Managing the hard-to-cook (HTC) phenomenon in bambara groundnut (*Vigna subterranea* (L.) Verdc.) processing for resource limited communities in Zimbabwe

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Thesis

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Chapter 1

General introduction

1.1. Food security issues in sub-Saharan Africa

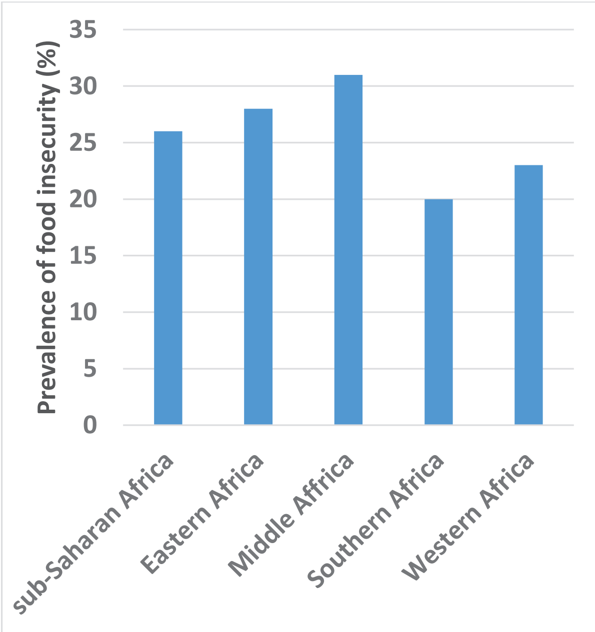
Realising food security remains a challenge in sub-Saharan Africa (SSA). Food security is defined as a situation in which all people at all times have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active healthy life [1, 2]. The underlying causes of food insecurity vary greatly among countries. Some of the major ones include natural disasters and an underdeveloped agricultural sector [3]. Agriculture affects food security since many SSA countries hinge on it as the mainstay of the economy, with over 70% of the rural population relying on agro-produce for food, income generation, and livelihoods [4-9]. Dependence on agriculture has shortcomings as the SSA region has been ravaged by successive droughts. Since over 95% of the food is grown under rain fed agriculture, food production is vulnerable to adverse weather conditions. To add to that, low fertility soils characterise farming land while significant food crop losses, both pre- and post-harvest, and minimal value addition also contribute to food insecurity [2]. The effect of a poorly developed agricultural sector is significant for subsistence farmers, who are located in marginal areas and have the least capacity to adapt to changing climatic conditions and economic shocks [2, 5].

All these factors contribute to the decline in farm food production, leading to a depth in food deficits. To cover this depth, countries in SSA have resorted to food imports to fill 15-20% of cereal availability [10]. Several countries remain highly dependent on food importation to ensure adequate food supply, e.g. Botswana, Cabo Verde and Mauritius relied on more than 80% of imports to supplement their cereal requirements (see Fig 1.1ii). Zimbabwe, which was a cereal net exporter from 1993–95 to 1998–2000, has become a net importer since 2001 [10]. Continuous food import is unsustainable, especially when high and rising food import bills take money away from other important development agendas without resolving food insecurity. Additionally, considering that average per capita income in SSA (US$ 3,400 in 2014) is three times lower than in Asia, Latin America and the Caribbean, and far below the world average of US$ 14,500, SSA countries cannot afford it.

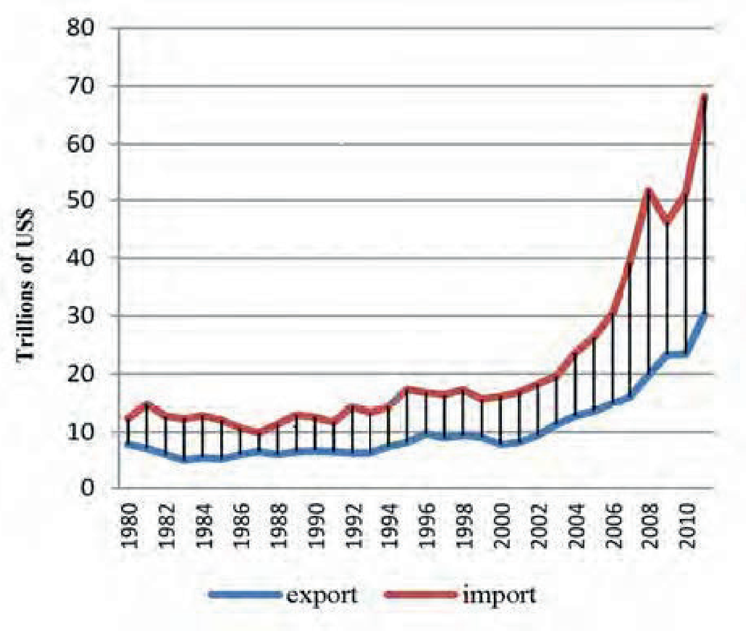
Consequently, a decline in food production negatively affects the food and nutritional status of the population, especially of the vulnerable groups such as children under five, pregnant women and the elderly [1, 11-13]. As such, the prevalence of food insecurity in SSA was estimated at an average 26% (see Fig 1.1i) with the following shares for the sub-regions: 20% for southern SSA, 23% for western SSA, 31% for middle SSA and 28% for eastern SSA [10]. The most recent estimates of food insecurity reveal that approximately 218 million people are undernourished in SSA; it means that about one out of four persons in the region does not have an adequate dietary energy supply. Estimates also show that, on average, one out of four individuals above 15 yr. of age in the region experienced severe food insecurity in 2014–15 based on self-reported individual experiences.

FAO [10] also reports that one in three children under the age of five is stunted while wasting affects about 7% of children under five yr., of which about 3.6 million suffer from severe wasting (see Fig 1.2 for sub-regional shares). Additionally, the region accounts for 23% of the global wasting burden. SSA sub-region shares are shown in Fig 1.2.

These statistics show that the severity of the various forms in which undernutrition manifests itself, vary at sub-regional levels. Overall, however, SSA continues to lag behind global and regional targets of halving the number of undernourished people. Therefore, the region needs to exert sustained efforts towards reaching the zero hunger target set in the African Union Malabo Declaration for 2025 and in line with the SDGs for 2030 [10].



i)



ii)

Fig 1.1 i) Prevalence of severe food insecurity across sub-regions of sub-Saharan Africa and ii) food trade in SSA [10]

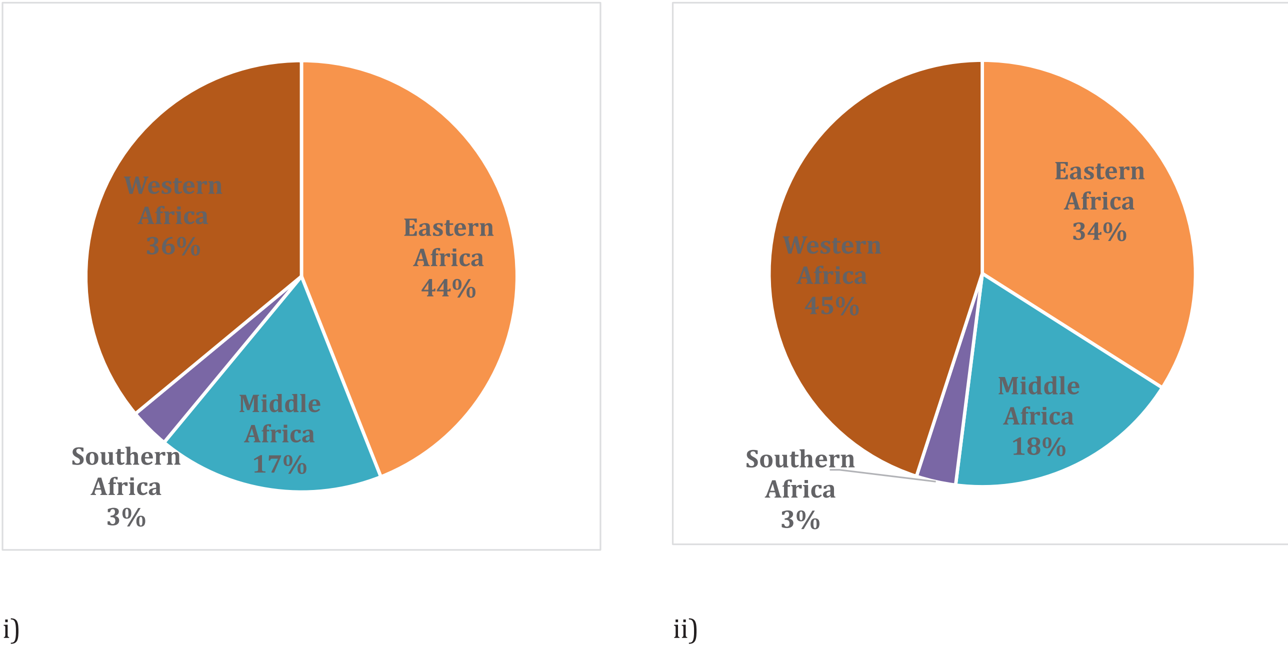


Fig 1.2 Share of stunted (i) and wasted (ii) children across sub-Saharan Africa as of 2015-16[10]

1.2. Global efforts to improve food security

According to Clover [1], the solution to food security lies in increasing food availability, food access and food adequacy for all. As such, many organizations, agencies, institutes, and programs are actively involved in reducing food insecurity (e.g. Food and Agriculture Organisation (FAO), International Food Policy Research (IFPRI), Consultative Group on International Agricultural Research (CGIAR)) [3]. In addition, many efforts (previously and at present) made by scientists from diverse scientific disciplines to improve food security suggest the need for a multifaceted strategy for sustainable food production systems. This idea developed because scientific efforts employed since the Green Revolution focused primarily on major crops and staples (e.g. maize, wheat, rice, soya bean, potato, etc.) as daily calorie needs for the population, thereby neglecting the local crop diversity and associated knowledge, culture and traditions [3]. Therefore, to secure food supply in SSA and the world at large, food scientists are nowadays encouraged to also exploit neglected and underutilized food sources [14]. Neglected and underutilized species (NUS) are those to which little attention has been paid or which are entirely ignored by agricultural researchers, plant breeders and policymakers [14]. To date there are plenty of underutilized crops with desirable nutritional profiles and potential to alleviate 'hidden hunger' and improve food security among the poor communities in SSA.

Even though NUS usually have lower yields than the main staple crops, they often compensate for this by being more resistant to biotic and abiotic challenges and providing dependable harvests in unfavourable climatic conditions or on difficult soils. Additionally, underutilized crops provide essential micro-nutrients and complement staple foods, provide flavoring, strengthen local gastronomic traditions and provide income opportunities for both the rural and urban poor. Moreover, since crop diversification is one of the best ways to ensure sustainable agricultural production systems, leveraging indigenous, drought-tolerant crops is suggested as a way to improve food security, build resilience and empower poor communities in SSA [9, 15-18].

1.3. Neglected and underutilized legumes as a contributor to healthy and sustainable diets

Legumes are instrumental to achieve worldwide food security also thanks to their high protein content. The importance of NUS legumes was cemented when the 68th UN General Assembly declared 2016 the International Year of Pulses under the banner 'nutritious seeds for a sustainable future'. The FAO was nominated to facilitate the implementation of the year in collaboration with governments, relevant organizations, non-governmental organizations and all other relevant stakeholders. The International Year of Pulses 2016 aimed to heighten public awareness of the nutritional benefits of pulses as part of sustainable food production towards food security and nutrition [19]. The year created a distinctive chance to encourage networks throughout the food chain to use pulse-based proteins, further global production of pulses, encourage better use of crop rotations and address the challenges in the trade of pulses. Moving forward, the anticipated output from the International Year of Pulses 2016 is increased knowledge of pulses, i.e. their sensory attributes, nutrition, health, trade and environmental sustainability issues. This knowledge is expected to help national, regional and local policymakers to formulate and implement policies and programmes to optimize use of legumes for improving nutritional status [19].

Previously, an impact analysis in SSA indicated that indigenous crops such as legumes can reduce vulnerability of rural households to food insecurity [9, 15]. Presently, Foyer, Lam [20] declares that a second green revolution is required to ensure food and nutritional security in the face of global climate change as legumes provide an innate capacity for symbiotic atmospheric nitrogen fixation, which provides economically sustainable advantages for farming. With the incumbent need to move towards sustainable diets, legumes present the answer to food security problems [19]. Definitions of sustainability generally address aspects of ecology, economy and society, and have different meanings depending on the context. In 2010, the FAO defined sustainable diets as "those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy while optimizing natural and human resources" as shown in Fig 1.3 [21]. To understand a sustainable diet, the agricultural, environmental, social-cultural, and economic determinants and effects of the food eaten as well as the nutritional value should be considered.

In line with sustainability, some of the documented benefits of including legumes in intercropping or rotation in agriculture include enhanced yield, increased nitrogen-use efficiency, reduced occurrence of diseases and, in some cases, improved access to other essential elements such as phosphorus [22].

