
Cu	-0.030	0.964
Fe	-0.578	-0.461
Mn	-0.708	0.644
Zn	0.777	0.547
Correlations between the two axes and the countries		
Kenya	-2.771	-1.036
Tanzania	2.148	-0.951
Zambia	-0.361	2.780

Malawi	3.128	-1.240
Zimbabwe	-2.633	-1.228
Mali	0.489	1.675

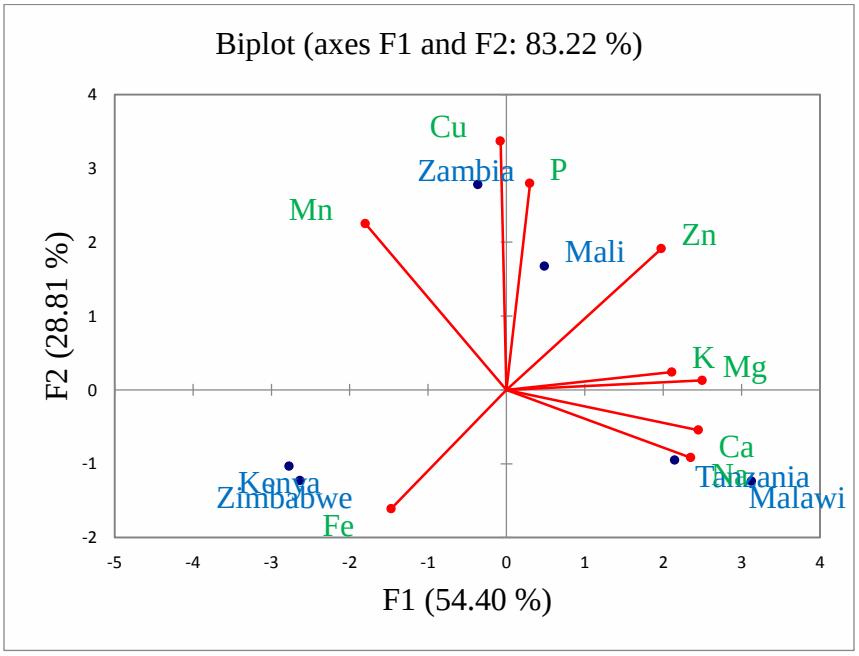

Figure 7: Biplot showing the relationships between the seed elements and the countries.

4.7.4 Baobab seed oil fatty acid profiles according to six African countries

The FA peaks based on retention times are presented in Figure 8 below. Fatty acid content for the baobab accessions ranged from 10.37 to 25.98%, 0.77 to 2.03%, 18.64 to 48.58%, 11.24 to 34.97% and 0.52 to 1.55% for palmitic, stearic, oleic, linoleic and linolenic acid, respectively as shown in Table 48. Interestingly, for oleic and linoleic acid, the highest and lowest content were obtained from two baobab accessions from Moshi provenance in Tanzania. The lowest palmitic acid content was obtained in seed oil from an accession also collected from Moshi, whereas highest content was present in an accession from FRC provenance, Zimbabwe. For stearic acid, the highest and lowest content were recorded in accessions from Chirundu in Zambia and Kayes provenance in Mali, while linolenic content, the lowest and highest were from Siavonga provenance, Zambia and Malindi provenance, Kenya. ANOVA revealed that concentration of individual FA varied significantly (P<0.001) among accessions, provenance and countries. On the other hand, irrespective of provenance, the mean oleic, linoleic and palmitic acid content in the seed oil were consistently higher accounting for 32.09-39.06%, 19.62-28.08

% and 14.95-22.87%, respectively. In contrast, extremely lower content of stearic and linolenic acid were present in the seed oil accounting for 1.05 -1.59% and 0.75 -1.33% respectively (Table 48).

Generally, baobab provenances with accessions that had lowest and highest mean content of stearic, oleic acid and linolenic acid were Kongwe and Taita, Kongwe and Malindi, Taita and Malindi, respectively, all from Eastern Africa region (Kenya and Tanzania). Furthermore, provenances with the highest and lowest mean palmitic and linoleic acid were from southern African (FRC-Zimbabwe and Siavonga-Zambia) and the eastern African provenances (Moshi-Tanzania and Malindi-Kenya), respectively (Appendix 11). The mean palmitic acid content in seed oil from southern Africa accessions from Hangwe, FRC, Mangochi, Mambwe, Siavonga and Chirundu provenances was significantly (P<0.001) higher than those from western (Mali) and eastern African region, with significantly lower content obtained from Tanzanian accessions represented by Kilolo, Kongwe and Moshi provenances.

Table 48: Fatty acid profile of baobab seed oil according to six African countries.

Country	Palmitic acid (%)	Stearic acid (%)	Oleic acid (%)	Linoleic acid (%)	Linolenic acid (%)
Zimbabwe	21.34±1.090^{a}	1.46±0.124^{abc}	33.71±1.734^{b}	24.36±1.189^{bc}	0.86±0.086^{bc}
Tanzania	16.51±0.884^{d}	1.30±0.283^{bd}	33.65±3.040^{b}	22.81±2.553^{cd}	0.96±0.200^{ab}
Malawi	20.58±0.507^{ab}	1.47±0.137^{ab}	33.80±2.201^{b}	25.35±2.103^{ab}	0.79±0.220^{c}
Zambia	20.57±0.721^{b}	1.21±0.127^{d}	35.80±1.079^{a}	26.53±2.742^{a}	0.86±0.172^{bc}
Kenya	18.13±0.622^{c}	1.50±0.138^{a}	36.16±1.287^{a}	23.58±2.742^{bcd}	1.03±0.275^{a}
Mali	17.62±1.422^{c}	1.48±0.149^{a}	32.90±1.232^{b}	22.08 ± 1.933^{d}	0.89±0.139^{abc}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	5.5	15.8	5.7	10.1	21.2

For the same column, means followed by the same letter are not significantly different. cv: coefficient of variation

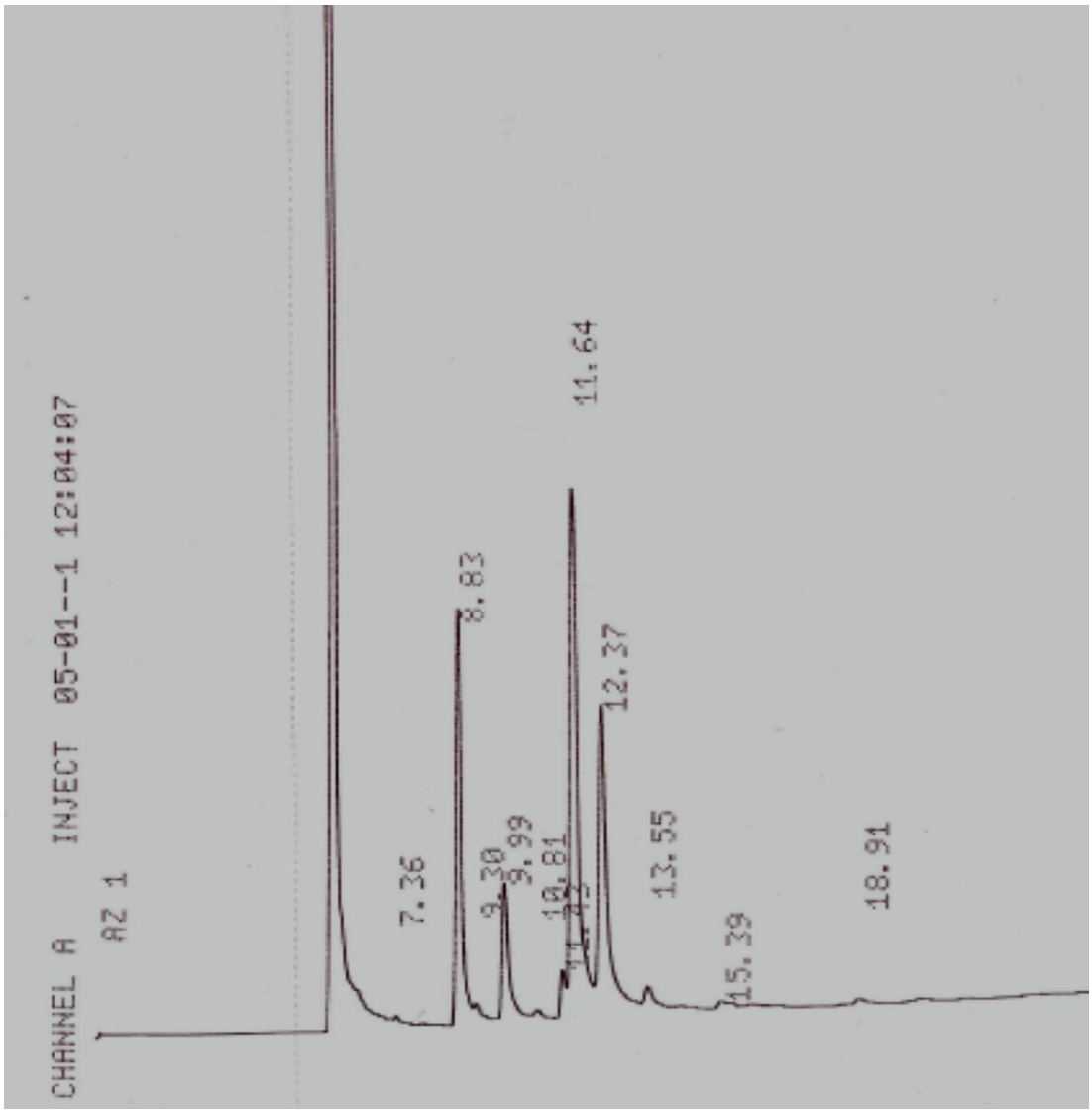

Figure 8: Peaks based on retention times (min): Palmitic acid (8.83), Heptadecanoic acid (internal standard 9.99), Stearic acid (11.43), Oleic acid (11.64), Linoleic acid (12.37), and linolenic acid (13.55).

Although palmitic acid content in accessions from Kenya (Kibwezi, Taita and Malindi) were higher than those from Mali (Mopti, Sikasso, Kayes and Seguo), however they were not significantly (P<0.001) different. On the other hand, there were no clear observable trends in terms of regional patterns for stearic, oleic, linoleic and linolenic acids, however there were significant (P<0.001) differences between the highest and lowest content for the four FA (Table 48). The pattern of FA profiles in baobab seed oil observed at individual accessions and provenance level with a predominance of oleic acid, linoleic, palmitic acid and low levels of stearic acid and linolenic was also observed at country level (Table 48). The mean FAs content

per country basis ranged from 16.5 to 21.34%, 1.2 to 1.5%, 32 to 36.1%, 22.08 to 26.53%, and 0.79 to 1.03 for palmitic, stearic, oleic, linoleic and linolenic acid, respectively. Comparison of the means revealed that seed oil from Kenyan (36.16%) and Zambian (35.8%) accessions had significantly (P<0.001) higher oleic acid content compared with seed oil from Malian (32.9%) as opposed to those from Zimbabwean, Tanzanian and Malawian accessions. Furthermore, mean palmitic acid content in Zimbabwean, Malawian and Zambian seed oil were significantly (P<0.001) higher than those obtained from Malian, Tanzanian and Kenyan. For mean stearic acid, seed oil from Tanzanian accessions had significantly (P<0.001) higher content than from Kenya and Mali, unlike Zimbabwean and Malawian (Table 48). On the other hand, mean linoleic acid from Zambian accessions was significantly (P<0.001) higher than from all other countries except Malawi, whereas seed oil from Kenyan accessions had significantly (P<0.001) higher mean linolenic acid compared to those from Zambia, Malawi and Zimbabwe (Table 48).

4.7.5 Principal component analysis and hierarchical analysis

The first two principal components (PC) extracted from PCA of fatty acid content in the baobab accessions accounted for 71.3% of total variations, with PC1 and PC2 accounting for 48.8% and 22.5%. PC1 had a positive correlation with palmitic, oleic and linoleic acids with Eigenvector coefficients of 0.54, 0.53, and 0.55, respectively, whereas PC2 had a strong positive correlation only with linolenic acid with a coefficient of 0.88. Projection of the five fatty acid variables on PC1 and PC2 axes, confirmed that palmitic, oleic, linoleic were positively correlated with PC1, whereas PC2 was positively correlated with linolenic. Furthermore, projection of the fatty acids revealed that palmitic and linoleic acid content in baobab seed oil were highly correlated and however their content was not correlated with linolenic acid unlike oleic acid (Fig. 9A). Furthermore, projection of the 109 accessions on PC1 and PC2 axes revealed a varied grouping pattern, with accessions 53, 74, and 78 having higher scores for PC1, while accessions 21, 42, 49 and 52 had the lowest score. On the other hand, accessions 98,100 and 102 all from Malindi had higher PC2 scores (Fig. 9B). Principal component analysis of the FAs variables at the provenance level revealed that PC1 and PC2 accounted for 42.9% and 29.2% variation. Projection of the Eigenvectors on a biplot showed that to PC1 was positively correlated to palmitic acid and linoleic acid and negatively correlated with linolenic acid, whereas oleic acid was positively correlated to PC2.

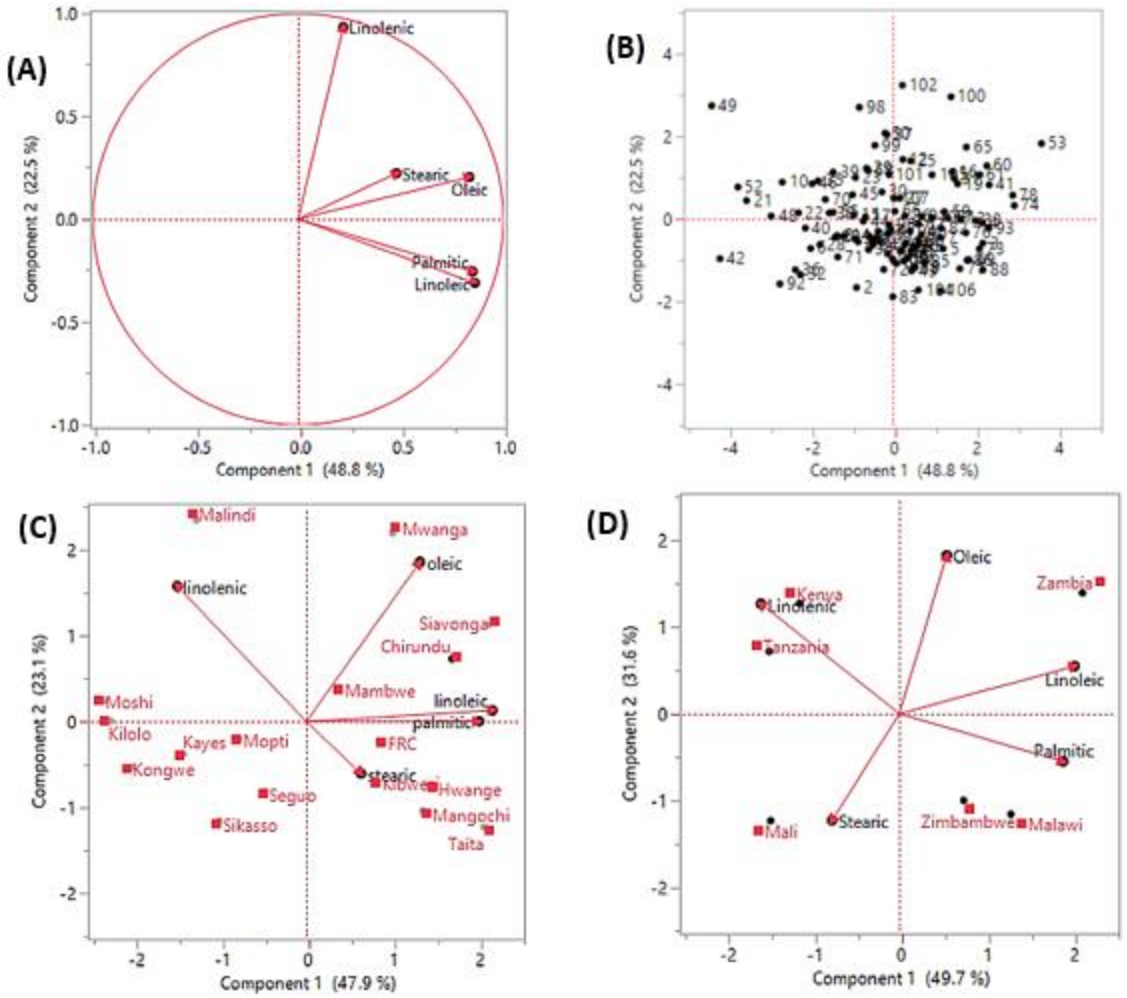

Figure 9: Principal Component Analysis of *Adansonia digitata* fatty acids. (A) Vector plot of the five fatty acid variables on PC1 and PC2 based on accessions; (B) Two dimensional scatter plot of the 109 baobab accessions plotted on PC1 and PC2 axes; (C) Biplot showing the projection of the fatty acid variables and the provenances based on PC1 and PC2; (D) Biplot showing the projection of the countries and the fatty acid variable on PC1 and PC2 axes.

Furthermore, palmitic acid and linoleic acid were also highly correlated when the cosine of the angle between these two fatty acids vectors are considered (Fig. 9C). Seed oil from Siavonga and Chirundu, Hwange and Taita accessions had higher palmitic and linoleic acid content, while at the same time they had very low linolenic acid, this is unlike seed oil from accessions obtained from Mwanga and Malindi provenances, which had higher Oleic and linolenic acid content, respectively (Fig. 9C). At country level, projection of the Eigenvectors on a biplot followed a trend similar to provenance, however PC1 and PC2 accounted for 49.7% and

31.6% of the variability. Unlike for provenances, stearic acid was negatively correlated with palmitic acid, linoleic and oleic acids. Nonetheless seed oil obtained from Kenya and Tanzanian accessions contained higher linolenic acid and the Malawian and Zimbabwean accessions had higher palmitic acid content, while Zambian and Malian accession had higher linoleic and stearic acid, respectively (Fig. 9D).

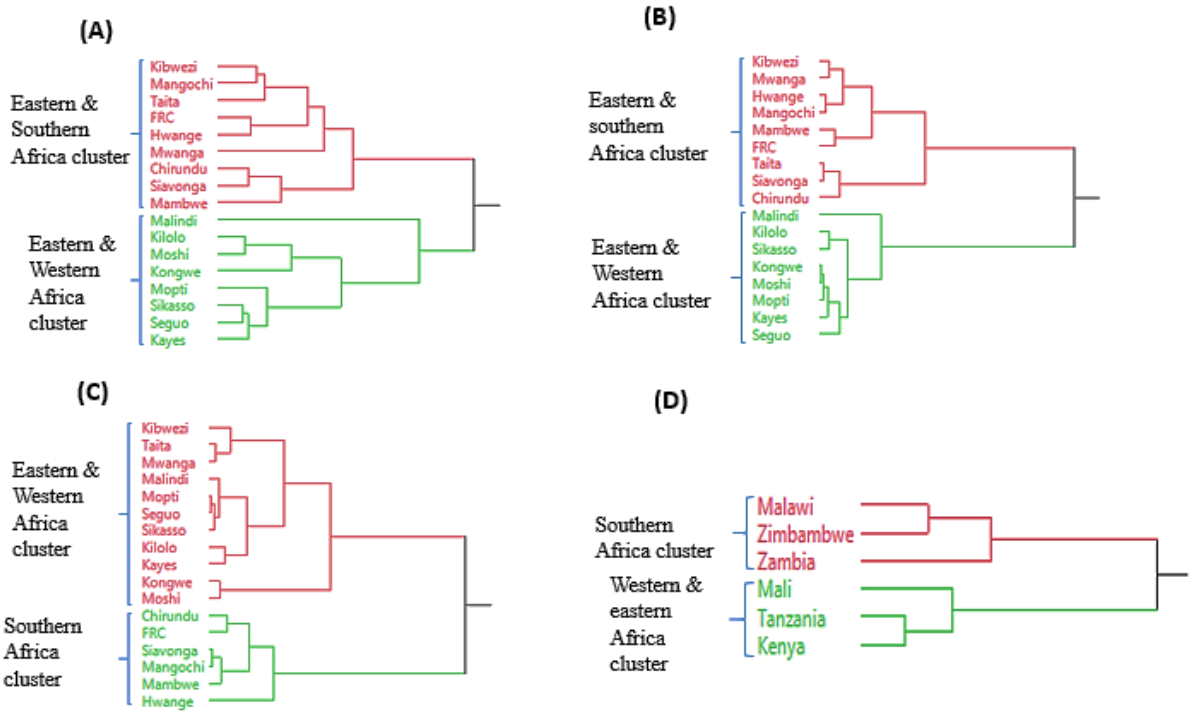

Figure 10: Agglomerative hierarchical cluster analysis of fatty acid content in baobab seed oil. (A) Dendrogram based on sum of all fatty acids (palmitic+stearic+ oleic+ linoleic+ linolenic) content at provenance level; (B) Dendrogram based on linoleic acid acid content of baobab seed oil; (C) Dendrogram based on palmitic acid content of baobab seed oil; (D) Dendrogram for hierarchical analysis of linoleic acid content of baobab accessions per country basis

Agglomerative hierarchical cluster analysis of all fatty acids at provenance level produced two clusters; eastern and southern Africa cluster and eastern and western Africa cluster (Fig. 10A). The eastern Africa provenances were distributed among the two clusters whereas the southern and western Africa provenances had occurred in distinct clusters. On the other hand, hierarchical analysis of the baobab accessions based on linoleic acid content, a strong measure of PC1s in this study, also produced two clusters dominated by provenances from southern Africa and western Africa, without a distinct eastern Africa cluster. However, Tanzanian provenances

except Mwanga, clustered with West African provenances, while those from Kenya with exception of Malindi clustered with the southern Africa provenances (Fig. 10B). Hierarchical analysis based on palmitic acid, another strong measure of PC1s also produced two clusters and unlike in linoleic acid, the southern Africa provenances formed distinct cluster whereas the eastern and western African provenances clustered together (Fig. 10C). At country level, hierarchal analysis of linoleic acid produced two clusters with eastern Africa countries and Mali clustering together, while southern Africa countries forming the second cluster (Fig. 10D), a similar pattern was also obtained with palmitic acid content.

4.7.6 Vitamin C concentration of baobab fruit pulp according to five African countries

The mean vitamin C levels were compared among the study countries. Results (Appendix 14 and Table 49) revealed that there existed statistical significant differences ($P < 0.001$) among the countries for fruit pulp vitamin C concentration. Tanzania had the highest mean (3.58 mgg^{-1}) Vitamin C concentration whereas Kenya had the lowest mean level at 2.66 mgg^{-1}. At provenance level, Taita and Mopti had the highest mean Vitamin C concentration (4.34 mgg^{-1} and 4.02 mgg^{-1}, respectively) while Seguo (2.73 mgg^{-1}), Kibwezi (2.34 mgg^{-1}) and Malindi (2.31 mgg^{-1}) had the lowest mean content as presented in Appendix 7.

Table 49: Comparison of pulp vitamin C content at country level.

Country	Vitamin C (mgg^{-1}**)**
Tanzania	3.58 ± 0.312^{a}
Zambia	3.28 ± 0.337^{b}
Kenya	2.66 ± 0.300^{d}
Malawi	2.97 ± 0.312^{c}
Mali	3.29 ± 0.618^{b}
P-value	< 0.001
CV (%)	11.5

Values (means ± S.E.M) followed by the same letter are not significantly different

4.8 Discussion

The moisture content of conventional fruits range between 75-95 $g100^{-1}g$ (Ruiz-Rodríguez *et al.,* 2011), in contrast the pulp moisture content from all the baobab fruits irrespective of provenance ranged between 8.81-9.93 $g100^{-1}g$. This range in fruit pulp moisture content was found to be similar to the values previous studies (Assogbadjo *et al.,* 2012; Parkouda *et al.,* 2012). The low water content would positively correlate with a long shelf life of the fruit due to decreased biochemical activity that would decompose key nutrients and cause pulp decay. Therefore, the pulp can be stored for long periods without deterioration of key nutrients. Also, the pulp moisture content is low when compared to other commonly consumed African fruits namely, *Balanites aegyptiaca, Schlerocarya birrea, Tamarindus indica, Dacryoedis eduli, Vitex doniana, Uapaca kirkiana, Ziziphus mauritiana* and *Syzygium guineeense*, some of which grow under the same environmental conditions as baobab (Stadlmayr *et al.,* 2013). The low pulp moisture content recorded across all provenances in this study can be attributed to the species' biology. Even though baobabs grow in dry areas they have an extensive root network and ability to store a lot of water in their stems, an ecophysiological adaptation that would limit moisture content in the pulp tissue. Factors such as sunlight and wind exposure contribute to fruit pulp dryness (Ruiz-Rodríguez *et al.,* 2011), therefore, there is need to investigate the effect of such factors on baobab fruit pulp.