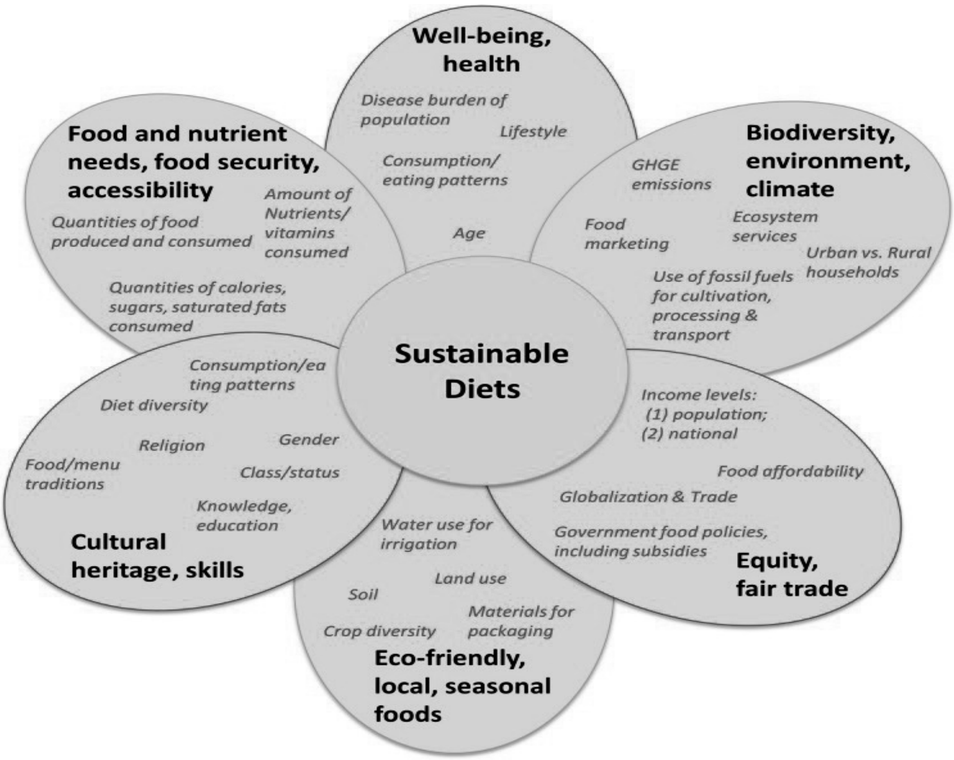


Fig 1.3 The key components (indicated as the large green ovals), determinants, factors, and processes of a sustainable diet as defined by FAO and Bioversity in 2010 [21].

Additionally, grain legumes favour reduction of greenhouse gas emissions in agricultural cropping systems (e.g. emissions declined by 56% on a per-hectare basis when a lupin crop preceded wheat) [23]. Overall the inclusion of grain legumes in cropping systems enhances productivity as well as increases diversity, accordingly reducing the reliance on a cereal monoculture and answering the food availability facet of attaining food security [1].

The beauty of legumes does not end with agronomic superiority, as legumes are also contain many nutrients important for human health. These include proteins, carbohydrates, fibre, minerals, vitamins, carotenoids and polyphenols [20]. Additionally legumes are also value for their low glycaemic index status. Accordingly, legumes hold a valuable position among foodstuffs because of their health-supporting properties.

1.4. Bambara groundnut (*Vigna subterranea*) as a solution to food insecurity

Bambara groundnut is a NUS legume that can contribute to food and nutrition security in SSA [24]. It originated in the Sahelian region of present day West Africa, from the Bambara tribe near Timbuktu, who now live mainly in Central Mali, hence its name 'Bambara' groundnut [25]. The nuts are also known as *jugo beans* (South Africa), *ntoyo* ciBemba (Republic of Zambia), *Gurjiya* or *Kwaruru* (Hausa, Nigeria), *Okpa* (Ibo, Nigeria), *Epa-Roro* (Yoruba, Nigeria) and *Nyimo* beans (Zimbabwe). Fig 1.4 shows bambara groundnut cobs before and after harvesting. The seeds vary in shape (round or elliptical) and colour (Fig 1.5). Bambara groundnut features in subsistence farming systems and is regarded as third in importance after cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogaea*). Due to its low status, it is seen as a snack or food supplement but not as a potentially lucrative cash crop [26, 27]. Additionally, it is usually given less value and less priority in land allocation because it is grown by women.

As other leguminous crops, bambara groundnut has a high adaptability quotient, which makes it suitable to semi-arid regions, where many other crops fail to survive due to lack of water and or nutrients [24, 27-29]. Bambara groundnut has an average yield of 650-850 kg/ha and a maturity period of 4-5 months [30].

(i) (ii)

Fig 1.4 (i) Fresh bambara groundnuts before harvest, and (ii) fresh bambara groundnuts ready for boiling

red black-eyed brown

Fig 1.5 Dry bambara groundnut varieties (red, black-eye and brown)

(i) (ii)

Fig 1.6 (i) Boiled bambara groundnut snack (*mutakura*), and (ii) boiled bambara groundnut relish in tomatoes, onion and cooking oil

Biochemical analyses revealed that bambara groundnut is a complete food, providing energy, proteins, dietary fibre, bioactive compounds, some essential amino acids, essential fatty acids and micronutrients such as zinc and iron [24, 25, 31]. For rural communities, it serves as a cheaper, alternative source of protein as compared to animal protein [26, 31-37]. The protein fraction of bambara groundnut contains relatively high proportions of the essential amino acids lysine and methionine [38, 39]. Thus, foods that combine bambara groundnut with a cereal, e.g. maize (*Zea mays*), which is low in lysine and tryptophan [17, 40-42] can be used to help alleviate the ever-increasing problems of malnutrition in developing countries [17]. In terms of protein quality, bambara groundnut has a high protein score (i.e. 80%) when compared to the 74% for soya bean (*Glycine max*), 65% for groundnut and 64% for cowpea [43, 44]. This protein score refers to protein that is available for the metabolic functions of the body when consumed. Thus, bambara groundnut is rated higher than groundnut and cowpea [45].

1.4.1. Constraints in bambara groundnut utilization

Despite the positive agronomic and nutritional potential of bambara groundnut, its use is still limited. One of the reasons for underutilization is the post-harvest hard-to-cook (HTC) phenomenon, which develops in legumes during storage at conditions of high temperature and high relative humidity, which are common in tropical and sub-tropical regions of SSA. Fig 1.6 show products of extended cooking time, namely boiled snack (locally known as *mutakura* and boiled relish). A summary of bambara groundnut derived products is shown in Fig 1.7.

In principle, the HTC phenomenon in legumes can be controlled by storing legumes at conditions of low temperature and humidity, e.g. in a refrigerator [46-48]. However, such storage conditions are not available for the poorest rural communities in SSA countries like Zimbabwe, which lack the capacity, infrastructure and the resources needed to implement such conditions. The long cooking times required for the preparation of HTC bambara groundnut are unsustainable in terms of costs and energy consumption as households depend on wood for energy.

While the demand for firewood continues to grow in many SSA countries, increased land use and deforestation have reduced the supply of firewood, leading individuals to travel to forests that are far from their homesteads for collection [49]. Moreover, HTC bambara groundnuts also exhibit hard-to-mill properties, which are a concern for processors [28]. Overall, these negative physical properties lead to a diminished use of bambara groundnut, resulting in a lack of diet diversification, reduced use of market potential and economic losses [50, 51]. Therefore, to increase the utilization of bambara groundnut by resource-limited communities, sustainable strategies must be formulated and implemented under local conditions to reduce cooking time, preserve energy and optimize milling properties. An important strategy would be to develop and promote locally appropriate processing techniques that can avoid the current post-harvest losses due to underutilization [3]. Such processing techniques must meet criteria of aptitude, digestibility of important nutrients as well as consumer acceptability of the products. Figs 1.8-9 shows alternative bambara groundnut products.

1.5. Role of indigenous knowledge systems in food processing

Over the past decades, food technological research has created a much better understanding of many processes that take place in the food production chain. This has led to many innovations that helped to improve the quality of food products as well as their shelf life and the sustainability of production systems. However, the majority of these innovations have been targeted at consumers with great purchasing power. Populations in transition countries with limited financial means and depending on inadequate diets have hardly benefitted, and opportunities to improve their food security have been missed out. In SSA, lack of documentation of traditional processing techniques emanating from indigenous knowledge systems (IKS) has resulted in the erosion of these as well as a move by communities towards Westernised diets. Indigenous legumes such as bambara groundnut has not been spared during this transition. With the unavoidable need to move towards sustainable food security, bambara groundnut can be explored as a model crop for SSA countries.

IKS in food processing practices form a bedrock of a community's composite and collective understanding, which is passed through generations [18, 52]. Rural communities, especially women, have ideas as to what strategies and tactics work in their day to day processing of traditional foods in their socio-cultural framework [2, 9, 16, 52]. Therefore, it is vital to learn and build on strategies that have worked for them in processing HTC legumes. To date, there is limited documented information on the indigenous knowledge for managing the HTC phenomenon in bambara groundnut processing southern SSA countries e.g. Zimbabwe [9].

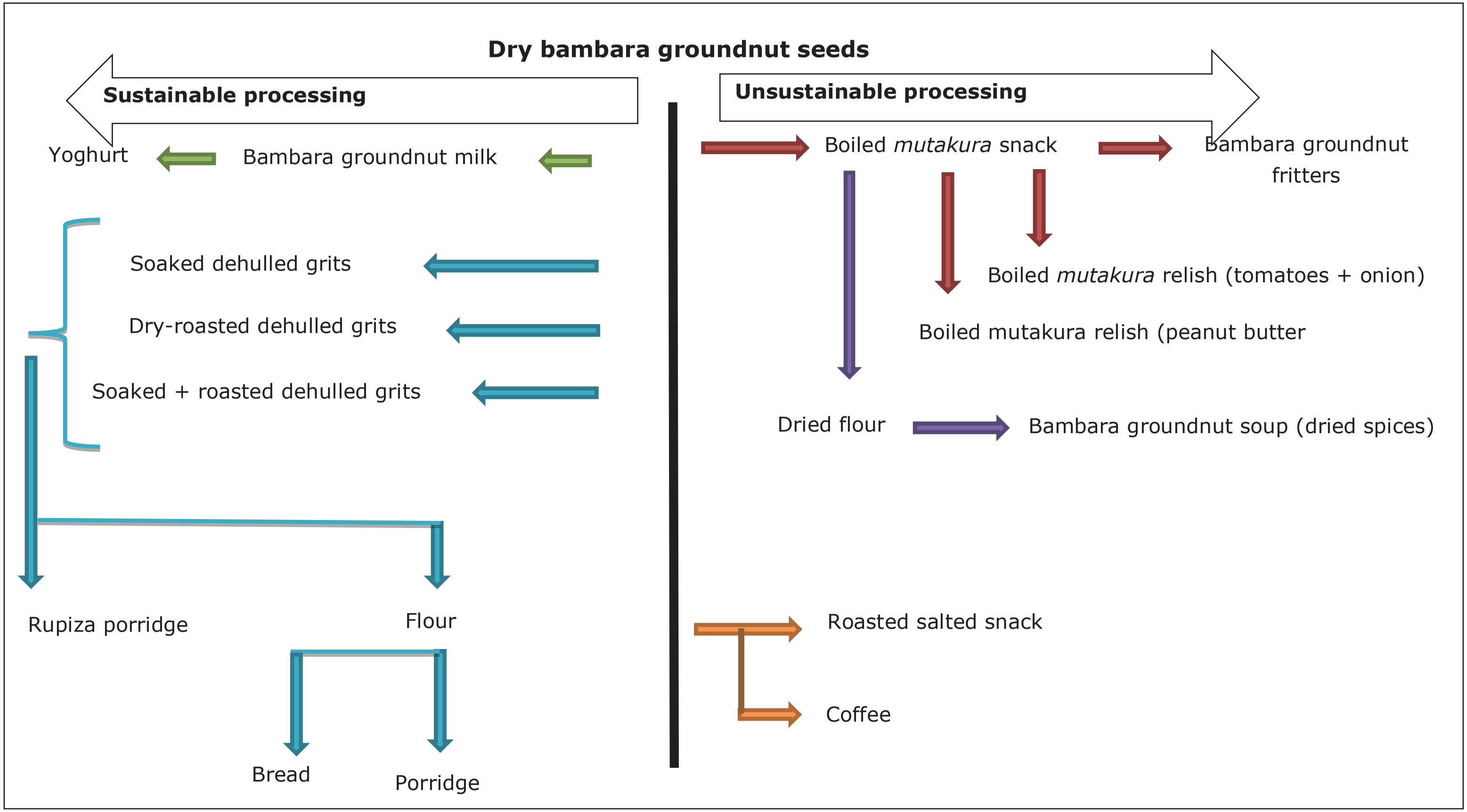


Fig 1.7 Bambara groundnut product tree. The left side represent sustainable processing and right side represent unsustainable processing

Fig 1.8 Unroasted and roasted black-eye bambara groundnut seeds for grits production

(i) (ii)

Fig 1.9 (i) Bambara groundnut grits (raw *rupiza*) (ii) cooked *rupiza* porridge

Thus, knowledge sharing, education and building from coping strategies are essential interventions for improving food security. In addition, information sharing will open avenues to off-farm employment and allows an active role in research and development of rural communities on matters that affect them [7]. Moreover, enabling local communities, especially women, to adapt and to depend on their local resources rather than external assistance promotes their empowerment [9].