The crude protein content of baobab pulp recorded in this study is comparable to that of *Tamarindus indica* fruit pulp, an indigenous fruit tree which grows under the same ecological conditions as baobab tree (De Caluwé *et al.,* 2010b). Other IFT species namely; *S. birrea, S. spinosa,* and *Vanguenia infausta* growing in Africa were reported to have crude protein levels ranging from 1.3 to 3.7 $g100\ g^{-1}$ (Nyanga *et al.,* 2013). Even though baobab fruit pulp has low protein content it is much higher than that of commonly consumed fruits, namely oranges, mangoes, grapes, banana and papaya which have a protein content of 0.7, 0.6, 0.5, 1.2 and 0.6 $g\ 100\ g^{-1}$, respectively (Ngemakwe *et al.,* 2017). The absence of inter-provenance variation within each country for pulp fibre content concurs with findings reported across agro-climatic zones of Benin (Assogbadjo *et al.,* 2012). This would suggest that environmental variations between trees do not affect the fruit pulp fibre content either in the West, East or South of Africa. The fruit pulp fibre content reported in literature are generally below 12.5 $g100g^{-1}$ dw, with levels varying from 6.0 g to 12.5 $g100g^{-1}$ dw (Coe *et al.,* 2013; Hyacinthe *et al.,* 2015). Research conducted on baobabs in Benin reported a mean of 11.0 $g100g^{-1}$ dw for pulp crude fibre for each of the three agro-climatic zones, namely;

Sudanian, the Sudano-Guinean zone and the Guineo-Congolian zone (Assogbadjo *et al.*, 2012). The crude fibre content reported in this study is of significant quantity and thus baobab pulp can be recommended as a good source of dietary fibre.

Dietary fibre includes a number of nonstarch polysaccharide substances including cellulose, hemicellulose, β-glucans, pectin, mucilage and gums plus the nonpolysaccharide lignin (Mišurcová *et al.*, 2012). Such fibers have pre- and post-biotic effects thus serving as an intestinal regulator in the case of gastric disorders (Mišurcová *et al.*, 2012). These health benefits are speculated to be a result of changes in intestinal viscosity, nutrient absorption, rate of passage, production of short chain fatty acids and production of gut hormones. The statistical significant differences within and between baobab provenances for pulp ash content suggest that environment greatly affects tissue biomass. A plant's tissue ash content is a reflection of its' inorganic matter. This can be confirmed by the low ash content observed in Mopti among all provenances (Appendix 7) which resulted in low calcium and potassium content (Appendix 9) of the pulp. Based on the link between ash and inorganic mater content, findings of this study suggest that baobabs from East and Southern Africa provenances are rich in mineral elements while those from West Africa (Mali) are poor sources of such elements. Since the West African provenances experienced warmer temperatures than the other regions (Table 3), this observation could have negatively affected the pulp ash content.

The proximate composition of baobab seeds recorded in this study shows that the seed tissue is rich in protein, fibre, fat, and carbohydrate. The very low seed moisture content recorded in Malian provenances can be correlated with the regions high temperatures (Table 3) which could contribute to seed desiccation. Thus baobab seed moisture content can be linked to provenance's annual temperature. Furthermore, the low variation of moisture content contrasts with the relatively large variation of fats and proteins which could indicate that a slight change in water content imposes a great change in the composition of the organic compounds (Manach *et al.*, 2017). Our results (Appendix 8) show a regional trend in seed protein content where seeds from West African provenances had the lowest crude protein content while those from East African provenances had the highest content. This would suggest that other than the warm climate of Mali, the region has soils that have a high carbon/nitrogen ratio, or poor in nitrates nitrites which make up protein in plant tissues.

Baobab seeds could be used to process flours rich in proteins and consumption could be a possible nutritional strategy to augment cereal diets low in proteins more so in East African communities where they are rarely utilized. The seeds have been documented to

contain high amounts of essential amino acids (Magaia & Skog, 2017). Contrary to other plant seed protein profiles, baobab seed protein contains a high amount of lysine. Because lysine is found in very minimal quantities in most cereal plants, baobab seed protein could potentially be used to improve cereal protein quality especially in areas where people are dependent on staple crops such as sorghum for their sustenance.

The differences recorded in our study for seed fibre content among the provenances and countries suggest that the origin of seeds (environment) greatly influences the concentration of fibre in the tissue. However, there was no specific regional trend for seed fibre content across the African regions sampled. The whole seeds of *A. digitata* analysed in our study contained high levels of crude fibre content (20.0 to 26.5 $g100g^{-1}$ dw). However, in separate studies conducted in Nigeria and Benin values three time lower than those found here were reported (6 to 8 $g100g^{-1}$ dw) (Aworh, 2015). Even though the provenances of origin did not seem to influence pulp fibre content, it had effects on seed fibre content within countries. The values reported here for seed fat content concur with those previously reported for baobabs in West Africa (Parkouda *et al.*, 2012; Parkouda *et al.*, 2015). However, higher values for crude fat have been reported. For instance, crude fat concentration of 28 $g100g^{-1}$ on average was reported in three provenances in Benin (Assogbadjo *et al.*, 2012). These differences in the seed fat content among the study provenances can be linked more strongly to genetic factors than geographical conditions since variations were very minimal across the provenances. The minor variation in seed oil yield from different provenances could be the result of differences in natural soil texture and other man-made effects.The average oil content of *A. digitata* seeds from our study was found to be less than those of four conventional oilseed crops: cotton (15.0-24%), soybean (17.0-21.0%), safflower (25-40%), and mustard (24-40%), grown in the United States, Brazil, China, and some other Asian and European countries. Other than seed maturation, fat content variability in *Dacryodes edulis* was due to generic differences (Stadlmayr *et al.*, 2013), an inference that can be made on the variation reported for baobab.

Baobab seeds are eaten raw, ground to powder or are roasted and have a pleasant nutty flavour (Chadare *et al.*, 2010). In the Sahel region of Africa, the seeds are used in the preparation of local sauces as thickening agents after pounding or as flavour enhancers when fermented (Diop *et al.*, 2006). One of the numerous products of baobab seeds is *Maari*, a condiment obtained from fermenting baobab seeds in Burkina Faso though it is found under other several names in Mali and Nigeria among other West African countries where it is part of the daily diet (Parkouda *et al.*, 2015). *Maari* is known in Nigeria as *Dadawa, Higgi* or

Issai and in Benin as *Dikouanyouri* (Chadare *et al.*, 2010). Since the fermentation of baobab seeds induces several biochemical changes which decrease protein and carbohydrate but increase fatty acids and free amino acids (Parkouda *et al.*, 2015), this preparation method should be adopted by people in the East and Southern Africa. It is estimated that consumption of 20 g of the seed flour can cover 15 to 34% of the protein RDI for children; while for pregnant women 60 g can cover 27% of the RDI based on the highest reported content (Chadare *et al.*, 2010). Moreover, consumption of 100 g can cover 22% of the energy RDI for pregnant women and 29.4% of energy RDI for children. It is important to note that such calculations are usually done considering the digestibility and bioavailability of the nutrients. Baobab seeds are hardly consumed as a food supplement in East Africa. The findings of this study provide evidence that the seeds are nutritious and should be included in our diets. More often, the seeds with pulp on them are roasted and sold as '*mabuyu*' but people hardly crack the seeds to extract and eat the fat rich kernel. Further, stakeholders should adopt nutritional policies that promote the consumption of roasted seeds or seed flour among school going children and communities affected by malnutrition.

Other than the geographical conditions outlined in Table 3, the variability in pulp and seed macronutrients within and between provenances could be attributed to soil microsite composition, pollination effects, and stress response by trees or even strain. The existence of variation in nutrient content within a species offers good opportunities for selection of elite trees for conservation and domestication, both *in situ* and *ex situ*. Since baobabs in the same population might have evolved to form ecotypes, genetic studies would help to account for the observed variations within provenances. Furthermore, differences in tree flowering periods within and between populations could affect the nutrient content among trees. This is because exchange of genetic material between trees through pollination would be difficult thus resulting in fruits that vary in their nutrient content. This variation could also be ascribed to the level of ripening for the fruits and age/developmental stage of the tree. The environmental conditions of the provenances have an effect on the proximate composition, a cause of variation also indicated in a study for Sclerocarya birrea (Hiwilepo-van Hal *et al.*, 2014). Huge variability between families (trees) within a population indicates existence of different races within population. Nutrient variability study within populations is a prerequisite for any tree improvement programme. The magnitude of variability within and between populations suggests proper domestication and improvement tool for enhancement of productivity of the species.

The pulp calcium concentration recorded here for Malian provenances averaging between 1800 to 3000 mgkg^{-1} was found to agree with the range (1600-3090 mg kg^{-1}) previously reported in Mali (Simbo *et al.*, 2013). The regional variation in pulp calcium content can be linked to the area's geographical conditions. Pulp from Malawi had remarkably high calcium content which can be used to supplement calcium poor diets more so for children, pregnant and lactating mothers, and the elderly. Inadequate dietary supply and a high risk of Ca deficiency in Malawi have been previously reported based on food balance sheets (FBSs) (Joy *et al.*, 2014). Interestingly, the calcium content reported here for baobab is more than that of commonly consumed fruits such as guava (18 mg 100 g^{-1}), orange, (11 mg 100 g^{-1}), pear (4 mg 100 g^{-1}) and strawberry (22 mg 100 g^{-1}) (Mahapatra *et al.*, 2012). Even though dairy products are a major source of calcium for human health, this study reveals that baobab fruit pulp is could be an excellent source of dietary calcium. However, studies on mineral bioavailability need to be conducted on baobab fruit pulp.

The high potassium content recorded in Malindi as opposed to other provenances can be correlated with the area's altitude and rainfall. According to Table 3, Malindi is located at a very low altitude (8 m) near Indian Ocean and experiences with high rainfall which could influence soil element mobility. Baobab pulp potassium content is much higher than that found in commonly consumed fruits, such as such as guava (4.17 mgg^{-1}), orange (2.00 mgg^{-1}), apple (0.90 mgg^{-1}) and banana (3.58 mgg^{-1}) (Mahapatra *et al.*, 2012). Potassium and sodium are known to regulate the muscle contraction and nerve impulse transmission and a high K/Na ratio could possibly play a role in excretion of excess water and salt (Gharibzahedi & Jafari, 2017). In this study the pulp sodium content was lower than potassium suggesting a high K/Na ratio. Baobab fruit pulp from Malawi had the highest concentration of potassium, magnesium, sodium and phosphorus which forms a strong basis for the recommendation of pulp from Malawi as an excellent source of macro elements. The high concentration of such elements in Malawi can be attributed to soil type, soil mineral mobility, adsorption and accumulation in the tissue.

The variability across the provenances could be due to regional precipitation which influences soil mineral element mobility and adsorption by plants (Alloway, 2013). Moreover, soils physio-chemical properties and agricultural activities could also influence the pulp microelement content. The mean estimated risk of iron and zinc deficiency in Eastern Region of Africa is 14% and 75% respectively (Joy *et al.*, 2014).Since baobab pulp from Kenya is reported to be rich in iron and zinc, it could be used as a potential dietary supplement in East Africa and regions in the Western world that face iron and zinc

deficiency. Generally, our findings would support the recommendation of fruit pulp as a possible strategy to tackle the problem of macro and microelement deficiencies through its inclusion in foods during fortification. In SSA, nutrition related programs for school going children should consider provision of pulp juices and also porridges/gruels that contain baobab pulp as an ingredient. Findings in this study suggest that baobab fruit pulp is a good source of macro (calcium, potassium and magnesium) and micro elements (iron, manganese and zinc) but he levels are influenced by the provenances of origin.

The intra-provenance and inter-provenance variability clearly indicates that elemental composition of the fruit pulp and seed tissues is greatly influenced by provenance of origin. A possible explanation for the intra-provenance variations detected here is that fruit and seed composition reflects the soil properties of the microsite of each plant (Izhaki *et al.*, 2002). For example, a microsite with relatively high potassium content in the soil may render production of fruits whose pulp and seeds contain high potassium content. In relation to tissue mineral element supply, we may expect contrasting outcomes given that the different provenances inhabit climatically and geologically different habitats that must produce variation in soil nutritional conditions (Elser *et al.,* 2010). This would support the variation at country level. In addition, the availability of nutrients in soil is highly heterogeneous, indicating a strong spatial and temporal variation that is often linked to seasonal and climatic variations (Elser *et al.*, 2010). In this study we can conclude that the existence of mineral variations among the study countries was greatly influenced by environment.

The high variability noted for sodium content could be explained partly by perturbations in soil sodicity. Low variability recorded for most of the macro elements indicates that variation in tissue elemental concentrations was more constrained for nutrients with highest requirements, usually the most abundant and considered the generally most limiting in nature (Han *et al.*, 2011). On the contrary, this would suggest that micro elements which are the least concentrated in the seed and pulp tissues and less required for plant growth would exhibit high variability within and between provenances. The relatively large variation in pulp and seed mineral concentration among the countries (Table 40 & 41) would show that plant physiological requirements in conjunction with biogeochemical characteristics influence elemental distribution spatially in soils and biogeographically across climate gradients, as well as constraining general levels of variability (Han *et al.*, 2011).

It is worth noting that the order of accumulation of both macro and micro elements in pulp and seed tissue is different. For instance, seeds contain higher phosphorus and magnesium than the pulp. However, for some countries it was evident that the microelement

concentration of either tissues was highly plastic across the provenances. This clearly shows that the concentration of mineral elements in these tissues is dependent on a plethora of processes like, mobilization, translocation and redistribution within plant tissues (Singh *et al.*, 2013). In East and Southern Africa countries, the least concentrated element for pulp and seeds was manganese while in West Africa (Mali) it was iron. Further, pulp and seed iron content in Kenya provenances was three to fivefold the content recorded for Malian provenances. Such observations suggest that the interaction of plant genotype and environment is responsible for perturbations in the ionome of plant tissue (Baxter, 2009). Studies of baobab ionome would provide insights into the plant-environment interaction that influence elemental accumulation since elemental profiles have been shown to reflect the plant's adaptation to the environment (Baxter, 2009). Based on the elemental data presented here, the baobab tree seems to have a complex gene regulatory network for acquiring and storing high content of potassium and calcium in the fruit pulp despite the environmental/climatic conditions across SSA.

Palmitic, oleic and linoleic acid classified as SFA, MUFA and PUFA respectively were dominant in the seed oil irrespective of the baobab accession or provenance. The levels of these FA in oil of seed accessions used our study are within the ranges reported elsewhere (Komane *et al.*, 2017; Razafimamonjison *et al.*, 2017), and the slight difference can be attributed to the length of storage of oil or FAME before analysis. This is because during storage, FA may undergo oxidative rancidity which would affect the natural FA quantities (Choe & Min, 2006). The levels of FA analyzed varied significantly between accessions, provenance and countries, however there was a uniform FA profile in terms of highest and lowest content across all provenances, despite seed oil originating from wild populations in different SSA geographical regions. The uniformity of FA profile despite of geographical distribution suggests that regardless of differences in climatic and edaphic factors, and evolution of baobab populations into ecotypes with the possibility of genetic drift, the seed oil FA content pattern remained highly conserved. Furthermore, lack of significant differences between mean content coupled with lack of clear regional or provenance pattern observed on stearic, oleic and linolenic acid content in baobab seed oil also suggests that these FAs variables may be conserved across the baobab population studied. This is because seed oil content and fatty acid composition are quantitative traits known to be under polygenetic control and also influence of environmental conditions. However significant differences and patterns of palmitic and linoleic acid content suggest candidate markers that can be used to segregate baobab population in SSA. Already, QTLs influencing seed oil

content and FA composition for palmitic acid (16:0), oleic (18:1), linoleic (18:2) and stearic have been reported in Arabidopsis and thus can be used enhance selection for individual or population with desirable fatty acids (Sanyal & Linder, 2012).

The PCA results of FA content at accessions, provenance and country levels, clearly demonstrate that palmitic acid and linoleic acid are true measure of PC1, while oleic acid as a measure of PC2. The PC1 results supports further the aforementioned suggestion that these two FA variables which are positively correlated can be used as markers or as a key component in screening and selection of baobab accessions from a diverse provenances and countries in SSA. Similarly, oleic acid can be used as a maker at the same level as palmitic or linoleic acid due to their high levels in the seed oil. Interestingly, linolenic acid can also be used as an indirect maker for selecting individual trees or baobab populations for higher levels of palmitic and linoleic acid. Since linolenic acid is negatively correlated with palmitic and linoleic acid (Fig. 9) a higher level of linolenic acid can be a pointer to lower palmitic and linoleic acid content in baobab seed oil. In the present study, the accessions 98, 99, 100, and 102 from Malindi provenance in Kenya at an elevation of 8 m above sea level had the highest values for linolenic acid which could be due to the influence of the quite distinct geographical site when compared with other provenances. The Malindi accessions were sampled from a site that is associated with the oldest baobab trees in eastern Africa and we could infer the high linolenic acid content to the age of trees as well as an effect of altitude. Nonetheless projection of the FA variables per country basis on the biplot (Fig. 9D) suggests that baobab seed from the east African populations generally have higher linolenic acid content. The level of linolenic acid in seed oil has been reported to be highly influenced by environmental factors, this has been demonstrated in oil crops such as soybean (Bellaloui *et al.*, 2015; Chae *et al.*, 2015)among other crops. There exists a strong negative relation between oleic acid and linolenic acid as well as stearic acid. In baobab seed oil, high oleic acid content is associated with low linolenic and stearic acid which is similar to an observation recorded for sunflower oil (Izquierdo *et al.*, 2013).

The separation of the individual baobab accessions based on the plane of PC1 and PC2 (Fig. 9B) suggested that they were scattered in all the four quadrants, possibly revealing a high level of genotypic variation among the accessions. Such findings strengthen the use of quantitative traits such as FA that could be used as a platform for genetic diversity studies within and among Africa mainland baobab populations. In earlier studies using baobab, significant quantitative variation in tissues nutrient content were documented, contributing to a foundation for genetic studies within the species in West African Sahel region (Parkouda *et*

al., 2012; Simbo *et al.*, 2013). Similarly, the present work highlights key variations that could be exploited in pursuit to understanding the species diversity across Africa.

Generally, the hierarchical clustering revealed the existence of two baobab clades in SSA namely; Western Africa and Southern African based on mean FA variables analyzed at provenance and country level. This clustering could be inferred to ecological differences coupled with genetic influence and supports a study that demonstrated variation between Western and Southern African populations although based on fruit morphology (Sanchez *et al.*, 2011). The accumulation of specific FA in the seed oil could possibly be related to the ecological conditions in SSA since the FA composition of seed oil is sensitive to environmental conditions as mentioned in other studies (Connor *et al.*, 2007). Previous studies have confirmed the existence of ecological influence on baobab fruit pulp, seed and kernel across ecological zones in Benin (Assogbadjo *et al.*, 2005). Although there were no distinct clades for eastern African population based on FA content in seed oil, there are reports indicating variation in leaf morphology and growth rate of 12 months old seedlings between Western and Eastern African baobab although no geographical pattern were revealed (Korbo *et al.*, 2012). The findings of the present study provide a strong basis for the study of within and among population genetic diversity to understand aspects of gene flow across the three regions.

The remarkable nutrient of *A. digitata* fruit pulp is its' vitamin C content. The lack of significant differences in vitamin C content among fruits of the same tree as observed in Mwanga, Mangochi, Sikasso, Seguo, Mopti and Kayes was also documented in Malian provenances (Simbo *et al.*, 2013). This finding has important implications for domestication because knowing the Vitamin C content of one fruit in a tree is indicative of the Vitamin C content of the other fruits in the same tree. The large variability within provenances could be linked to genetic effects or individual response to climatic conditions since the trees grow under the same environmental conditions in the provenances. Trees from Mopti, Moshi, Kongwe and Taita offer a great opportunity for obtaining cultivars for vegetative propagation in efforts to conserve this desirable trait and also protect the natural stands from over-exploitation. The high Vitamin C content of trees growing in these provenances indicates that there could be more superior trees because only a few of them were sampled. Since asexual reproduction through grafting has been successfully achieved for baobab trees (Anjarwalla *et al.*, 2017), it is now possible to domesticate baobabs using mother trees that show superior traits like high vitamin C content. The vegetative mass propagation would lead to increased cultivation of this species and thus meeting the increasing demand for baobab pulp. Inter-tree

variability for vitamin C was also documented for other fruit tree species; For instance high variability has been shown in Kiwi (*Actinidia deliciosa*) and *Capsium anuum* (Nishiyama *et al.*, 2004). Family and provenance variation in vitamin C have also been reported for *Sclerocarya birrea* sub-species caffra in South Africa (Hiwilepo-van Hal *et al.*, 2014).

Vitamin C content in fruits exhibits quantitative inheritance and several Quantitative Trait Loci (QTL) for its concentration have been identified in tomato (*Solanum sp*.) (Calafiore *et al.*, 2016). These QTL can be successfully conserved within baobab tree families during vegetative propagation. Grafting of elite trees found within this study would ensure the propagation of vitamin C dense baobab cultivars. Since the mechanism of vitamin C accumulation in fruits is associated with a class of transporters (Nucleobase Ascorbate Transporter, NAT), baobab tree could be used as a model organism for studying biosynthesis of vitamin C. Such genetic discoveries would be critical in explaining the higher vitamin C content in baobab fruit pulp than in other tropical fruit tree species. Generally, the present study confirms that the African baobab tree is an excellent source of vitamin C and could be used to alleviate the vitamin deficiency. This extremely high vitamin C content of baobab fruit could possibly positively correlate with a high antioxidant capacity. Since scavenging of electrons is a biological role of Vitamin C, baobab pulp could be considered as a possible new antioxidant ingredient for the nutraceutical and functional food market. Fresh fruits and vegetables are the main source of vitamin C for humans and primates who are unable to synthesize vitamin C because of mutations in the enzyme, L-gulono-1, 4-lactone dehydrogenase which catalyzes the final step of its biosynthesis (Smirnoff, 2000). Even though vitamin C has been linked to many biological roles, the only proven function is the prevention of scurvy.

In the recent years, attention has been given to nutritional properties of natural antioxidant compounds, since their consumption has been demonstrated to be associated with reduced risk of cancer, heart and degenerative diseases. The main antioxidant compounds found in plants and fruits are carotenoids, phenolic compounds and vitamin C (Roleira *et al.*, 2015). Even though vitamin C deficiency is not prevalent in many areas worldwide, its dietary intake cannot be overlooked. In most dry areas of SSA, farming of exotic fruits such as oranges, berries and lemons is a challenge and so baobab tree which has adapted well to this ecological zones would serve as the best source for dietary vitamin C. Nowadays, people in towns are accustomed to consuming the same fruits such as mangoes, bananas, oranges, pawpaw, thus they are looking for newer and nutritious fruits as an potential alternative. The

present research confirms that baobab fruit can be used to prepare nutritious juices rich in vitamin C offering a new flavour and texture in the market.

The nutritional characterization of IFT provides a basis for studying intra-specific diversity and identification of mother trees with superior traits. These traits can be multiplied vegetatively since such a method ensures conservation of desirable traits (Tchoundjeu *et al.*, 2006), followed by dissemination of the improved plants to farmers and cultivation on farms (Tchoundjeu *et al.*, 2006). For baobab, such propagation methods would entail grafting. Baobabs superior in Vitamin C have been successfully grafted in Mali and grating of baobabs in Kenya using top cleft and side veneer methods was also achieved with great success (Anjarwalla *et al.*, 2017) . This meant that such grafting methods could contribute to the development of baobab domestication and breeding programmes. Further research conducted in Mali to select superior baobab trees showed that that the combination of nutritional and morphological traits would be a key prerequisite for selecting mother trees (Simbo *et al.*, 2013). Training of local farmers on the nutritional importance of the tree would have significant impact on its utilization and conservation. In addition, selection of mother trees would require traditional knowledge since different communities have preference to certain traits over others (Sanchez *et al.*, 2011). Besides traits desired by local farmers and consumers, the preference of the international market should also be considered when domesticating this tree. Based on the present study, domesticating baobabs in the underutilized regions will contribute significantly to the availability of such nutrients leading to improved food and nutrient security, health and community welfare.

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions are drawn from this study:

i. Baobab fruit pulp and seeds contain significant amounts of macronutrients that can serve as a good source of dietary fibre, protein and fat. The pulp is of low moisture content (<11%) and generally considered as dry and this implies that the fruit can have a higher shelf-life that most other fruits in the same ecology. The levels of these macronutrients, moisture and ash in baobab fruit pulp and seeds vary across countries.

ii. The dry fruit pulp is an excellent source of calcium, potassium, sodium, iron and zinc whereas the seeds are rich in phosphorus, potassium, calcium, magnesium, copper, iron and zinc. Generally, both tissues are good dietary sources of nutritionally essential minerals. The concentration of these elements in the plant tissues varies across geographical regions with baobabs from Malawi having the highest content of macro elements.

iii. The major fatty acids of baobab seed oil are oleic acid, linoleic acid and palmitic acid whereas linolenic and stearic acids are the minor fatty acids. Thus, the seed oil has a high ratio of unsaturated to saturated fatty acids. The quantities of individual fatty acids vary between trees and even among the study countries. However, the general order of accumulation (oleic > linoleic > palmitic > stearic > linolenic) remains conserved in all baobab seed oil samples.

iv. Baobab fruit pulp is a rich source of vitamin C. Among all the micronutrients of the pulp, vitamin C is the most abundant with the levels varying between trees, within and between provenances and among countries.