Furthermore, IKS have shown the importance of adopting traditional crops (NUS) as a source of community resilience to climatic change and as a suitable strategy within a national food policy framework to guide nutritional interventions [18]. As such, emphasis is placed on indigenous foods supplementing maize in diets [9]. Since maize has been supplemented commercially with soya bean by non-governmental organisations, a similar approach is recommended for local communities, namely to utilise bambara groundnut under local conditions. In terms of processing, the goal is then to implement locally developed practises and indigenous knowledge systems to supply culturally acceptable, nutritious foods for resource-limited communities using bambara groundnut as a model crop.

1.6. Research aim and thesis outline

Promoting sustainable diets based on bambara groundnut requires an inclusive approach that encompasses the whole food chain (see Fig 1.10). Bambara groundnut, though an ideal crop for semi-arid regions, has inherent seed properties that are precursors of the development of the HTC phenomenon. Thus, the crop thrives in the unfavourable environment, but cannot escape the seed hardening that the climate promotes. The hardening process affects utilization, food diversity and ultimately food security.

In the framework of IKS and sustainable processing technologies, the current research effort seeks to establish baseline information on the exploitation of bambara groundnut in semi-arid regions of a SSA country, namely Zimbabwe, by exploring the existing opportunities and challenges associated with a bambara groundnut based sustainable diet. Since HTC is one the presumed bottlenecks, the strategy is to develop and optimise processing technologies to address the HTC phenomenon in bambara groundnuts processing for resource-limited communities. This study is expected to add to existing data for stakeholders in academia, public policy, civil society, and the private sector from various fields, especially economics, psychology, behaviour change, anthropology, nutrition, environment, climate change, and health and agriculture to facilitate a wider use of HTC bambara groundnuts amongst other legumes in the poorest sections of Zimbabwe and sub-Saharan Africa.

To achieve this goal and to help traditional bambara groundnut processors and consumers maximise this important resource, the following specific objectives were defined:

i. understand the development of the hard-to-cook phenomenon in legumes, the impact on food security and the technological solutions that can be implemented during processing;

ii. determine present bambara groundnut processing techniques and eating habits with reference to methods that increase processing aptitude;

iii. evaluate the use of alkaline salts as a way of circumventing the HTC phenomenon in the processing of legumes;

iv. evaluate grits production as an alternative processing strategy for an optimal utilization of bambara groundnut nutrients;

v. assess the impact of variety and processing methods on the nutritional and functional properties of bambara groundnut flour.

This thesis consists of seven chapters in which five discusses the mentioned objectives. The five chapters are preceded by a general introduction (**chapter 1**) and concluded by general discussion and implications (**chapter 7**) as shown in Fig 1.11

This thesis presents an overview of nutritional and agronomic importance of bambara groundnut and how the development of HTC impacts food security. In **chapter 2**, we gather and document indigenous knowledge on the utilization of bambara groundnut in comparison to its sister legumes, i.e. cowpea and groundnut in Zimbabwe. This approach is to obtain first-hand information from the bambara groundnut stakeholders, which are farmers, processors, traders and consumers. The factors that contribute to the HTC development are reviewed in a bid to understand methods that can revert its effect during processing. Moreover, current documented processing methods for bambara groundnut and other legumes are reported and are assessed for sustainability (**chapter 3**). In **chapter 4**, we study the mechanism of softening or reduction in cooking time as a result of using cooking aids, i.e. alkaline salts. As cooking time is a hurdle in utilization, the applicability and sustainability of this method from West SSA is assessed and the reason for why it is not implemented in southern SSA. As an alternative to the use of alkaline salts, **chapter 5** presents grits production as a strategy to circumvent HTC while optimising nutrient bio-accessibility. This chapter investigates the option of making different grit products and assesses consumer acceptance., **chapter 6** integrates the effects of processing in coming up with different types of flour and evaluates their potential uses for food preparation. Finally, **chapter 7** consolidates all the chapters giving recommendations on the thesis findings.

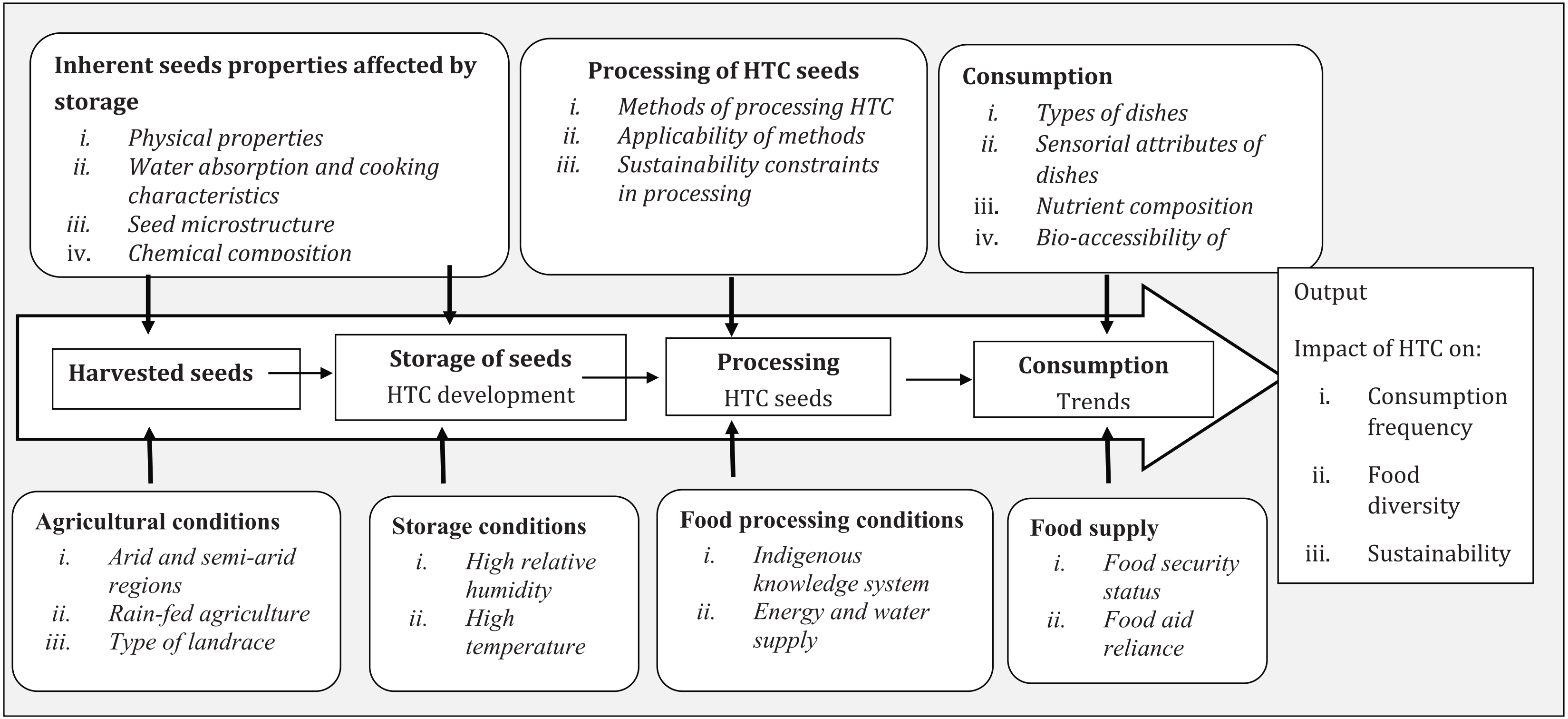


Fig 1.10 Conceptual framework of relationships in HTC development and management of bambara groundnut processing in Zimbabwe

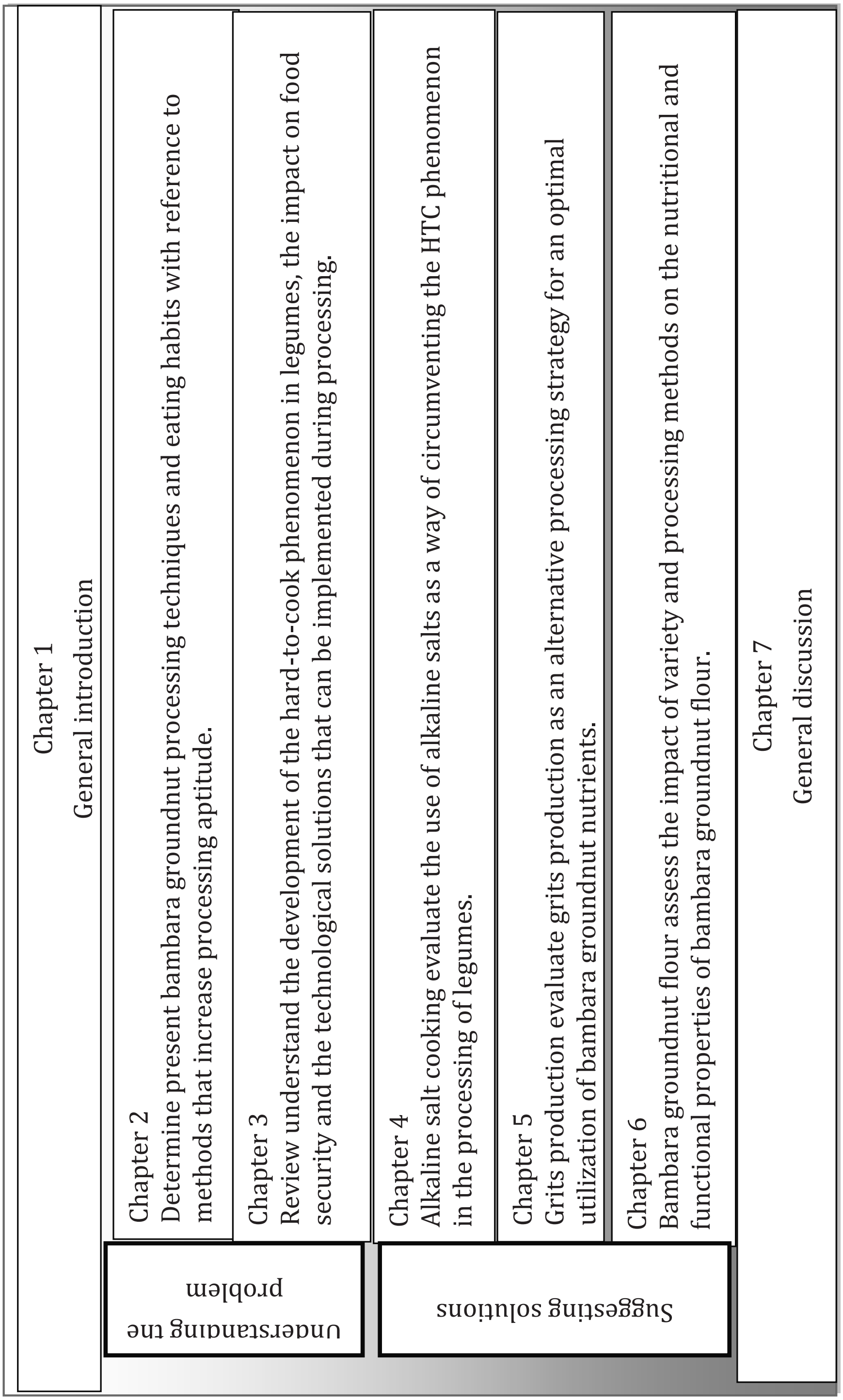


Fig 1.11 Thesis overview

Chapter 2

Utilization of bambara groundnut (*Vigna subterranea* (L.) Verdc.) for sustainable food and nutrition security in semi-arid regions of Zimbabwe

Published as:

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Abstract

Bambara groundnut (*Vigna subterranea* (L.) Verdc.) is an indigenous legume crop, cultivated by subsistence farmers throughout sub-Saharan countries. Research findings indicate that the crop has great nutritional and agronomic potential, but it remains scientifically neglected. A baseline study was conducted in seven districts in semi-arid regions of rural Zimbabwe to gather knowledge on current production and utilization of bambara groundnut, assess its role in providing sustainable food and nutrition security for rural populations and determine priorities for follow-up research. Results revealed a variety of bambara groundnut processing techniques, which included boiling, soaking, roasting and milling across the surveyed districts. Reported constraints to processing and consumption included long cooking time, difficulties with milling and high firewood and water requirements. Fifty to eighty percent of respondents in all districts consumed bambara groundnut once or twice weekly from August to December. Preferred consumer attributes were taste, the satiating effect, nutritional benefits or a combination of these. Current, culturally acceptable processing techniques need improvement to support sustainable bambara groundnut processing while optimising nutrient bio-accessibility. Ultimately, community resilience to food and nutrition insecurity can be promoted by exchange of bambara groundnut processing knowledge amongst the production areas, involving the different stakeholders in the food supply chains.

Keywords: *Zimbabwe; bambara groundnut; traditional processing; hard-to-cook phenomenon; food security.*

1. Introduction

Subsistence farming and 'cash' cropping (i.e. crop cultivation for income generation) are the foundation of sustainable food security for rural communities in sub-Saharan Africa [53, 54]. In Zimbabwe and other sub-Saharan countries, subsistence farming depends on natural rainfall, making agricultural activities extremely sensitive to environmental changes [55, 56]. About 90% of the rural areas in Zimbabwe are situated in semi-arid agro-ecological regions (i.e. region III, IV and V) [57], which are characterised by low rainfall ($\leq$ 800 mm), making these regions unfavourable for intensive cropping of maize, the preferred staple cereal [58].

In recent years, increasing weather variability and successive droughts have resulted in decreased agricultural productivity, thus negatively affecting food security. Meanwhile, agricultural organizations and policymakers have recognized the role and untapped potential of neglected and underutilized crops (NUS) for food and nutrition security, generating income in rural areas, adapting to climate change, and mitigating climatic, agronomic and economic risks [14, 59]. Researchers recommend promoting the cultivation of indigenous, drought-tolerant crops, such as legumes, and among the proposed legumes is bambara groundnut (*Vigna subterranea* (L.) Verdc.), whose high adaptability makes it suitable for semi-arid regions where other crops fail to thrive [60]. According to Hillocks [61], the land area considered suitable for bambara groundnut cultivation is 84% for Zimbabwe, 100% for Swaziland, 98% for Uganda and 95% for Zambia.

Nutritionally, bambara groundnut represents a cheap protein-rich source that can improve the food and nutrition security status of rural households. Biochemical analysis of the carbohydrate, fat, protein and mineral content reveals that bambara groundnut produces an almost balanced diet. The nut was found to be richer in essential amino acids than groundnut [62], with a protein score of 80% as compared to 65% for groundnut, 74% for soya bean and 64% for cowpea [63]. However, like other legumes, bambara groundnut lacks sulphur-containing proteins, thus blending with a staple cereal such as maize, which contains higher levels of sulphur-containing amino acids, results in a complete food [64]. Bambara groundnut contains micronutrients such as zinc, iron, calcium and potassium. Red-seed varieties have almost twice as much iron as the cream seeds. Thus, they are especially valuable in areas where iron deficiency occurs [65].

Freshly harvested and dry bambara groundnut are consumed in many ways after processing. Freshly harvested seeds are consumed as snacks after grilling or boiling for approximately an hour [66, 67]. Dry seeds are boiled or first soaked then boiled to make a snack or porridge [66]. Dried seeds are difficult to grind due to their hard and tightly fitting seed coat. These seeds are pounded to flour, which is baked to make small flat cakes and bread [66, 68]. In Eastern Africa, bambara groundnuts are roasted, milled, and the flour is used to make a soup, a relish, and also a substitute for coffee. Additionally, a thin porridge [27, 33] and stiff porridge can be made from the flour [27]. Despite all these possible uses and the nutritional and agronomic potential, bambara groundnut remains scientifically neglected [69]. An important reason for underutilization is the hard-to-cook (HTC) phenomenon in combination with inadequate processing techniques [70]. HTC in legumes is characterized by extended cooking time (3-4 h) [27] needed to ensure adequate softening during cooking [71], and the hard seed coat makes dehulling challenging [28]. HTC in legumes is associated with structural cell modifications (e.g. autolysis of cytoplasmic organelles and lignification of middle lamella) and compositional changes (e.g. formation of insoluble pectate and interactions of proteins and phenolic compounds), which occur in the cotyledons and seed coats [70]. The HTC problem may not seem serious to people living in developed countries, who have energy resources and state-of-the-art techniques to utilize HTC legumes as well as access to a variety of protein-rich foods. However, due to the ravages of protein deficiencies, this food source is indispensable for people living in subsistence conditions who cannot afford meat [72]. According to Burchi, Fanzo [73], there are four dimensions of food security, namely food availability, food accessibility, food utilization and stability. In terms of production, bambara groundnut is managed in a traditional manner, e.g. by women who use informal seed sources and give it a low priority in land allocation [74]. Nonetheless, bambara groundnut is frequently available and accessible to rural households but underutilized because of processing bottlenecks [75, 76], causing a lack of diversity in rural diets [54]. Over the past decades, processing solutions were developed to improve the quality of local food products as well as their shelf life, but these are often not applicable for resource-limited rural communities [77]. Thus, sustainable processing approaches that fit the local social-cultural framework in rural Zimbabwe and other sub-Saharan communities are urgently needed [14, 55, 78]. Processing methods for HTC legumes used in other sub-Saharan countries, such as Ghana and Nigeria, include chemical treatments (*cooking aids*), biological treatments (*germination and fermentation*), and physical treatments (*milling, roasting and canning*) [70].

This paper examines the factors that affect the role of this crop in the broader context of production, processing, consumption and trade in the Zimbabwean context. The objective of the study was to take stock of the indigenous knowledge on the bambara groundnut value chains to gain insight in the way in which this protein-rich crop contributes to sustainable food and nutrition security in semi-arid regions. This research documented the current land allocation for crops and traditional processing methods for bambara groundnut in Zimbabwe. The study also assessed processing constraints and analysed the preference and consumption frequency of bambara groundnut. Specific research questions guiding the research include: (i) why do people consume bambara groundnut, and why not?, (ii) what do consumers like about this food, and what not?, (iii) what is the perception of processors on bambara groundnut processing techniques, which are the best methods and what are the problems?, (iv) how do use and processing techniques compare between districts and neighbouring countries?, and (v) does cultural background have a role on crop utilization?

2. Methodology

2.1. Study area

Data were collected in rural areas in the driest parts of Zimbabwe (Fig 2.1), specifically in agro-ecological region III (Uzumba and Binga (Lusulu), IV (Buhera, Mudzi, Pfungwe and Lower Gweru) and V (Bikita), see Table 2.1. Region III receives 500-800 mm annual rainfall and is subject to seasonal droughts and severe mid-season dry spells. Region IV receives 450-650 mm annual rainfall and is characterised by frequent seasonal droughts and severe dry spells during the rainy season. Region V receives less than 450 mm annual rainfall [79]. A mixed sampling approach was applied at different stages, starting with a 'snowball approach' through use of network referencing [80] at Mbare farmers' market (17° 51′ S, 31° 2′ E) in Harare (i.e. the largest informal market for agro-produce in Zimbabwe) to establish current locations of key farming areas and growers/suppliers of bambara groundnut. This was followed by judgement sampling [81] using the expert opinions of *eMKambo* (an organisation that records the movement of agro-produce in informal markets in Zimbabwe) and the Department of Research and Speciality Services (DRSS). DRSS is a government department mandated to provide research-based technologies and technical information for advisory services to support enhanced agricultural productivity. The chosen locations were amongst the major bambara groundnut growing areas in Zimbabwe and were selected for their socio-cultural diversity. The *Tonga* tribe mainly populates Binga in Matabeleland north province, whereas a mixture of *Shona* and *Ndebele* tribes populates Lower Gweru in Midlands's province. The *Shona* tribe inhabits the rest of the districts.

2.2. Field data collection and sampling of respondents

Surveys to gather data were conducted from May to December 2014. The DRSS and the Department of Agricultural Extension Services (Agritex), both under the Ministry of Lands, Agriculture and Rural Settlement in Zimbabwe approved the study. Study areas were visited prior to the surveys for familiarization with the

communities. Ward councillors, Agritex officers and village headmen were consulted before meeting household representatives to obtain verbal informed consent after explanation of research intentions and protocols. Respondents were notified of the forthcoming study and also their informed consent was obtained. For the sampling plan, Boyd, Westfall [82] recommend a sample size of at least 5% of the total population. A sample representing 5% of the total number of households in a ward was randomly drawn from a list of households supplied by Agritex officers. A ward is defined as an administrative municipal in a district that is subdivided into villages [83]. A household was defined as all members, related or unrelated, who share the same dwelling unit. Data were collected from at least five selected villages in identified wards (ward size average 8-11 villages). With an estimated average size of 50-100 households per village, at least 5% of the households in a village was interviewed, i.e. 27-43 informants in each ward.
Data were collected through focus group discussions, formal individual interviews, practical observations and demonstrations using interpreters where necessary. Table 2.1 shows the demographic profile of respondents for each district and agro-ecological region.

Semi-structured formal interviews were conducted with 231 respondents (of which 91% were females and 9% males) of various ages and diverse educational backgrounds. The majority of respondents (93%) had received formal education in the form of primary and secondary education. Subsistence farming, petty trade, illegal mining [84] and remittances (i.e. from relatives and food aid) were the livelihood sources of the respondents. Female respondents came from male-headed households, except the < 10% who were divorced or widowed.

The survey was split into categories to include subsistence farmers, traders (informal and formal), consumers and individual processors as shown in Table 2.2 [85]. Focus group discussions were conducted in Mudzi (14 participants) and Lower Gweru district (16 participants). In addition, fifty traders in Harare (from Mbare and Lusaka farmers' markets, 17° 53'S, 30°59' E) and in Chitungwiza (from

Chikwanha, 17°59' S, 31°04' E and Makoni 18° 00' S, 31° 04' E farmers' markets) were interviewed.

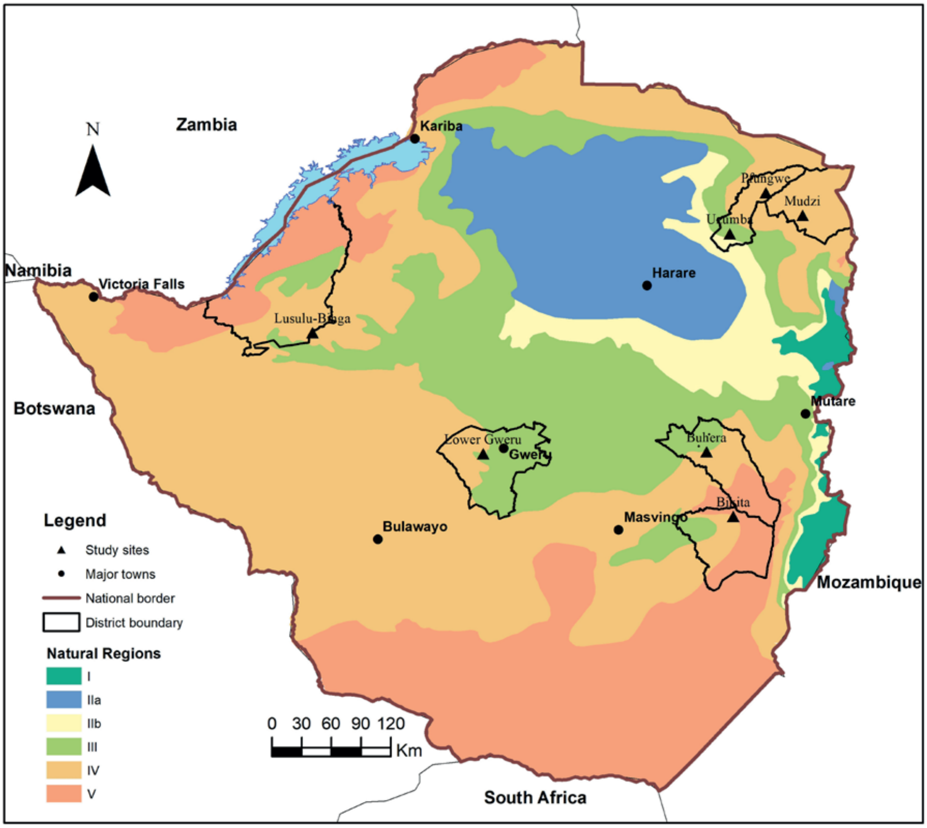

Fig 2.1 Map of Zimbabwe showing bambara groundnut surveyed districts and agro-ecological zones.
Regions III (Uzumba and Binga), IV (Buhera, Mudzi, Pfungwe and Lower Gweru) and V (Bikita) receive 500-800 mm, 450-650 mm and < 450 mm, respectively.