5.2 Recommendations

The following recommendations are drawn from this study:

i. Baobab fruit pulp and seeds should be pursued as supplement to the diets of rural and urban communities who often lack enough supply of nutrients such as fibre, protein, fat and minerals. Health and nutrition projects should be adopted with the theme of promoting baobab products for value addition and increased utilization in East Africa, a region where they remain underutilized. Such projects should focus on children in schools who are in macro nutrients to boost their health.

ii. The existing baobab populations should be conserved both *in situ* and *ex situ*. Germplasm for conservation should be collected from the elite provenances from this study. For instance, Mopti, Taita, Moshi Rural provenances should be exploited for collection of germplasm when sourcing for trees with high vitamin C content whereas Malindi and Kibwezi should be conserved for harvesting pulp rich in dietary fibre. The cultivation techniques should entail vegetative propagation such as grafting to conserve the desirable traits of superior trees. The domestication and breeding programmes should be linked to market expansion and commercialization. The acceptance of baobab products in the US and EU markets reflects the existence of a growing market.

iii. Soil physio-chemical properties and genetic studies should be conducted within populations and further correlated to the nutritional data to understand the effects of soil types and genetics on nutritional content of baobabs. The genetic investigations may be conducted in field or laboratory to ensure uniformity of the environmental conditions.

iv. The effects of fruit storage and processing on nutrient content and bioavailability should also be studied. Both storage and processing techniques influence various biochemical and physiological changes in fruits.

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APPENDICES

Appendix 1a: Table of mean square errors (MSE) from the ANOVA table (Kibwezi & Malindi) and *P* – value from T-test (Taita) on proximate composition of baobab fruit pulp among trees in Kenyan provenances

Source of variation	DF	moisture	Crude protein	Crude fibre	Ash
Trees (Kibwezi)	4	0.023^{***}	0.2675^{***}	4.024^{NS}	0.442^{***}
Trees (Malindi)	4	0.002^{NS}	0.2667^{NS}	2.52^{NS}	0.4625^{***}
Trees (Taita)	*P*-value	NS	*	NS	NS

Appendix 1b: Table of mean square errors (MSE) from the ANOVA table (Kibwezi & Malindi) and *P* – value from T-test (Taita) on proximate composition of baobab seeds among trees in Kenyan provenances

Source of variation	DF	moisture	C. protein	C. Fibre	C. Fat	Carbohydrates	Ash
Trees (kibwezi)	4	0.066^{***}	4.145^{**}	11.598^{*}	7.594^{***}	12.756^{**}	0.086^{NS}
Trees (Malindi)	4	0.226^{***}	6.050^{***}	20.97^{NS}	3.794^{*}	9.141^{**}	0.117^{**}
Trees (Taita)	*P*-value	*	NS	NS	*	NS	NS

Appendix 1c: Table of mean square errors (MSE) from the ANOVA table (Kibwezi & Malindi) and *P* – value from T-test (Taita) on elemental composition of baobab fruit pulp among trees in Kenyan provenances

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Trees. KB	4	0.039***	0.230^{*} **	0.003^{*} **	0.00000^{NS}	2.836***	116.45***	163.89***	72.85^{*} **	8.545^{NS}
Trees. ML	4	0.008***	0.3732***	0.0005***	0.0027^{NS}	3.045***	184.93***	74.89^{*} *	261.03***	906.63***
Trees. TT	*P*-	*	*	NS	NS	**	*	NS	NS	NS

SoV: Source of variation; KB: Kibwezi; ML: Malindi; TT: Taita

Appendix 1d: Table of mean square errors (MSE) from the ANOVA table (Kibwezi & Malindi) and *P* – value from T-test (Taita) on elemental composition of baobab seeds among trees in Kenyan provenances

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Trees.KB	4	0.008***	0.009*	0.003NS	0.0000NS	0.011***	8.588**	474.0**	60.55**	81.45**
Trees.ML	4	0.005***	0.003NS	0.002**	0.00005NS	0.027***	26.24***	550.37***	106.09***	10.177***
Trees.TT	*P*-	NS	NS	NS	NS	NS	**	**	*	**

KB: Kibwezi; ML: Malindi; TT: Taita

Appendix1e: Table of mean square errors (MSE) from the ANOVA table (Kibwezi & Malindi) and *P* – value from T-test (Taita) on fatty acid composition of baobab seeds among trees in Kenyan provenances

Source of variation	DF	palmitic	Stearic	Oleic	Linoleic	Linolenic
Trees.KB	6	2.041*	0.022NS	12.724***	26.22NS	0..095**
Trees.ML	6	7.309**	0.051NS	10.099NS	10.250NS	0.084NS
Trees.TT	*P*-	NS	NS	NS	NS	NS

Appendix 1f: Table of mean square errors (MSE) from the ANOVA table (Kibwezi & Malindi) and *P* – value from T-test (Taita) on vitamin C composition of baobab fruit pulp among trees in Kenyan provenances

Source of variation	DF	Vit C
Trees (Kibwezi)	4	62358.***
Trees (Malindi)	4	12885.7***
Trees (Taita)	*P*-value	NS

Appendix 2a: Table of mean square errors (MSE) from the ANOVA table on proximate analysis of baobab pulp among trees in Zambian provenances

Source of variation	DF	moisture	Crude protein	Crude fibre	Ash
Trees (Chirundu)	6	0.1702***	0.3130**	2.3067^{NS}	1.3699***
Trees (Mambwe)	6	0.0293**	0.1401**	2.6683^{NS}	0.0847**
Trees (Siavonga)	6	0.0221*	0.4320***	1.7359***	0.6052***

Appendix 2b: Table of mean square errors (MSE) from the ANOVA table on proximate analysis of baobab seeds among trees in Zambian provenances

Source of variation	DF	moisture	C. protein	C. Fibre	C. Fat	Carbohydrates	Ash
Trees (Chirundu)	6	0.4641***	0.940^{NS}	5.6693***	5.9625**	7.121*	0.0493**
Trees (Mambwe)	6	0.2226***	7.3134*	0.7827***	8.4092**	19.397**	0.1569**
Trees (Siavonga)	6	0.2183**	0.9025^{NS}	5.1477***	3.272^{NS}	3.343^{NS}	0.2238***

Appendix 2c: Table of mean square errors (MSE) from the ANOVA table on elemental analysis of baobab pulp among trees in Zambian provenances

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Trees. CH	6	0.0113***	0.2840***	0.0096***	0.0003^{NS}	1.799***	436.62***	226.601***	5.08***	15.260***
Trees. MB	6	0.0111***	0.3261***	0.0015***	0.0001^{NS}	4.979***	14.839***	221.06**	17.394***	202.76***
Trees. SV	6	0.0191***	0.2593***	0.0019***	0.0006**	4.818***	36.71**	32.615**	31.28**	232.90***

CH: Chirundu provenance, MB: Mambwe provenance, SV: Siavonga provenance

Appendix 2d: Table of mean square errors (MSE) from the ANOVA table on elemental analysis of baobab seeds among trees in Zambian provenances

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Trees. CH	6	0.0043***	0.0138**	0.0196***	0.00001NS	0.1130***	178.96***	58.89**	124.10***	25.34**
Trees. MB	6	0.0044***	0.0219***	0.0029***	0.00001NS	0.0196***	111.00***	94.289***	8.6971***	118.08***
Trees. SV	6	0.0028***	0.0308***	0.0042NS	0.00005NS	0.0282***	26.94**	98.74**	50.22**	10.173*

CH: Chirundu provenance, MB: Mambwe provenance, SV: Siavonga provenance

Appendix 2e: Table of mean square errors (MSE) from the ANOVA table on fatty acids analysis of baobab seeds among trees in Zambian provenances

Source of variation	DF	palmitic	Stearic	Oleic	Linoleic	Linolenic
Trees (Chirundu)	6	7.8160***	0.1766***	2.537NS	14.10NS	0.0054NS
Trees (Mambwe)	6	12.6005***	0.0513NS	44.668***	24.887***	0.051NS
Trees (Siavonga)	6	13.0732***	0.1651**	34.840***	8.117**	0.0956NS

Appendix 2f: Table of mean square errors (MSE) from the ANOVA table on Vitamin C analysis of baobab pulp among trees in Zambian provenances

Source of variation	df	Vitamin C
Trees (Chirundu)	7	16684.0***
Trees (Mambwe)	20	11998.0***
Trees (Siavonga)	17	13148.0***

Appendix 3a: Table of mean square errors (MSE) from the ANOVA table on proximate composition of baobab fruit pulp among trees in Tanzanian provenances

Source of variation	DF	moisture	Crude protein	Crude fibre	Ash
Trees (kilolo)	6	1.2648^{*}	1.2567^{***}	1.749^{NS}	0.2811^{***}
Trees (kongwe)	6	1.2791^{***}	0.0459^{NS}	0.8071^{NS}	0.6338^{***}
Trees (Moshi)	6	0.2612^{*}	0.3377^{***}	0.4642^{***}	0.2402^{***}
Trees (mwanga)	6	0.0418^{**}	0.8354^{***}	2.1906^{***}	0.6467^{***}

Appendix 3b: Table of mean square errors (MSE) from the ANOVA table on proximate analysis of baobab seeds among trees in Tanzanian provenances

Source of variation	DF	moisture	C. protein	C. Fibre	C. Fat	Carbohydrates	Ash
Trees (kilolo)	6	1.4757^{***}	1.6809^{NS}	2.3696^{***}	6.817^{***}	9.1455^{**}	0.0526^{**}
Trees (kongwe)	6	0.5333^{***}	1.6147^{*}	2.5537^{**}	2.5334^{***}	4.768^{**}	0.0663^{*}
Trees (Moshi)	6	0.2041^{***}	6.9706^{**}	4.8604^{*}	1.8952^{**}	14.9152^{***}	0.6282^{***}
Trees (mwanga)	6	0.1387^{***}	4.1305^{**}	5.7871^{***}	1.708^{NS}	7.454^{*}	0.2394^{*}

Appendix 3c: Table of mean square errors (MSE) from the ANOVA table on elemental composition of baobab fruit pulp among trees in Tanzanian provenances

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
T.Kilolo	6	0.0041^{***}	0.1491^{***}	0.0023^{***}	0.0001^{NS}	0.00004^{NS}	28.97^{*}	44.83^{***}	0.8095^{NS}	92.167^{***}
T.Kongwe	6	0.0049^{***}	0.1374^{***}	0.011^{***}	0.0001^{NS}	0.00009^{*}	2.95^{NS}	2.786^{NS}	1.500^{NS}	19.33^{NS}
T.Moshi	6	0.0004^{*}	0.0433^{***}	0.0077^{***}	0.0003^{***}	0.000016^{**}	29.735^{***}	118.67^{***}	34.476^{***}	198.14^{***}
T.Mwanga	6	0.0146^{***}	0.0438^{***}	0.0027^{***}	0.00002^{NS}	1.955^{***}	46.47^{***}	147.19^{***}	32.443^{***}	187.21^{***}

SoV: Source of variation; T. Trees

Appendix 3d: Table of mean square errors (MSE) from the ANOVA table on elemental analysis of baobab seeds among trees in Tanzanian provenances

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Trees.Kilolo	6	0.0176^{***}	0.0129^{**}	0.0009^{*}	2.350^{***}	0.0100^{***}	98.90^{***}	200.95^{***}	1.738^{*}	26.952^{*}
Trees.Kongwe	6	0.0056^{***}	0.0137^{**}	0.0016^{**}	1.261^{***}	0.0220^{*}	302.95^{***}	439.64^{***}	2.785^{*}	73.238^{**}
Trees.Moshi	6	0.0085^{***}	0.0138^{**}	0.0022^{***}	1.517^{**}	0.0110^{***}	7.405^{NS}	12.452^{NS}	2.952^{*}	11.62^{NS}
Trees.Mwanga	6	0.0025^{***}	0.0053^{*}	0.0009^{*}	0.00007^{NS}	0.0058^{***}	270.44^{***}	393.03^{***}	7.817^{***}	260.59^{***}

Appendix 3e: Table of mean square errors (MSE) from the ANOVA table on fatty acids analysis of baobab seeds among trees in Tanzanian provenances

Source of variation	DF	palmitic	Stearic	Oleic	Linoleic	Linolenic
Trees (kilolo)	6	7.9405^{**}	0.554^{NS}	87.960^{***}	39.602^{***}	0.1118^{*}
Trees (kongwe)	6	10.0117^{**}	0.0530^{NS}	73.136^{***}	36.567^{***}	0.0742^{NS}
Trees (Moshi)	6	20.2442^{***}	0.0577^{*}	143.20^{**}	89.830^{**}	0.0733^{NS}
Trees (mwanga)	6	6.9800^{**}	0.0664^{NS}	33.37^{NS}	6.50^{NS}	0.07095^{NS}

Appendix 3f: Table of mean square errors (MSE) from the ANOVA table on vitamin C content of baobab fruit pulp among trees in Tanzanian provenances

Source of variation	df	Vitamin C
Trees (kilolo)	25	17950.0^{***}
Trees (kongwe)	26	9277.7^{***}
Trees (Moshi)	24	15503.1^{***}
Trees (mwanga)	7	33761.1^{***}

Appendix 4a: Table of mean square errors (MSE) from the ANOVA table on proximate analysis of baobab pulp among trees in Malian provenances

Source of variation	DF	moisture	Crude protein	Crude fibre	Ash
Trees (Mopti)	6	0.2825^{***}	0.2784^{***}	2.3157^{NS}	0.3121^{NS}
Trees (Sikasso)	6	0.0126^{***}	0.0273^{***}	0.763^{NS}	0.354^{NS}
Trees (Kayes)	5	0.009^{*}	0.2585^{***}	0.3767^{NS}	0.1803^{NS}
Trees (Seguo)	6	0.020^{*}	0.1845^{***}	2.045^{NS}	0.400^{**}

Appendix 4b: Table of mean square errors (MSE) from the ANOVA table on proximate analysis of baobab seeds among trees in Malian provenances

Source of variation	DF	moisture	C. protein	C. Fibre	C. Fat	Carbohydrates	Ash
Trees (Mopti)	6	0.099^{*}	9.070^{***}	8.041^{***}	5.230^{***}	20.99^{***}	0.1251^{**}
Trees (Sikasso)	6	0.050^{***}	2.067^{*}	2.128^{***}	2.456^{***}	9.248^{***}	0.208^{**}
Trees (Kayes)	5	0.2438^{***}	4.517^{NS}	3.643^{***}	3.608^{**}	10.668^{**}	0.2494^{*}
Trees (Seguo)	6	0.046^{***}	5.947^{*}	1.828^{***}	3.175^{NS}	13.789^{*}	0.2386^{**}

Appendix 4c: Table of mean square errors (MSE) from the ANOVA table on elemental analysis of baobab pulp among trees in Malian provenances

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Trees (Mopti)	6	0.009^{***}	0.134^{***}	4.512^{***}	0.00001^{NS}	0.0001^{**}	436.4^{***}	16.45^{***}	5.738^{***}	69.83^{***}
Trees (Sikasso)	6	0.005^{***}	0.047^{***}	0.0004^{**}	0.00004^{NS}	8.333^{**}	2.786^{NS}	41.11^{***}	2.285^{**}	82.81^{***}
Trees (Kayes)	5	0.006^{*}	0.1886^{*}	0.003^{***}	0.0002^{NS}	0.0001^{NS}	83.75^{NS}	121.35^{NS}	16.48^{NS}	165.60^{NS}
Trees (Seguo)	6	0.020^{***}	1.485^{***}	0.001^{***}	1.820^{***}	0.00004^{NS}	31.12^{**}	302.7^{***}	15.40^{***}	27.16^{***}

Appendix 4d: Table of mean square errors (MSE) from the ANOVA table on elemental analysis of baobab seeds among trees in Malian provenances

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Trees (Mopti)	6	0.005^{***}	0.019^{***}	0.002^{***}	8.238^{*}	0.021^{***}	4.00^{NS}	417.90^{***}	5.33^{NS}	23.31^{**}
Trees (Sikasso)	6	0.001^{***}	0.007^{**}	0.005^{**}	2.390^{***}	0.005^{***}	3.405^{NS}	867.64^{***}	5.119^{NS}	85.57^{***}
Trees (Kayes)	5	0.008^{***}	0.011^{**}	0.0008^{*}	1.960^{**}	0.009^{***}	3.283^{NS}	14.88^{**}	3.800^{NS}	25.33^{**}
Trees (Seguo)	6	0.008^{***}	0.164^{NS}	0.0009^{**}	3.612^{***}	0.016^{***}	238.9^{***}	625.9^{***}	7.66^{**}	373.9^{***}

Appendix 4e: Table of mean square errors (MSE) from the ANOVA table on fatty acid analysis of baobab seeds among trees in Malian provenances

Source of variation	DF	palmitic	Stearic	Oleic	Linoleic	Linolenic
Trees (Mopti)	6	12.26^{***}	0.047^{NS}	54.25^{***}	26.072^{NS}	0.042^{NS}
Trees (Sikasso)	6	9.608^{NS}	0.1326^{***}	76.80^{***}	31.38^{***}	0.065^{NS}
Trees (Kayes)	5	5.905^{NS}	0.319^{**}	8.149^{*}	11.204^{NS}	0.069^{NS}
Trees (Seguo)	6	12.14^{***}	0.066^{NS}	83.72^{***}	12.75^{**}	0.089^{***}

Appendix 4f: Table of mean square errors (MSE) from the ANOVA table on Vitamin C analysis of baobab pulp among trees in Malian provenances

Source of variation	DF	Vitamin C
Trees (Mopti)	6	$32086.^{***}$
Trees (Sikasso)	6	$14426.^{*}$
Trees (Kayes)	5	$22590.^{*}$
Trees (Seguo)	8	$29529.^{***}$

Appendix 5a: Table of mean square errors (MSE) from the ANOVA table on proximate analysis of baobab seeds among trees in Zimbabwe provenances

Source of variation	DF	moisture	C. protein	C. Fibre	C. Fat	Carbohydrates	Ash
Trees (FRC)	6	0.619^{***}	4.950^{**}	10.810^{***}	1.007^{NS}	8.688^{*}	1.319^{***}
Trees (Hwange)	6	0.594^{***}	4.663^{NS}	4.482^{***}	5.830^{NS}	20.155^{*}	0.718^{***}

Appendix 5b: Table of mean square errors (MSE) from the ANOVA table on elemental analysis of baobab seeds among trees in Zimbabwe provenances

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Trees (FRC)	6	0.003^{***}	0.008^{**}	0.001^{**}	0.00001^{NS}	0.019^{***}	236.3^{***}	95.50^{***}	10.26^{***}	402.1^{***}
Trees (Hwange)	6	0.005^{***}	0.006^{*}	0.001^{***}	0.00001^{NS}	0.007^{***}	63.36^{***}	646.9^{***}	11.43^{***}	33.608^{***}

Appendix 5c: Table of mean square errors (MSE) from the ANOVA table on fatty acids analysis of baobab seeds among trees in Zimbabwe provenances

Source of variation	DF	palmitic	Stearic	Oleic	Linoleic	Linolenic
Trees (FRC)	6	8.836^{***}	0.08^{NS}	22.61^{***}	7.805^{NS}	0.084^{NS}
Trees (Hwange)	6	24.37^{**}	0.103^{NS}	63.117^{***}	21.020^{NS}	0.043^{NS}

Appendix 6a: Table of mean square errors (MSE) from the ANOVA table on proximate analysis of baobab pulp & seeds among trees in Malawi

Source of variation	DF	moisture	C. protein	C. Fibre	C. Fat	Carbohydr-ates	Ash
Mangochi (pulp)	6	0.3024^{***}	0.6079^{***}	1.6889^{***}	NA	NA	0.7608^{***}
Mangochi (Seeds)	6	0.3160^{***}	1.6448^{**}	2.7173^{***}	2.6453^{***}	2.3230^{NS}	0.2104^{***}

Appendix 6b: Table of mean square errors (MSE) from the ANOVA table on elemental analysis of baobab pulp & seeds among trees in Malawi

SoV	DF	Ca	K	Mg	Na	P	Cu	Fe	Mn	Zn
Mangochi Trees (pulp)	6	0.007^{***}	0.045^{**}	0.002^{***}	1.535^{***}	2.396^{***}	16.405^{NS}	7.643^{NS}	2.452^{NS}	23.905^{*}
Mangochi Trees (Seeds)	6	0.004^{***}	0.020^{***}	0.0003^{NS}	6.431^{NS}	0.007^{***}	8.500^{NS}	54.83^{*}	4.405^{*}	27.310^{*}

Appendix 6c: Analysis of variance on Vitamin c content of baobab pulp from Malawi

Variate: **vit_c**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
tree	22	260699.5	11850.0	12.14	<.001
Residual	46	44891.2	975.9		
Total	68	305590.7			

Appendix 6d: Table of mean square errors (MSE) from the ANOVA table on fatty acids of baobab seeds among trees in Malawi

Source of Variation	DF	Palmitic	Stearic	Oleic	Linoleic	Linolenic
Trees	6	6.039^{***}	0.165^{**}	68.62^{***}	18.19^{NS}	0.019^{NS}

Appendix 7: Baobab fruit pulp moisture, protein, fibre, ash and vitamin C content according to the study provenances

Provenance	Moisture (g 100 g^{-1})	Crude protein (g 100 g^{-1} dw)	Crude fibre (g 100 g^{-1} dw)	Ash (g 100 g^{-1} dw)	Vitamin C (mgg^{-1})
Kibwezi	9.79 ± 0.026^{abc}	2.42 ± 0.051^{b}	8.44 ± 1.937^{ab}	4.23 ± 0.099^{bc}	2.34 ± 0.268^{i}
Taita	9.82 ± 0.032^{ab}	2.08 ± 0.195^{cd}	7.82 ± 0.828^{abc}	4.66 ± 0.090^{ab}	4.34 ± 0.278^{a}
Malindi	9.85 ± 0.027^{a}	2.04 ± 0.313^{cdef}	9.61 ± 3.428^{a}	4.48 ± 0.122^{ab}	2.31 ± 0.203^{b}i
Chirundu	8.82 ± 0.063^{e}	2.06 ± 0.158^{cde}	7.10 ± 0.823^{bc}	4.51 ± 0.130^{ab}	3.17 ± 0.281^{efg}
Siavonga	8.95 ± 0.063^{e}	2.65 ± 0.059^{a}	7.75 ± 0.048^{bc}	4.68 ± 0.084^{a}	3.23 ± 0.341^{ef}
Mambwe	8.89 ± 0.054^{e}	2.02 ± 0.111^{cdef}	6.42 ± 0.943^{c}	3.82 ± 0.085^{c}	3.37 ± 0.330^{de}
Kilolo	9.77 ± 0.436^{abc}	2.44 ± 0.138^{b}	6.80 ± 0.945^{c}	4.40 ± 0.130^{ab}	3.14 ± 0.261^{fg}
Kongwe	9.24 ± 0.267^{bde}	1.58 ± 0.135^{i}	6.84 ± 1.090^{bc}	3.98 ± 0.155^{c}	3.71 ± 0.249^{bc}
Moshi rural	8.98 ± 0.224^{e}	1.82 ± 0.027^{gh}	6.54 ± 0.083^{c}	4.54 ± 0.088^{a}	3.91 ± 0.233^{ab}
Mwanga	8.97 ± 0.063^{e}	2.15 ± 0.179^{c}	7.51 ± 0.291^{bc}	4.59 ± 0.118^{ab}	3.59 ± 0.309^{cd}
Mopti	9.57 ± 0.070^{abcd}	1.97 ± 0.053^{defg}	6.35 ± 0.940^{c}	3.40 ± 0.586^{d}	4.02 ± 0.556^{a}
Sikasso	9.89 ± 0.016^{a}	1.86 ± 0.033^{dfgh}	6.63 ± 0.451^{c}	3.97 ± 0.765^{c}	3.13 ± 0.485^{efg}
Kayes	9.94 ± 0.038^{a}	1.73 ± 0.090^{hi}	6.52 ± 0.482^{c}	3.86 ± 0.383^{c}	2.98 ± 0.577^{fgh}
Seguo	9.88 ± 0.057^{a}	1.87 ± 0.108^{dfgh}	7.25 ± 0.799^{bc}	4.21 ± 0.181^{bc}	2.73 ± 0.394^{hi}
Mangochi	8.94 ± 0.071^{e}	1.91 ± 0.039^{defg}	7.27 ± 0.083^{bc}	4.40 ± 0.054^{ab}	2.97 ± 0.312^{gh}
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
cv	4.0	6.2	15.6	7.1	11.4