Table 2.1 Demographic profile of respondents in the surveyed districts per agro-ecological region in Zimbabwe

Region	**District**	**Ward**	**N**	**Gender**		**Education**		**Age (years)**				
				Female	**Male**	**Educated**	**Not educated**	**19-29**	**30-39**	**40-49**	**50-59**	**60+**
III	Uzumba	8	27	24	3	26	1	2	5	8	1	11
III	Binga	21	40	29	11	36	4	9	9	14	7	1
IV	Pfungwe	2	43	40	3	39	4	7	9	7	9	11
IV	Mudzi	21	30	28	2	30	0	8	8	7	3	4
IV	Buhera	14	31	31	0	29	2	2	3	7	7	12
IV	Lower Gweru	3	30	28	2	30	0	6	3	7	7	7
V	Bikita	20	30	30	0	24	6	6	2	11	2	9
3	7	7	231	210	21	214	17	40	39	61	36	55

Table 2.2 Type of data collected from focus group discussions and formal interviews

Level	Data collected
Farmer level	Gender, farm size, crop prioritization (legumes and other food crops), farming inputs, harvesting and storage practices, sources of seeds, preferred seed characteristics, constraints in bambara groundnut farming, and farmer's knowledge on the agronomical benefits of bambara groundnut cultivation.
Consumer level	General consumer information on frequency and reasons for consumption of bambara groundnut. Consumption preference (*fresh or dry seeds*), place of purchase (*e.g. informal market, farmers, and supermarket*), bambara groundnut prices relative to cowpea and groundnut. Properties considered during the buying process (*e.g. colour and size*). Preferred bambara groundnut attributes to be improved.
Processor level (individual and in groups)	Legume processing and raw material perception, processing techniques and quality of products. Sources of the bambara groundnuts, parameters considered when purchasing the seed, properties of good quality bambara groundnut ideal for processing and prices relative to cowpea and groundnut.
Trader level (formal and informal)	Places of purchase and sales of bambara groundnuts, types of purchased bambara groundnut (*fresh or dry*), consumer perception of quality seed (*e.g. colour and seed size*), criteria that determine selling price and periods of availability.

2.3. Data processing and analysis

Statistical analysis was done using IBM SPSS (v 23) and Microsoft Excel. Descriptive statistics (graphs / tables of arithmetic means ±SD, percentages or frequencies) are given for land allocation, bambara groundnut seed selection, production Figs, legume preference, bambara groundnut based products, consumption frequency and processing constraints. Percentage land allocation per crop was calculated by taking a ratio of land (ha) allocated to that crop and the total amount of farmed land (sum of land given to this and other crops). Land allocation (ha) for bambara groundnut was tested for normality using QQ plots and variation in land allocation between regions was assessed using ANOVA at 5% level of significance. Association of the presence (yes/no) of processing constraints and firewood accessibility was tested using chi-square test of independence. All maps were constructed using QGIS Version 2.8 [86].

3. Results and discussion

3.1. Bambara groundnut production

For this study, farm size per household was categorised as small (< 2.5 ha), medium (2.5-5 ha) and large (> 5 ha) Among the different districts, most respondents (70-95%) had a medium-sized farm (2.5-5 ha), concurring with the 0.5-2.5 ha farm size reported by Madebwe, Madebwe [52]. Diverse crops such as maize (*Zea mays*), groundnut, cowpea, bambara groundnut, as well as small grains, like sorghum (*Sorghum bicolour*), finger millet (*Eleusine coracana*) and pearl millet (*Pennisetum glaucum*), and occasionally sunflowers (*Helianthus annuus*) were grown by households as previously reported by Nhamo, Mupangwa [87] and Madebwe, Madebwe [52]. According to Makate, Wang [88], crop diversification practised by rural farmers is perceived as an ecologically feasible and cost effective way of mitigating drought and other uncertainties experienced in subsistence agriculture. As reported that subsistence agriculture is the source of livelihoods, food security and income generation in the surveyed districts [9], crop diversification brings household resilience of farming systems and nutritional diversity [88], which is a step towards increasing productivity and fighting malnutrition [1].

Table 2.3 shows the percentage of land allocated to each crop in each district, used as a measure of a crop's significance in a household, either for food, income generation or both. As explained by respondents, Zimbabwe is a patriarchal society and women are not the custodians of the land [89, 90]. Hence land allocation is by men, who give preference to crops they consider indispensable [91]. However, unfavourable climatic conditions experienced in these semi-arid regions override the patriarchal factor in land allocation for maize; for example, Bikita in region V recorded the least (%) land allocated to maize.

Respondents explained that poor maize productivity led to the cultivation of small grains as their staple, which in this case accounts for 31.6% of allocated land [92]. The patriarchal factor becomes relevant in legume land allocation as reiterated by the respondents, agreeing with previous researchers, who reported bambara groundnut to be a women's crop [93, 94]. However, Binga and Buhera districts were exceptions; here both men and women were involved in production because bambara groundnut is a cash crop to them. Results reveal that households in different districts esteem legume crops contrarily, such that Bikita, Binga and Buhera prioritize bambara groundnut, Uzumba and Pfungwe prioritize groundnut, and Mudzi and Lower Gweru allocate approximately equally areas for the three legumes. Analysis of variance (ANOVA) regarding bambara groundnut land allocation in different agro-ecological regions was not logical to perform because of unbalanced representation of regions. For this reason, analysis of variance in land allocation for crops was performed at district level, which resulted in a significant effect of district on land allocation for all crops including bambara groundnut at $p < 0.05$ level, e.g. bambara groundnut [F (6, 224) = 21.5, p = 0.000]. Although the sampling method was not completely randomised, it still properly represents land allocation by the populations in the regions and districts visited

Table 2.3 Land allocation to crops and bambara groundnut seed selection in districts.

Region	District	Average ratio of land allocation (%)*					Bambara groundnut	
		Maize	Groundnut	Cowpea	Other corps	Bambara groundnut	(ha)	% Seed selection
III	Uzumba (n=27)	33.1 ± 9.2	25.6 ± 6.7	14.9 ± 6.5	10.8 ± 11.7	15.5 ± 5.6	$0.30^{ab} \pm 0.16$	47.1
III	Binga (n=40)	36.9 ± 12.8	20.5 ± 10.8	5.5 ± 7.8	9.4 ± 12.5	27.6 ± 9.9	$0.53^{d} \pm 0.27$	82.5
IV	Pfungwe (n=43)	34.8 ± 10.5	21.9 ± 6.3	16.1 ± 6.5	9.6 ± 10.1	17.5 ± 6.5	$0.38^{bc} \pm 0.21$	46.5
IV	Mudzi (n=30)	49.2 ± 6	19.9 ± 6.1	14.8 ± 4.9	0.3 ± 1.4	15.9 ± 2.9	$0.21^{a} \pm 0.07$	93.3
IV	Buhera (n=31)	37.3 ± 8.1	18.3 ± 8.8	9.4 ± 5.5	9.8 ± 8.3	25.3 ± 9	$0.53^{cd} \pm 0.21$	35.5
IV	Lower Gweru (n=30)	40.2 ± 11.2	16.2 ± 5.8	13.3 ± 6.2	10.5 ± 5.3	16.5 ± 5.2	$0.21^{a} \pm 0.12$	60
V	Bikita (n=30)	1.7 ± 6.7	19.8 ± 8.7	15.7 ± 6.8	31.6 ± 12.5	31.2 ± 12.4	$0.60^{d} \pm 0.14$	20
	Average %	33.3 ± 2.5	20.3 ± 1.9	12.8 ± 0.9	11.7 ± 4.2	21.4 ± 3.2	0.398 ±0.233	55

*as percentage ratio of ha/total ha for all crops of all respondents.

Different superscript letters (a, b, c and d) in a column indicate means that are significantly different

Land allocation among legumes is not a clear indicator of rainfall patterns in the districts, except for Uzumba in region III, an area considered to be good for groundnut production [87]. Land allocation for legumes seems to be governed by end use, which could be income generation, consumption or both. Those who grow bambara groundnut as a cash crop, allocate more land to its cultivation (i.e. Binga and Buhera). In contrast, cowpea is mostly grown as a dual crop for exploiting both the leaves as relish eaten with thick maize porridge and the seeds as boiled snack; this was not so for bambara groundnut [95]. The downside of bambara groundnut production as compared to cowpea was the labour intensity due to the essential 'earthing up' and the harvesting that requires pulling the crop out of the soil. From these findings, land allocation of maize reflects the amount of rainfall received, while land allocation for legumes reflects the significance of end use.

To produce bambara groundnut, female farmers, who are the custodians of the crop, use seeds from their previous harvest, from relatives or buy seeds in the market place [14]. Commercially produced seeds are not available [93]. Thus, sharing and using seeds from the previous crop bring convenience, community self-sustenance and the continuation of local customs that brings value to traditional systems [9]. Unfortunately, these practices sometimes result in poor germination and reduced yield as reported in some districts, agreeing with De Kock [27]. This points toward the need to expedite bambara groundnut breeding programs to improve the quality of seed sources.

Table 2.3 shows bambara groundnut seed selection practices in various districts, indicating that some respondents cultivate selected landraces, while others used mixed landraces, contradicting Plahar [32], who reported sole cultivation of mixed landraces in Zimbabwe. Respondents clarified the need for seed selection to be driven by some markets places. This development appears to be beneficial to farmers in terms of production as they are able to assess landrace performance in terms of drought tolerance and yield. If this is pursued over a period of time, breeders will have starting points as part of the preliminary work to develop better varieties would already have been accomplished by farmers [96].

Most respondents (63.6%) knew about the agronomical benefits of bambara groundnut farming, i.e. improved soil fertility [61], and accordingly did not use fertilizers [87]. Fortunately, bambara groundnut does well even with low input farming and poor soils [97], ensuring a definite harvest and food availability for these already financially constrained farmers [94]. The distribution of bambara groundnut production is shown in Fig 2.2. As expected, respondents in Bikita had a high bambara groundnut production because the district allocated more land to its cultivation. All respondents stored bambara groundnut in their shells to avoid damage by weevils.

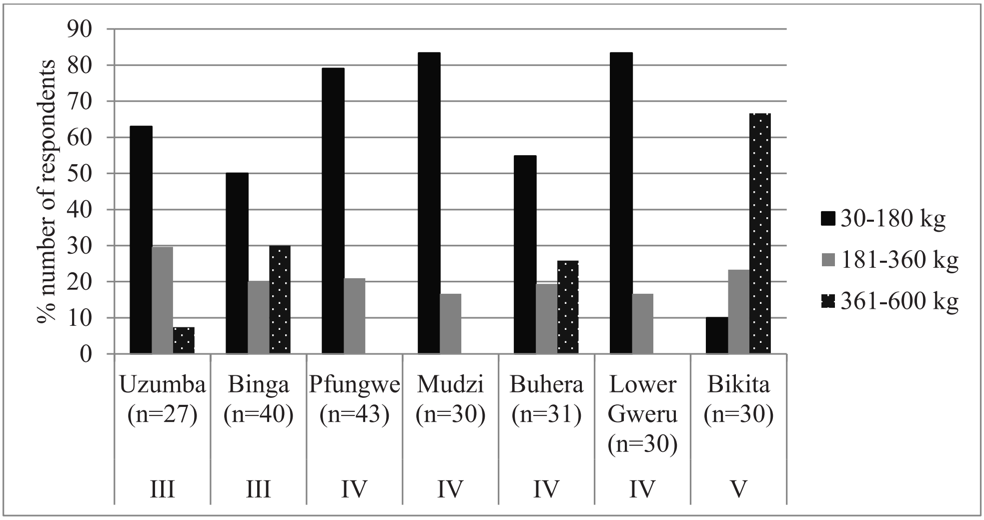

Fig 2.2 Bambara groundnut production across districts (as percentage of respondents).
Shelled bambara groundnut production is categorised as low (30-180 kg), medium (181-360 kg) and high (361-600 kg) at a 60% shelling percentage

3.2. Marketing bambara groundnut

Cash cropping has been suggested as a way to improve food security for smallholder farmers [54]. Local trading of bambara groundnut for income generation and exporting to neighbouring countries such as South Africa was previously reported [32, 98]. According to Plahar, Annan [32], the biggest exporter of bambara groundnut in Africa is Zimbabwe with exports estimated between 1,500 and 3,000 tonnes per year. Currently, bambara groundnut is cultivated for home consumption, batter trade (i.e. exchange of goods), as income generator for a household's sustenance or a combination of these factors, concurring with the findings of Quaye and Johnson-Kanda [94] in Ghana. Fifty to eighty-eight percent of the households sold bambara groundnut locally or at farmers' markets and/or exported to neighbouring countries either in their capacity or through middle-persons, who link them to informal and formal markets (e.g. supermarkets). Traders in Buhera and Bikita exported to South Africa, whilst Mudzi farmers sold at Nyamapanda (a border post with Mozambique), agreeing with the reports by Plahar, Annan [32]. This shows the complexity of the bambara groundnut supply chain and the potential to improve the trading network.