Moisture and Vitamin C expressed on fresh weight basis

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. CV: Coefficient of variation

Appendix 8: Baobab seeds' proximate composition according to the study provenances

provenance	Moisture (g 100 g^{-1})	Protein (g 100 g^{-1} dw)	Fibre (g 100 g^{-1} dw)	Fat (g 100 g^{-1} dw)	Carbohydrates (g 100 g^{-1} dw)	Ash (g 100 g^{-1} dw)
Kibwezi	6.97 ± 0.043^{abc}	14.99 ± 0.466^{ab}	22.47 ± 1.310^{efg}	12.62 ± 0.326^{abc}	61.11 ± 0.857^{fg}	4.01 ± 0.290^{ab}
Taita	7.01 ± 0.056^{ab}	15.93 ± 0.300^{a}	20.93 ± 3.364^{g}	13.49 ± 0.350^{a}	59.50 ± 0.574^{g}	3.78 ± 0.051^{ab}
Malindi	7.04 ± 0.088^{a}	13.26 ± 0.258^{d}	25.11 ± 3.620^{ab}	11.77 ± 0.677^{abcd}	63.74 ± 0.561^{cde}	3.89 ± 0.062^{ab}
Chirundu	6.31 ± 0.145^{bdef}	13.46 ± 1.045^{d}	22.90 ± 0.447^{defg}	11.21 ± 0.713^{acd}	64.91 ± 1.304^{bcd}	4.10 ± 0.080^{ab}
Siavonga	6.50 ± 0.156^{abcde}	13.85 ± 0.535^{bd}	23.58 ± 0.273^{cde}	10.35 ± 1.354^{d}	65.16 ± 1.426^{bc}	4.14 ± 0.087^{ab}
Mambwe	6.20 ± 0.104^{befg}	14.00 ± 1.000^{bcd}	22.32 ± 0.139^{efg}	12.53 ± 0.805^{abc}	63.43 ± 1.495^{de}	3.83 ± 0.108^{b}
Kilolo	6.61 ± 0.175^{abcde}	16.02 ± 0.895^{a}	23.29 ± 0.175^{cde}	13.04 ± 0.264^{abc}	60.03 ± 0.935^{g}	4.31 ± 0.082^{ab}
Kongwe	6.95 ± 0.175^{abc}	15.10 ± 0.568^{a}	22.31 ± 0.513^{efg}	13.35 ± 0.209^{ab}	60.50 ± 0.647^{g}	4.09 ± 0.108^{ab}
Moshi	6.81 ± 0.090^{abcd}	13.17 ± 0.733^{d}	26.25 ± 0.960^{a}	11.93 ± 0.354^{abcd}	64.23 ± 0.649^{bcd}	3.86 ± 0.163^{b}
Mwanga	6.26 ± 0.076^{bef}	15.38 ± 0.681^{a}	23.47 ± 0.386^{cde}	12.08 ± 1.249^{abcd}	62.22 ± 1.282^{ef}	4.06 ± 0.234^{a}
Mopti	5.51 ± 0.151^{h}	13.09 ± 0.338^{d}	23.99 ± 0.226^{bcd}	11.43 ± 0.303^{abcd}	65.82 ± 0.547^{b}	4.14 ± 0.124^{ab}
Sikasso	5.86 ± 0.058^{fgh}	12.93 ± 0.668^{d}	23.20 ± 0.212^{def}	11.98 ± 0.268^{abcd}	64.83 ± 0.681^{bcd}	4.39 ± 0.140^{a}
Kayes	5.58 ± 0.079^{h}	13.66 ± 1.034^{d}	23.05 ± 0.306^{defg}	12.36 ± 0.519^{abcd}	64.50 ± 0.890^{bcd}	3.89 ± 0.201^{ab}
Seguo	5.71 ± 0.038^{gh}	11.21 ± 0.973^{e}	24.63 ± 0.346^{bc}	11.45 ± 1.352^{abcd}	67.44 ± 1.490^{a}	4.19 ± 0.171^{ab}
FRC	5.92 ± 0.144^{fgh}	14.98 ± 0.423^{abc}	22.55 ± 0.598^{efg}	12.88 ± 0.236^{abc}	62.26 ± 0.596^{ef}	3.96 ± 0.209^{ab}
Hwange	5.85 ± 0.140^{fgh}	13.92 ± 0.469^{bcd}	21.81 ± 0.385^{fg}	11.48 ± 0.510^{abcd}	65.76 ± 0.929^{b}	3.00 ± 0.157^{c}
mangochi	5.90 ± 0.118^{fgh}	15.18 ± 0.391^{a}	23.56 ± 0.136^{cde}	12.66 ± 0.510^{efgh}	62.08 ± 0.811^{cde}	4.18 ± 0.109^{ab}
P-values	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

cv	6.6	5.8	4.5	12.2	1.9	9.6

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. CV: Coefficient of variation

Appendix 9: Baobab fruit pulp mineral element concentration according to the study provenances

Provenance	Ca ($mgkg^{-1}$)	K (mgg^{-1})	Mg ($mgkg^{-1}$)	Na ($mgkg^{-1}$)	P ($mgkg^{-1}$)	Cu (μgg^{-1})	Fe (μgg^{-1})	Mn (μgg^{-1})	Zn (μgg^{-1})
Kibwezi	2800 ± 100^{e}	18.5 ± 0.05^{fg}	1300 ± 50^{fg}	300 ± 100^{efg}	570 ± 20^{e}	47.1 ± 0.80^{def}	61.5 ± 2.14^{ab}	26.3 ± 0.48^{b}	81.3 ± 2.49^{a}
Taita	2400 ± 80^{fg}	17.6 ± 0.62^{gh}	1600 ± 50^{de}	300 ± 70^{efg}	750 ± 30^{cd}	49.1 ± 0.86^{cde}	58.0 ± 2.23^{b}	23.8 ± 0.43^{a}	79.1 ± 2.08^{a}
Malindi	2900 ± 100^{de}	25.3 ± 0.89^{a}	1200 ± 40^{g}	700 ± 230^{bc}	570 ± 20^{e}	42.3 ± 0.75^{fgh}	53.1 ± 1.84^{c}	29.5 ± 0.56^{cd}	58.9 ± 2.10^{c}
Chirundu	3000 ± 110^{d}	21.1 ± 0.74^{de}	1700 ± 60^{cd}	700 ± 210^{bc}	850 ± 30^{b}	45.1 ± 0.82^{defg}	40.7 ± 1.48^{e}	11.3 ± 0.20^{g}	16.6 ± 0.57^{h}
Siavonga	3600 ± 130^{bc}	17.2 ± 0.61^{h}	1900 ± 70^{b}	200 ± 80^{fg}	730 ± 30^{d}	43.8 ± 0.76^{efgh}	45.7 ± 1.30^{d}	23.6 ± 0.97^{d}	66.2 ± 3.38^{b}
Mambwe	2900 ± 100^{de}	21.9 ± 0.77^{cd}	1200 ± 40^{g}	400 ± 110^{ef}	780 ± 30^{cd}	39.9 ± 0.83^{h}	58.5 ± 2.05^{b}	23.4 ± 0.42^{d}	41.2 ± 1.50^{d}
Kilolo	3600 ± 100^{bc}	19.3 ± 0.55^{f}	1200 ± 40^{fg}	700 ± 80^{bc}	770 ± 50^{cd}	46.8 ± 2.74^{def}	16.5 ± 0.96^{g}	3.7 ± 0.53^{h}	26.0 ± 1.46^{fg}
Kongwe	3500 ± 130^{bc}	18.7 ± 0.54^{fg}	1800 ± 60^{c}	800 ± 80^{b}	740 ± 50^{d}	49.1 ± 3.66^{d}	17.6 ± 1.22^{g}	5.0 ± 1.55^{h}	26.0 ± 7.09^{fg}
Moshi R	3400 ± 90^{c}	20.3 ± 0.46^{e}	1900 ± 180^{b}	600 ± 40^{c}	800 ± 50^{bc}	53.6 ± 1.46^{bc}	38.0 ± 1.07^{e}	13.8 ± 0.70^{f}	39.2 ± 1.67^{de}
Mwanga	2200 ± 80^{g}	23.1 ± 0.82^{b}	1300 ± 50^{f}	200 ± 70^{g}	570 ± 20^{e}	41.5 ± 0.72^{gh}	64.1 ± 2.23^{a}	25.2 ± 0.46^{bc}	63.1 ± 2.17^{bc}
Mopti	1800 ± 70^{h}	13.8 ± 0.40^{j}	1200 ± 30^{fg}	400 ± 8^{ef}	840 ± 40^{b}	56.5 ± 3.31^{ab}	12.8 ± 0.84^{h}	4.4 ± 0.37^{h}	23.5 ± 1.33^{g}
Sikasso	2400 ± 80^{f}	13.3 ± 0.40^{j}	1500 ± 50^{e}	600 ± 80^{cd}	850 ± 30^{b}	44.8 ± 2.64^{efg}	13.1 ± 0.85^{h}	3.8 ± 0.53^{h}	22.3 ± 1.31^{g}
Kayes	3000 ± 360^{de}	13.7 ± 1.53^{j}	1900 ± 100^{b}	600 ± 90^{cd}	760 ± 90^{cd}	58.7 ± 9.70^{a}	14.7 ± 6.92^{gh}	14.0 ± 3.84^{f}	35.5 ± 7.24^{e}
Seguo	2900 ± 90^{de}	15.6 ± 0.50^{i}	1700 ± 70^{cd}	600 ± 20^{cd}	840 ± 40^{b}	53.3 ± 1.53^{bc}	12.0 ± 0.59^{h}	13.0 ± 0.59^{f}	30.0 ± 0.84^{f}
Mangochi	4300 ± 120^{a}	22.2 ± 0.64^{bc}	2300 ± 60^{a}	1000 ± 30^{a}	1100 ± 30^{a}	28.9 ± 2.40^{i}	26.7 ± 2.20^{f}	16.3 ± 0.80^{e}	22.5 ± 2.00^{g}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
cv	4.4	3.8	4.6	19.1	5.3	6.7	6.8	8.0	8.1

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. CV: Coefficient of variation

Appendix 10: Baobab seeds' mineral element concentration according to the study provenances

Provenance	Ca ($mgkg^{-1}$)	K (mgg^{-1})	Mg ($mgkg^{-1}$)	Na ($mgkg^{-1}$)	P ($mgkg^{-1}$)	Cu (μgg^{-1})	Fe (μgg^{-1})	Mn (μgg^{-1})	Zn (μgg^{-1})
Kibwezi	1900 ± 60^{j}	9.1 ± 0.29^{def}	3320 ± 120^{gij}	170 ± 50^{h}	5.6 ± 0.19^{i}	28.2 ± 0.775^{ij}	70.0 ± 2.598^{a}	19.3 ± 0.734^{e}	23.2 ± 0.811^{i}
Taita	1800 ± 60^{j}	9.7 ± 0.34^{bcdef}	3580 ± 130^{efg}	190 ± 60^{gh}	6.2 ± 0.21^{def}	30.3 ± 0.533^{hi}	67.3 ± 2.397^{a}	15.2 ± 0.275^{f}	36.1 ± 1.392^{bc}
Malindi	2350 ± 80^{gh}	8.9 ± 0.31^{def}	3240 ± 110^{j}	200 ± 60^{gh}	6.5 ± 0.23^{cde}	25.7 ± 0.452^{jk}	56.0 ± 2.003^{cd}	23.1 ± 0.434^{bc}	14.6 ± 0.284^{k}
Chirundu	2340 ± 80^{ghi}	10.4 ± 0.36^{bcde}	3570 ± 138^{fgh}	200 ± 60^{gh}	7.5 ± 0.27^{b}	41.9 ± 0.748^{c}	48.1 ± 1.671^{fg}	23.1 ± 0.439^{bc}	28.7 ± 0.980^{efg}
Siavonga	2600 ± 100^{ef}	10.7 ± 0.37^{bcd}	3900 ± 340^{de}	220 ± 70^{gh}	8.2 ± 0.32^{a}	49.6 ± 0.870^{b}	51.6 ± 1.797^{ef}	24.2 ± 0.445^{ab}	36.1 ± 1.226^{b}
Mambwe	2500 ± 90^{f}	10.3 ± 0.36^{bcdef}	3450 ± 120^{ghij}	240 ± 70^{fgh}	7.6 ± 0.26^{b}	47.4 ± 0.837^{b}	53.5 ± 1.863^{de}	19.9 ± 0.363^{de}	30.9 ± 1.077^{de}
Kilolo	3500 ± 100^{a}	13.4 ± 0.36^{a}	4200 ± 120^{bc}	450 ± 10^{cd}	6.8 ± 0.19^{c}	24.5 ± 2.070^{kl}	36.6 ± 3.059^{h}	7.4 ± 0.655^{h}	28.1 ± 2.449^{fgh}
Kongwe	3500 ± 100^{a}	11.6 ± 0.33^{b}	4700 ± 130^{a}	540 ± 20^{b}	6.6 ± 0.74^{cd}	32.1 ± 2.828^{gh}	47.7 ± 4.080^{g}	7.8 ± 0.655^{gh}	33.0 ± 2.876^{cd}
Moshi R	2900 ± 80^{c}	14.0 ± 0.39^{a}	4000 ± 110^{cd}	470 ± 10^{c}	6.1 ± 0.18^{efgh}	22.9 ± 1.946^{l}	32.3 ± 2.739^{i}	7.6 ± 0.707^{h}	26.8 ± 2.449^{gh}
Mwanga	1900 ± 70^{j}	0.90 ± 0.31^{d}	3400 ± 120^{ghij}	250 ± 80^{fg}	5.7 ± 0.20^{fhi}	35.7 ± 0.652^{ef}	60.0 ± 2.272^{bc}	19.3 ± 0.352^{e}	19.9 ± 0.449^{j}
Mopti	2400 ± 70^{g}	10.9 ± 0.32^{ef}	3800 ± 110^{de}	390 ± 10^{de}	5.9 ± 0.17^{fghi}	37.0 ± 2.070^{de}	24.4 ± 1.604^{j}	23.0 ± 1.414^{c}	26.2 ± 1.535^{h}
Sikasso	2680 ± 80^{de}	9.4 ± 0.27^{cdef}	4000 ± 330^{cd}	380 ± 10^{e}	6.8 ± 0.20^{c}	35.4 ± 2.035^{ef}	24.2 ± 1.711^{j}	24.6 ± 1.336^{a}	26.0 ± 1.389^{h}
Kayes	2720 ± 80^{d}	9.6 ± 0.27^{cdef}	3700 ± 110^{ef}	400 ± 10^{cde}	5.5 ± 0.16^{i}	38.5 ± 2.255^{d}	17.9 ± 0.866^{k}	23.5 ± 1.291^{abc}	30.1 ± 1.683^{ef}
Seguo	2600 ± 80^{ef}	6.5 ± 4.76^{g}	3500 ± 100^{ghi}	300 ± 10^{f}	6.1 ± 0.20^{efg}	52.7 ± 1.946^{a}	35.7 ± 1.254^{hi}	24.0 ± 0.926^{abc}	42.6 ± 1.581^{a}
FRC	2500±100f	9.0 ± 0.17^{def}	3300 ± 70^{gij}	220 ± 10^{gh}	6.1 ± 0.21^{efg}	33.9 ± 2.791^{fg}	56.4 ± 1.80^{cd}	19.2 ± 0.585^{e}	22.6 ± 3.64^{i}
Hwange	2200±120h	8.6 ± 0.14^{f}	2900 ± 60^{k}	250 ± 10^{fg}	5.0 ± 0.09^{j}	31.1 ± 1.443^{h}	60.3 ± 4.63^{b}	20.5 ± 0.618^{d}	15.2 ± 1.05^{k}
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
cv	3.3	12.3	4.4	14.6	4.4	4.9	6.2	4.5	6.1

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. CV: Coefficient of variation

Appendix 11: Baobab seeds oil fatty acid concentration according to the study provenances

Provenance	Palmitic acid	Stearic acid	Oleic acid	Linoleic acid	Linolenic acid
Kibwezi	18.44 ± 0.503^{ef}	1.54 ± 0.140^{b}	33.94 ± 0.571^{de}	25.81 ± 3.955^{abcde}	0.84 ± 0.074^{b}
Taita	19.04 ± 0.961^{cdef}	1.59 ± 0.129^{b}	34.43 ± 0.725^{bcde}	27.89 ± 0.577^{ab}	0.75 ± 0.092^{b}
Malindi	17.47 ± 0.554^{fg}	1.43 ± 0.140^{a}	39.06 ± 1.855^{a}	19.62 ± 1.507^{i}	1.33 ± 0.416^{a}
Chirundu	21.09 ± 0.715^{ab}	1.19 ± 0.082^{acd}	35.83 ± 1.151^{bcd}	27.12 ± 3.300^{abc}	0.85 ± 0.104^{b}
Siavonga	20.50 ± 0.830^{abcd}	1.27 ± 0.125^{abcd}	37.08 ± 1.208^{abc}	28.08 ± 1.031^{a}	0.85 ± 0.177^{b}
Mambwe	20.13 ± 0.599^{bcd}	1.19 ± 0.162^{acd}	34.49 ± 0.843^{cde}	24.39 ± 1.147^{bcdefg}	0.88 ± 0.215^{b}
Kilolo	16.44 ± 0.874^{gh}	1.31 ± 0.202^{abcd}	32.13 ± 1.733^{e}	21.09 ± 1.066^{hi}	0.99 ± 0.161^{b}
Kongwe	15.36 ± 0.952^{hi}	1.05 ± 0.210^{d}	32.08 ± 1.324^{e}	21.93 ± 0.733^{fghi}	0.87 ± 0.184^{b}
Moshi	14.95 ± 0.849^{i}	1.30 ± 0.111^{abcd}	32.62 ± 3.578^{e}	21.99 ± 2.802^{fghi}	0.99 ± 0.197^{b}
Mwanga	19.30 ± 0.859^{de}	1.55 ± 0.472^{ab}	37.78 ± 4.405^{ab}	26.25 ± 4.069^{abcd}	1.01 ± 0.249^{b}
Mopti	17.70 ± 0.920^{fg}	1.37 ± 0.175^{abc}	33.93 ± 1.156^{de}	21.80 ± 2.813^{ghi}	0.88 ± 0.145^{b}
Sikasso	17.90 ± 1.749^{f}	1.55 ± 0.087^{ab}	32.09 ± 1.462^{e}	21.56 ± 1.183^{ghi}	0.89 ± 0.187^{b}
Kayes	17.08 ± 2.084^{fg}	1.49 ± 0.166^{abc}	32.38 ± 1.067^{e}	22.23 ± 2.202^{efghi}	0.96 ± 0.131^{b}
Seguo	17.74 ± 0.413^{fg}	1.52 ± 0.155^{ab}	33.14 ± 1.183^{de}	22.74 ± 0.970^{efghi}	0.87 ± 0.064^{b}
FRC	21.82 ± 0.561^{a}	1.42 ± 0.092^{abc}	34.13 ± 0.884^{de}	23.67 ± 0.664^{bdefgh}	0.87 ± 0.067^{b}
Hwange	22.87 ± 0.944^{abc}	1.50 ± 0.082^{ab}	33.29 ± 1.492^{de}	25.06 ± 0.987^{abcdef}	0.86 ± 0.053^{b}
mangochi	20.58 ± 0.507^{abcd}	1.47 ± 0.137^{abc}	33.80 ± 2.201^{de}	25.35 ± 2.103^{abcde}	0.79 ± 0.220^{b}
P-values	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
cv	5.3	15.6	6.0	10.1	21.1

For the same column, values (means ± S.E.M) followed by the same letter are not significantly different. CV: Coefficient of variation

Appendix 12: Table of mean square errors (MSE) from the ANOVA table on elemental concentration of baobab fruit pulp

Source of variation	df	Ca	K	Mg	Na	P	Cu	Fe	Zn
Country	4	0.1109***	4.2156***	0.0221***	0.0077***	0.0055***	1841.53***	11498.05***	9174.98***
Count.prov	10	0.0345***	0.6769***	0.0119***	0.0053***	0.0007***	294.38***	2375.51***	3449.59***
Count.prov.tree	80	0.0108***	0.2938***	0.0029***	0.0003***	0.0003***	102.15***	106.85***	142.89***
residual	95	0.0001	0.0051	0.0001	0.0001	0.0001	9.82	5.24	10.04

df: degree of freedom, count: country, prov: provenance

Appendix 13: Table of mean square errors (MSE) from the ANOVA table on elemental concentration of baobab seeds

Source of variation	df	Ca	K	Mg	Na	P	Cu	Fe	Mn
Country	5	0.0442***	0.6610***	0.0500***	0.0058***	0.2124***	2257.30***	6983.97***	1414.34***
Count.prov	11	0.0229***	0.3339***	0.0163***	0.0006***	0.0353***	437.67***	907.70***	164.51***
Count.prov.tree	92	0.0056***	0.0231*	0.0029***	0.00003***	0.0208***	103.26***	318.63***	23.31***
residual	109	0.0001	0.0155	0.0002	0.00002	0.00007	2.97	5.59	0.61

df: degree of freedom, count:; country, prov: provenance

Appendix 14: Analysis of variance (ANOVA) table performed on Vitamin C across five countries

Source of variation	d.f	s.s	m.s.	v.r.	F pr.
country	4	421148.	105287.	70.92	<.001
country.provenance	10	737993.	73799.	49.71	<.001
country.provenance.tree	186	3187558.	17137.	11.54	<.001
Residual	402	596844.	1485.		
Total	602	4943543.			

d.f: degrees of freedom, s.s: sum of squares, m.s: mean square error, v.r: variance ratio, F pr; F probability

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ORIGINAL RESEARCH

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Nutritional variation in baobab (*Adansonia digitata* L.) fruit pulp and seeds based on Africa geographical regions

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Abstract

Baobab (*Adansonia digitata* L.) is an indigenous fruit tree associated with the Savannah drylands of sub-Saharan Africa. Local communities mainly utilize the leaves, pulp, and seeds of baobab as a source of food and for income generation. The present study was conducted to determine the nutritive attributes of baobab fruit pulp and seeds across provenances in east, west, and southern Africa and to determine whether the nutrient content varied with the provenance of origin. Pulp and seed proximate composition and mineral element concentration were determined using the AOAC 1984 methods and inductively coupled plasma atomic emission spectroscopy (ICP-AES), respectively. The results showed that there exist significant variation ($p < .05$) in pulp moisture, protein, fiber, ash, and elemental content among provenances. The highest mean pulp crude fiber (8.68 g 100 g^{-1} dw) was recorded in Kenya. At country level, Malawi had the highest mean pulp potassium (22.2 mg g^{-1}), calcium (4,300 mg kg^{-1}), magnesium (2,300 mg kg^{-1}), sodium (1,000 mg kg^{-1}), and phosphorus (1,100 mg kg^{-1}) levels. Kenya had the highest mean pulp iron (57.4 μg g^{-1}) and manganese (27.2 μg g^{-1}) content, while Mali had the lowest iron (13.1 μg g^{-1}) and manganese (8.6 μg g^{-1}). At country level, the mean seed calcium content was highest (3,200 mg kg^{-1}) in Malawi and lowest (2,000 mg kg^{-1}) in Kenya. The highest mean iron content of 63.7 μg g^{-1} was recorded in seeds from Kenya, while the lowest (25.8 μg g^{-1}) was in Mali. Baobab seed mineral and proximate content varied significantly ($p < .001$) among the selected countries. Overall, baobab fruit pulp and seeds contain significant amounts of nutritionally essential minerals and proximate components but the amounts varied significantly among the selected countries. This variation offers opportunities for selecting provenances to concentrate on during germplasm collection for conservation and domestication of baobab.

KEYWORDS
baobab, minerals, proximate composition, pulp, seeds, variation

RESEARCH PERMIT: ACQUISITION OF GERMPLASM FOR RESEARCH

World Agroforestry Centre

September 08, 2018

To whom it may concern

RE: ACQUISITION OF GERMPLASM MATERIAL FOR RESEARCH

This is to clarify that the World Agroforestry Centre (ICRAF) GRU receives germplasm material for research from partners via material transfer agreements (MTA). If a partner does not have their template, the attached ICRAF collection MTA template is used. Further distribution of the same material to a third party for training and research is also carried out via a MTA where ICRAF will act as the provider.

The samples used in the *Adansonia digitata* analysis by ICRAF Fellow, Mr. Urbanus Kinuthia, were received from national partners from Kenya, Malawi, Mali, Tanzania, Zambia and Zimbabwe via an ICRAF MTA.

Thank you for your understanding.

Yours Sincerely,

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