The bambara groundnut trading places visited were Harare (Mbare and Lusaka farmers' markets) and Chitungwiza (Chikwanha and Makoni farmers' markets). The largest suppliers of bambara groundnut at these market places included farmers from Buhera, Bikita, Wedza, Uzumba, Maramba and Pfungwe districts. The traders at the market places reported all year round availability of dry bambara groundnuts, and that selling price drivers included season and supply, i.e. the seeds become more expensive towards the next planting season [99]. As previously reported by farmers, bambara groundnut sold was of mixed and individual landraces. Those who bought selected landraces typically used them for seed-fair shows or religious purposes, *viz.* especially the black-seeded landrace. As for market price, 83% of respondents reported a higher price for bambara groundnut than cowpea, whilst mixed reviews on bambara groundnut versus groundnut were given. The average selling price for bambara groundnut was 3.5 to 4 US$ per kg in local supermarkets. The recorded prices of a 20-litre bucket of dried and shelled cowpea, groundnut and bambara groundnut as of December 2015 were 10, 20 and 23 US$, respectively, at Mbare farmers' market.

The high price for bambara groundnut emphasized its importance for income generation and indicates why this crop should be given more priority.

No common criteria like a grading system for measuring the quality of bambara groundnut for trading was in place. Quality aspects considered included taste (based on previous experience), colour, size, plumpness, and absence of weevils and rot. These aspects were also reported by Mwangela, Makoka [100]. The absence of a stipulated grading system for bambara groundnut reinforces how relegated the crop is. Consequently, designing a standard grading system is yet another necessity to improve the value chain of bambara groundnut [101].

3.3. Processing of bambara groundnut in rural Zimbabwe

Bambara groundnut processing in rural Zimbabwe is at household level and occasionally as a collective practice by women during functions or community activities [27]. Information of processing techniques was either passed on from older family members or shared from women cooperatives. Processing methods include soaking, boiling, roasting, milling and several combinations of these methods to produce diverse products as shown in Fig 2.3 and Table 2.4, agreeing with methods from East and West African countries [27, 68].

Most districts had superior processing diversity as compared to Binga and Bikita. The Binga district constitute the minority Tonga tribe who reside along the Zambezi river in the North of Zimbabwe, whilst Bikita is part of the majority Shona tribe. There are no clear cultural-processing linkages in the study, however Pfungwe, Buhera and Uzumba had older respondents who had better knowledge of processing. Simple domestic processing equipment used includes traditional grinding tools and solar tent dryers, which are designed to optimise the drying process [102].

3.3.1. Boiled bambara groundnut-based products

The common method of processing bambara groundnuts in Zimbabwe is boiling in water for approximately 2-4 h to make a snack or substitute product for bread called *mutakura* [27]. Optional ingredients added during boiling include cowpea and groundnut and or maize to make an assorted *mutakura*. *Mutakura* may also be mixed with peanut butter or cooking oil and other ingredients (*viz.* tomatoes, onion, and paprika) to make a relish eaten with thick maize porridge. Additionally, *Jambalaya* is a product of *mutakura* mixed with Irish potatoes (*Solanum* sp.) or sweet potatoes (*Ipomoea batatas*). Respondents in Pfungwe recommended porridge from mashed peanut-based *mutakura* as a complementary and weaning food for children as it is considered 'healthy', concurring with already published research that the legume is rich in nutrients [40, 43].

In Lower Gweru, dried bambara groundnut based soup is prepared from solar dried *mutakura* after boiling, mashing, drying and milling. The flour is mixed with fresh, grated tomatoes, onions, and spices to make dough that is further dried in a solar tent dryer to the desired moisture content. Subsequently, the dried *mutakura* mixture is roasted (until golden brown), then ground with a mortar and pestle, and finally sieved to make a soup. Lower Gweru respondents stressed the improvement of flavour and nutritional attributes after addition of the soup to relish dishes. Flavour development can be attributed to the formation of desirable flavour compounds during roasting [37]. Despite all these diverse dishes, the long cooking time involved in boiling bambara groundnut remains a major setback to its utilization as recounted by consumers (50-75%) as shown in Table 2.5, concurring with studies of Mwangela, Makoka [100] in Malawi and Quaye and Johnson-Kanda [94] in Ghana. Moreover, as narrated by Bressani [76] and Mubaiwa, Fogliano [70], high-energy consumption and firewood scarcity are important factors limiting bean preparation and consumption.

To prove this concept, an association between the firewood accessibility constraints and processing constraints of bambara groundnut was tested. Many respondents (79.2 %) with difficulties in firewood access reported constraints in processing, whereas 38.5% of those with easy access reported problems of processing, $\chi^2(1) = 38.352$, $p < 0.001$, N=231. Firewood accessibility was not a limiting factor for approximately 50% of respondents in Pfungwe and Uzumba as they still had sufficient trees in their forests or had adjusted to the time it takes to boil the legume, whereas respondents in Bikita and Buhera complained of firewood shortages, indicating deforestation in the area. On the other hand, Binga and Pfungwe respondents reported shortages of potable water as a limiting factor since boiling takes a lot of water. According to the sustainable diets concept, deforestation [49, 103] and excessive water consumption are serious problems reducing the sustainability index of bambara groundnut [21]. These findings point towards the urgent need for alternative processing methods to circumvent HTC. Nevertheless, the products and recipes specified for boiled bambara groundnut offer opportunities to solve the problem of dietary diversity, which is necessary to achieve good child nutrition, considering that some dishes improve food edibility by young children [104].

Reported remedies for circumventing HTC in the boiling processing include grading of seeds before cooking to standardise variety and or seed size because mixed seeds have dissimilar physical and water absorption properties [35, 105]. Varietal differences in processing aptitude were revealed by some respondents. Apparently, light coloured seeds have inherent thin seed coats (e.g. white) and are therefore faster to cook and mill as compared to darker landraces. These findings agree with the work of Plahar and Annan [106], who reported that in Ghana consumers who boil bambara groundnut, prefer the cream-coloured seeds (low in tannin) and choose the red-coloured seeds (high in tannin) for flour production. This finding indicates the necessity to determine the correlation between processing aptitude of varieties and nutrient indicators.

HTC can also be tackled by coarse-milling (i.e. in Pfungwe and Buhera) for size reduction prior to boiling. Consequently, the seed coat, which is a barrier to hydration, is partially removed [107] and the surface area for water absorption is increased. Additionally, HTC was addressed by pre-soaking in Bikita (33.3%), Buhera (9.7%), Mudzi and Lower Gweru (6.7%). This practice reduce the cooking time as previously reported by Annan, Plahar [43], but most respondents claimed that it also alters taste and texture. In addition, Buhera respondents (9.7%) were aware of cooking aids such as *kanwa* that is widely applied in West African countries (e.g. Ghana and Nigeria) to reduce cooking time [32, 39, 108], but were against them because of gastrointestinal problems (laxative effect) and altered sensorial attributes [109].

Kanwa is known as *gowa* in some parts of Zimbabwe, where it is used as a tenderizer in cooking leafy vegetables, common beans, and okra [110], but is rarely used for bambara groundnut. Since taste is the main attribute liked by bambara groundnut consumers in Zimbabwe, processing solutions that address the HTC phenomenon must not negatively impact sensorial properties.

Alternative products

Bambara groundnuts may also be roasted to produce diverse products such as roasted snacks, *rupiza* (dehulled grits), pre-soaked *mutakura* grits and bambara groundnut milk as shown in Table 2.4. Roasting and soaking are pre-treatments employed prior to further processing of bambara groundnut into different products as presented in Fig 2.3. Soaking prior to drying, roasting and milling is employed for easy removal of the seed coats in the preparation of pre-soaked *mutakura* [60].

Rupiza is a product mainly of dry-roasted cowpea [111, 112] and occasionally bambara groundnuts made by coarse milling to produce grits, which are boiled and mixed with peanut butter before serving. Generally, 12% of the respondents were aware of bambara groundnut *rupiza*, with a better awareness in Uzumba and Pfungwe. Bambara groundnut *rupiza* takes 45 min to 1 h to boil and this cooking time is comparable to the boiling time of freshly harvested bambara groundnut pods [50]. Hence *rupiza* production is a solution to the problem of the long cooking time with a 75% reduction in cooking time as compared to cooking with alkaline salts [70].

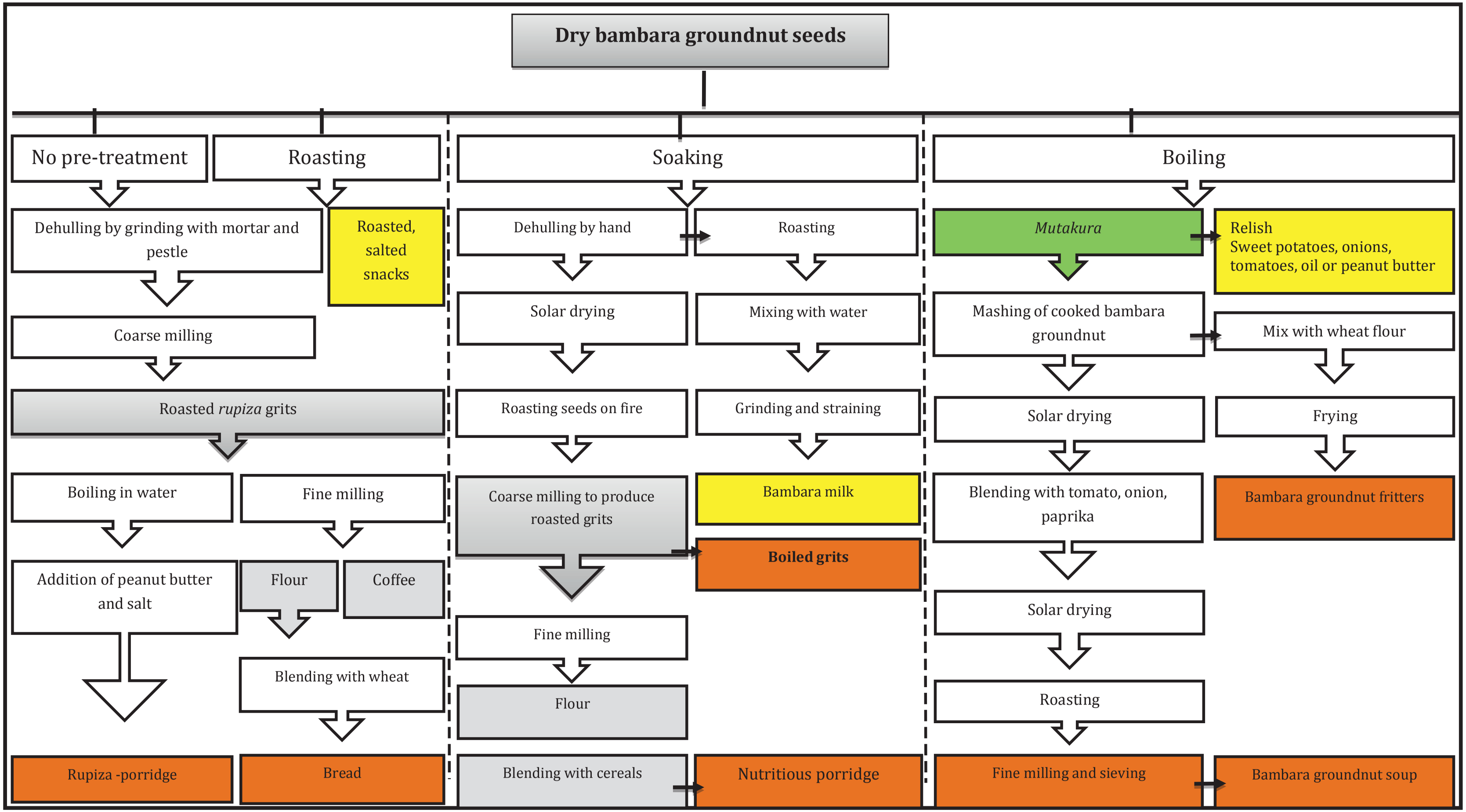

Fig 2.3 Bambara groundnut processing into various products in the semi-arid regions of Zimbabwe.
The white boxes indicate processing steps and grey boxes indicate intermediate products. Green, yellow and orange are used to explain the scale of adoption and popularity of the products. Green indicates products already largely used, orange and yellow are products with minimum use. The products in orange are suggested for further improvement

Table 2.4 Preferred bambara groundnut-based products and their major processing practices according to agro-ecological zone and district (as percentage of respondents)

Place		**Boiling**					**Roasting**		**Milling**			**Soaking**
		Mutakura			**Relish**							
Region	**District**	**snack**	**porridge**	**soup**	**oil**	**peanut**	**snack**	**coffee**	**flour/bread**	***rupiza***	**porridge**	**milk**
III	Uzumba (n=27)	100	0	0	0	0	11.8	41.2	5.9	35.3	0	0
III	Binga (n=40)	100	0	0	20	7.5	0	0	0	7.5	0	0
IV	Pfungwe (n=43)	100	7	0	48.8	34.9	32.6	0	27.9	37.2	11.6	7
IV	Mudzi (n=30)	100	0	0	100	100	0	0	0	0	56.7	0
IV	Buhera (n=31)	100	0	0	19.4	9.7	22.6	0	12.9	9.7	0	16.1
IV	Lower Gweru (n=30)	100	0	73.3	93.3	100	16.7	0	0	10	0	0
V	Bikita (n=30)	100	0	0	45	0	5	0	0	0	0	0

Table 2.5 Constraints to bambara groundnut cooking according to agro-ecological zone and district (as percentage of respondents)

Region	District	Long cooking time (%)	Constraint in accessibility %	
			firewood	water
III	Uzumba (n=27)	58.8	55.6	0
III	Binga (n=40)	55	0	92.5
IV	Pfungwe (n=43)	72.1	44.2	34.9
IV	Mudzi (n=30)	53.3	13.3	53.3
IV	Buhera (n=31)	64.5	61.3	12.9
IV	Lower Gweru (n=30)	53.3	80	36.7
V	Bikita (n=30)	58.1	66.7	30

However, the use of traditional milling tools is a tedious time and energy consuming process [28] due to the thick seed coat and strong attachment between the seed coat and cotyledons caused by mucilage and gums at the interface [113]. Using commercial, locally available grinding machines can facilitate this issue.

Fig 2.3 shows different types of flour produced in surveyed districts. The intensity of dry roasting differentiates between the production of coffee and flour; to produce coffee, dark roasting is performed. Bambara groundnut-based coffee is a substitute for tea for 80% of the respondents in Uzumba. In a study by Nti [37], an improved method of producing flour in Nigeria involves soaking seeds in water for 30 min, boiling for 25 min, and thereafter drying at 60-65ºC in a hot air dryer for 10 h. Products of moist heat treatment and dehulling enhanced consumer appeal for both traditional and newly formulated bambara groundnut foods. In terms of district application, bambara groundnut and wheat flour blends are used for bread making and fritters as previously reported by De Kock [27], whilst a blend of bambara groundnut and maize flour (including other optional ingredients) is used to make a nutritious porridge. In all districts, no clear distinction for the applications of produced flour were encountered, i.e. whether flours are multipurpose or ideal for specific applications.

A minor product of roasting and boiling is the production of bambara groundnut milk previously reported by Murevanhema and Jideani [31] and Poulter and Caygill [114], whereby bambara groundnut is soaked overnight and thereafter dehulled to remove the seed coats. Dehulled bambara groundnuts are then roasted, mixed with water (ratio 1:5), crushed until the water changes in colour and the seeds have been reduced in size. Afterwards, the milk is filtered (residue removal) and boiled (optionally) to remove odours and then added to tea [31, 114, 115]. According to Poulter and Caygill [114], raw and pasteurised bambara groundnut milk contained 2.0 g protein per 100 ml.

3.4. Legume preference and consumption

Legume consumption preferences results, i.e., bambara groundnut, cowpea and groundnut, across districts showed that 93.3 % of respondents in Lower Gweru highly ranked bambara groundnut followed by 50-60% in Bikita, Mudzi, and Buhera, whilst a minority of consumers in Pfungwe and Uzumba (25%) preferred it most. Overall, 42% of respondents prefer bambara groundnut as compared to 31% and 29% who prefer groundnut and cowpea, respectively.

Consumption frequency of dry bambara groundnut in districts varied as shown in Fig 2.4. Respondents (50-80%) in all districts consumed bambara groundnut once to twice a week (i.e. especially from August to December). Exceptions were in Binga, where 45% of respondents reportedly consume bambara groundnut every day in summer followed by 33% in Bikita. The preferred attributes of bambara groundnut from a consumer perspective were taste, the satiating effect, its nutritional benefits or a combination of these attributes.

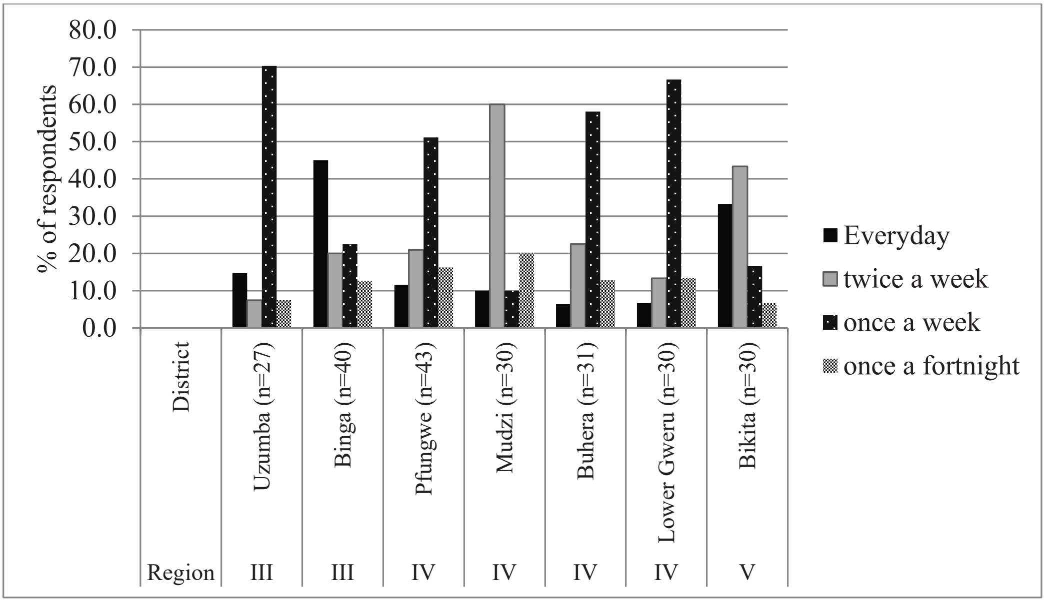

Fig 2.4 Consumption frequency of bambara groundnut in various districts (as percentage of respondents)

Fig 2.5 shows the relationship between consumption frequency and these preferred attributes. Assessment of linkages shows that 43% of respondents who consume bambara groundnut everyday prefer its taste, whilst 38% of everyday consumers also prefer a combination of attributes (nutrition, satiety and taste). Nutrition as an independent attribute scores low, but this is not surprising as some respondents did not have any knowledge about the nutritional importance of bambara groundnut (i.e., as a source of protein). Overall, 39.4% of respondents appreciated a combination of nutrition, satiety and taste of bambara groundnut, thus any alteration in processing that distorts this is undesirable.

The relationship between consumption frequency and bambara groundnut ranking shows that respondents who highly ranked bambara groundnut were frequent consumers (i.e. 59.1% everyday consumers and 50.8% twice-a-week consumers). Nevertheless, even intermittent consumers (i.e. once a week and once a fortnight) ranked bambara groundnut fairly high, namely 45 and 48%, respectively. These frequencies show the contribution of crop to dietary diversity and food security. Unfortunately, some who consume bambara groundnuts complain of stomach pain, flatulence and general discomfort. This mostly concerns bambara groundnut and not cowpea. This could mean that bambara groundnut contains a higher amount of flatus-causing oligosaccharides than cowpea [116], implying the need to address this problem.

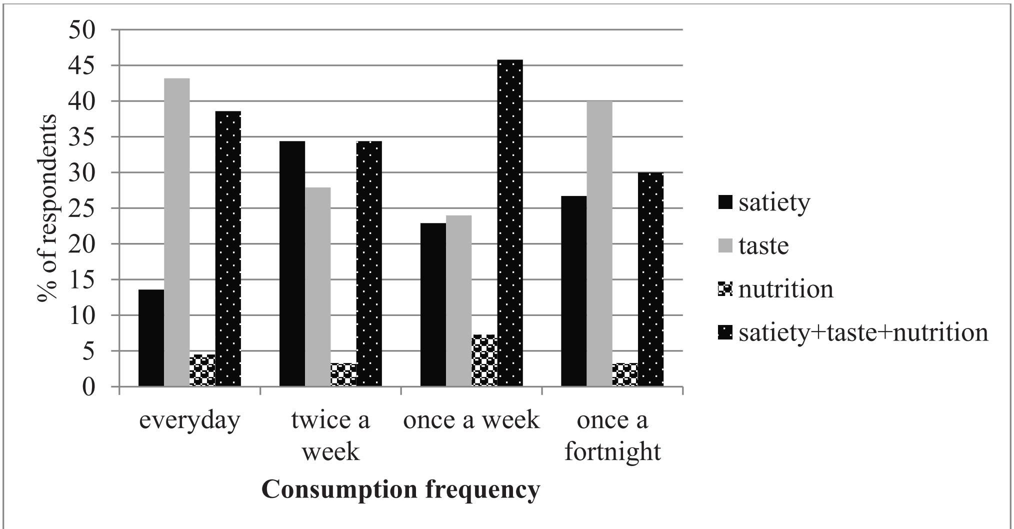

Fig 2.5 Relationship between consumption frequency of bambara groundnut and preferred attributes (as percentage of respondents)

4. Conclusions and recommendations

The findings from the land allocation for crops in semi-arid districts in Zimbabwe show that farmers practise crop diversification and are aware of crops that suit their agro-ecological zones. Land allocation for legumes is governed by end use such as income generation, consumption or both. Lack of commercial seeds is a major problem in bambara groundnut farming, but a positive development of farming selected seed is identified as a step towards preliminary breeding programs to obtain drought tolerance and increased yields. The bambara groundnut value chain is characterised by the absence of stipulated grading systems, which show how relegated the crop is. Development of standard grading systems is highly recommended.

The survey showed soaking, boiling, dehulling, roasting and milling as important processing techniques for bambara groundnut in Zimbabwe, but there was no clear cultural trend on processing diversity.

The goal of legume processing is not only to solve HTC phenomena but also to retain the important sensorial and nutritional aspects of the legume-based products. The processing techniques can be evaluated from various angles, such as sustainability of the method, i.e. firewood and water consumption, processing time and aptitude, as well as the sensorial and nutritional aspects of the final product. The high-energy consumption, water and firewood scarcity are important factors limiting bambara groundnut preparation and consumption. Deforestation and excessive water consumption are serious problems reducing the sustainability index of bambara groundnut. These findings necessitate investigating the correlation between processing aptitude of processing techniques and sustainability indicators to optimise current processing methods. Appraisal of nutrient bioaccessibility and product functionality are necessary in evaluating the quality of the food products. As such, protein digestibility and micronutrient bioaccessibility studies are paramount as nutrient deficiency is still a problem that plagues sub-Saharan African communities compounded by the ravages of HIV and AIDS [58].

The limited information exchange as evidenced by variation in processing activities in various districts demonstrate the need for this exercise, i.e. among local Zimbabwe communities and in the other sub-Saharan region, for improved food security [18]. Non-governmental organizations are recommended to carry out awareness and sensitization workshops for information sharing and oversee adoption of new techniques in different areas. The government, through the ministries of agriculture, nutrition and health, is recommended to authorize policy incentives on legume farming and processing. Studies on the food technological and nutritional aspects of bambara groundnut based products are recommended. Ultimately, knowledge sharing, education, building from existing strategies and applied researches are essential interventions for improving food and nutrition security through bambara groundnut.

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7. Compliance with ethical standards

Conflict of interest : The authors declare that they have no conflict of interest.

Chapter 3

Hard-to-cook phenomenon in bambara groundnut (*Vigna subterranea* (L.) Verdc.) processing: Options to improve its role in providing food security

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Abstract

Indigenous legume crops are pivotal in providing proteins and food security to sub-Saharan African rural communities, but most of these crops are underutilized because of the so-called hard-to-cook (HTC) phenomenon in combination with inadequate processing techniques. This review studies the case of bambara groundnut, which is third in importance after groundnut and cowpea and especially adapted to semi-arid areas. Published data on the hard-to-cook (HTC) phenomenon implicate microstructural and compositional changes as factors leading to its development. Useful and sustainable techniques to process HTC legumes in developing countries include cooking with alkaline salts, milling, roasting, fermentation, and malting. Improvement of these processing techniques in relation to nutrient bioaccessibility, safety, and consumer acceptance of the products is urgently needed. Recommendations are to lessen the problems of food security in sub-Saharan African countries through, amongst other means, the optimization of bambara groundnut processing methods.

Keywords: *Bambara groundnut, hard-to-cook phenomenon, hard-to-mill phenomenon, processing, food security, sub-Saharan Africa.*

1. Introduction

In sub-Saharan Africa, indigenous crops such as legumes play an important role, especially during times of famine, by providing nutrition and a source of income [18, 32, 117]. Promoting indigenous, drought-tolerant crops is a possible way of alleviating the impacts of climate change and successive droughts experienced in arid and semi-arid regions [15]. Bambara groundnut (*Vigna subterranea* (L.) Verdc.) is an underutilized indigenous crop, which is cultivated by subsistence women farmers throughout Zimbabwe [27, 118, 119] as well as other tropical and sub-tropical countries in sub-Saharan Africa and some parts of Latin America and Asia [25, 27, 120]. Its origin has been traced back to the Sahelian region of present-day West Africa and its name is derived from the Bambara tribe, who at present live in Mali [25, 121].

Bambara groundnut is commonly grown as a rotational crop with legumes like groundnut and cowpea and cereals like maize, sorghum and millet in agro-ecological regions that receive minimal annual rainfall [27, 118]. In Zimbabwe, five agro-ecological regions are distinguished, numbered in descending order of agricultural productivity, soil type and annual rainfall [79, 122]. Ninety percent of the rural areas in Zimbabwe are situated in agro-ecological regions III, IV and V, which receive low rainfall (800 mm or less) in relatively short seasons, making them unsuitable for intensive cropping of maize [7, 79, 122]. According to Hillocks, Bennett [118], the land area considered appropriate for bambara groundnut cultivation was, for example: Swaziland 100%, Uganda 98%, Zambia 95%, Burundi 89%, Zimbabwe 84% and Central African Republic 79%. In Zimbabwe, bambara groundnut is considered an important crop for improving food security because of its capacity to tolerate harsh climatic conditions under a low-input agricultural system where many other crops fail [50, 123, 124]. The most recent production figures from Zimbabwe's Central Statistics Office in 1997 show a countrywide production estimate of 15,138 x 10^3 kg, with 10,161 x 10^3 kg from the rural areas, 3219 x 10^3 kg from resettlement areas, 1694 x 10^3 kg and 64 x 10^3 kg from small sale and large scale commercial farms, respectively [50]. Like the other legumes, bambara groundnut improves soil fertility (i.e., increases the level of soil nitrogen) through a symbiotic relationship with bacteria that form root nodules [30].

In Africa, bambara groundnut is ranked third in importance after groundnut (*Arachis hypogea*) and cowpea (*Vigna unguiculata*) [69, 120] and although research findings suggest that bambara groundnut is a crop with great nutritional and agronomic potential, it remains one of the most neglected [27]. The major factor limiting the utilization of bambara groundnut is the hard-to-cook (HTC) phenomenon, which develops during high temperature (30-40ºC) and high relative humidity (>75%) storage in tropical and sub-tropical regions [24, 28, 32, 37, 118, 125]. In Zimbabwe and other sub-Saharan countries, bambara groundnut is consumed in numerous ways at different stages of maturity. Freshly harvested pods are eaten as snacks after boiling for approximately an hour [24, 27, 32, 50, 118]. HTC bambara groundnuts may be roasted and eaten as snacks [27]. The seeds may also be milled into flour, baked to make small flat cakes and bread [68]. Additionally, thin porridge [33] and stiff porridge have been made from the flour [27]. In Eastern Africa, bambara groundnuts are roasted, milled and the flour is used to make a soup, a relish and also a substitute for coffee [126].

HTC bambara groundnuts require longer boiling time (namely 3-4 h) [27] and therefore higher energy expenditure to become edible as compared to cowpea or common bean (*Phaseolus vulgaris*) [118]. Cooking time of other legumes is reported to be: for soya bean 3.6 h [127] common bean 1.5 h [128] cowpea 2.4 h [129] and mung bean 0.5 h [130]. The HTC problem may not seem serious for people living in the developed worlds, who have energy resources and state-of-the-art techniques to utilize HTC legumes. However, in Zimbabwe boiling HTC bambara groundnuts is challenging, especially for those of lower socio-economic status, who rely on firewood to provide energy for cooking and heating [131, 132]. According to [76] a longer cooking time and high energy consumption are important factors limiting bean preparation and consumption. In Zimbabwe, firewood constitutes 49% of the total energy used [133] with over 90% of rural and urban households depending on firewood energy as a result of countrywide power shortages experienced on a daily basis [103, 133]. Recent studies show that on average a household in Zimbabwe uses approximately 8 m^3 of firewood per year for domestic purposes [132, 133]. Therefore, it is a concern that, while demand for firewood continues to grow in rural Zimbabwe, rapid land use and deforestation have reduced the supply of firewood, leading individuals to travel to forests that are very far from their homesteads for collection [49]. Consequently, due to limited energy supply available for boiling, consumption of bambara groundnut is reduced. Additionally, it was found in other legumes that hardening of legume seeds causes a decrease in nutritional quality (e.g., in-vitro protein digestibility) [134] and extended boiling leads to reduced palatability and reduced protein digestibility [135, 136]. Furthermore, HTC phenomena in bambara groundnut result in hard-to-mill properties, which are a concern to processors, who find it difficult to find proper dehulling and milling techniques [24, 28, 118, 137].

Amarteifio, Tibe [123] and De Kock [27] described the variation in preferences for bambara groundnut seeds between Botswanan and Zimbabwean consumers; consumers from the Southern and Central districts of Botswana prefer the white and cream-coloured landraces, whereas those in the Northern part close to the Zimbabwean border, prefer the red landraces. Red seeds were reported to be more popular than cream-coloured seeds in Zimbabwe [118]. In Ghana, consumers who boil bambara groundnut, prefer the cream-coloured seeds (low in tannin) and those in flour production choose the red-coloured seeds (high in tannin) [138].

Utilization, market potential and crop improvement of bambara groundnut have been reviewed previously by Hillocks, Bennett [118] who stressed the importance of the crop, but gave limited information on the methods of its processing after the development of the HTC phenomenon. The present review investigates published data on nutritional information and the physical properties of bambara groundnut relative to the development of the HTC phenomenon. For each constituent, the average, minimum and maximum values are reported after conversion to the same unit. Further, current methods of managing HTC in legumes are categorised as chemical, physical, and biological treatments. Evaluation of the applicability and sustainability of these processing methods is with reference to resource-limited communities (RLC). Knowledge on HTC phenomena and assessment of changes that occur during storage of legumes will enable the improvement of current bambara groundnut processing procedures. Finally, formulation of research needs will depend on identified knowledge gaps. Research needs will target to strengthen the knowledge base of this important neglected legume.

2. Nutritional composition of bambara groundnut seeds

Biochemical analysis of the composition of carbohydrate, fat and protein reveal that bambara groundnut produces an almost balanced diet [31, 37] Tables 3.1, 2, and 3 present the average, minimum and maximum values of chemical composition (i.e., proximate, mineral and vitamin content) of bambara groundnut seeds, respectively. In comparison to other legumes, bambara groundnut has a lower protein content. Like most legumes, the sulphur containing are the limiting amino acids, such as methionine and cysteine; nevertheless, bambara groundnut seeds contain a relatively high proportion of methionine as a percentage of the protein [25, 38, 39, 43, 118] and all other essential and non-essential amino acids meet FAO requirements [38, 127]. Moreover, the protein score (i.e., amino acid score of the most limiting amino acid) is 80% for bambara groundnut as compared to 74% for soya bean (*Glycine max*), 65% for groundnut (*Arachis hypogaea*) and 64% for cowpea (*Vigna unguiculata*), showing that bambara groundnut has a high protein quality [43].

Bambara groundnut contains higher levels of fatty acids (i.e., palmitic and linoleic acids) in comparison to groundnut [139, 140]. Furthermore, bambara groundnut contains a substantial quantity of vitamin A, thiamine, riboflavin, niacin, carotene, and trace quantities of ascorbic acid [44, 141]. Bambara groundnut contains micronutrients such as zinc and iron. [31] calcium and potassium, but is poor in phosphorus and magnesium [25]. The red seeds have been reported to contain almost twice as much iron as the cream seeds; thus, they are proposed to be valuable in areas where iron deficiency is a problem [25, 27]. According to a survey in Northern Ivory Coast, bambara groundnut seeds were useful in treating cases of anaemia. Milk (i.e., a watery extract produced from milled bambara groundnut) was reported to compare favourably in flavour and mineral composition with cowpea and soya bean Poulter [142]. A drawback in bambara groundnut and other legumes is the lower bio-accessibility of the proteins and minerals due to anti-nutrient factors such as tannins, trypsin inhibitors, lectins, and phytates [31, 143, 144].

3. Physical properties of bambara groundnut seeds

Food materials respond in a distinctive, specific way to physical treatments involving mechanical, thermal, electrical, and electromagnetic processes. The response of food materials to processing gives essential quantitative knowledge for the rational design of methods and in this case, for the estimation of the response of HTC bambara groundnut to different processing methods [153-156]. A better understanding of the way bambara groundnut responds to physical, biological and chemical treatments allows for optimum design of sustainable processing methods and machinery to ensure maximum utilization of bambara groundnut [155].

Important physical characteristics of raw and processed bambara groundnut seeds include particle size and shape, mass, volume, particle and bulk density, porosity, rapture strength and surface area. Physical properties of bambara groundnut and their relation to moisture content have been studied [35, 105, 107]. These physical properties differ amongst bambara groundnut landraces and are dependent on inherent seed properties, interactions of chemical components during growth and seed storage conditions [157].

Table 3.1 Proximate composition of bambara groundnut seeds.

Parameter	Minimum	Average	Maximum	References
Moisture (g/100 g)	5.8	8.6	11.5	[29, 43, 144-148]
Crude protein (g/100 g)	17.1	18.9	22.9	[27, 29, 43, 123, 144-149]
Crude lipid (g/100 g)	2.9	6.3	9.2	[27, 29, 43, 123, 144-149]
Ash (g/100 g)	2.9	3.7	5.1	[27, 29, 43, 123, 144-149]
Crude fiber (g/100 g)	1.4	4.0	7.2	[27, 29, 43, 123, 144-149]
Acid detergent fiber (g/100 DM)	8.0	8.3	8.6	[26, 123]
Neutral detergent fiber (g/100 DM)	10.8	15.5	20.1	[26, 123]
Carbohydrate (g/100 g)	55.8	61.7	68.0	[27, 29, 43, 123, 144-149]
Energy (kcal/100 g)	367	385	395.3	[27, 43, 148]
Dry matter (%)	89.1	90.9	93.0	[26, 38, 123, 150]
Acid detergent lignin (g/100 DM)	0.3	1.6	3.4	[123]
Tannin (g CE/100 g)	0.25	0.90	2.27	[37, 43, 138]
True protein digestibility (%)	na	77	na	[150]

DM, dry matter; CE, catechin equivalent; na, not available.

Table 3.2 Mineral composition of bambara groundnut seeds.

Parameter	Minimum	Average	Maximum	References
K (mg/100 g)	470	1234	2200	[26, 97, 149]
P (mg/100 g)	33.3	317	613	[26, 43, 97, 148, 149])
Ca (mg/100 g)	37	56	70	[26, 43, 97, 148, 149]])
Na (mg/100 g)	0.9	5.3	20.2	[26, 97, 149, 151, 152]
Mg (mg/100 g)	57.1	184	335	[26, 97, 152]
Fe (mg/100 g)	1.2	3.1	7	[26, 97, 148]
Zn (mg/100 g)	0.6	1.1	1.2	[26, 29]
Mn (mg/100 g)	1	1.8	5.5	[26, 29]
Cu (mg/100 g)	0.2	0.6	1.3	[26, 29, 97]

Table 3.3 Vitamin composition of bambara groundnut seeds [148]

Parameter	Minimum	Average	Maximum
Thiamine (mg/100 g)	0.22	0.47	0.62
β-Carotene (mg/100 g)	na	0.01	na
Riboflavin (mg/100 g)	0.14	0.15	1.12
Niacin (mg/100 g)	0.6	1.8	2.4
Ascorbic acid	na	Trace	na

na, not available.

The physical properties of bambara groundnut landraces have been reported to be indispensable determinants of the behaviour of the seeds during cooking and rehydration [37]. Since physical properties are expected to change during processing, recognition of these changes helps to avoid potential processing failures [155].

3.1. Seed coat colour and thickness

Seed colour and seed coat thickness are important parameters to evaluate in order to recommend the bambara groundnut landraces that should be suitable for boiling and milling for resource limited communities. According to Beninger and Hosfield [158] the presence of flavonoids (i.e., flavonol glycosides, anthocyanins), condensed tannins (proanthocyanidins) and carotenoids determines the seed coat colour of legumes. In addition, concentrations of tannins located mainly in the seed coat correlate with seed colour [138, 159]. Dark-coloured bambara groundnut seeds (i.e., black) contained higher concentrations of tannins as compared to light-coloured (i.e., cream) seeds [37, 142, 145]. Table 3.4 presents the average seed coat thickness of bambara groundnut seeds. The relationship between seed colour and seed coat thickness was reported [37]. The studied bambara groundnut landraces (cream, brown, maroon, black) from Northern Ghana had distinct variations in the seed sizes and seed coat thicknesses [37]. Two varieties of cream-coloured bambara groundnut were found to have smaller seed sizes (thousand seed weight), and thinner seed coats (0.11 and 0.12 mm) as compared to the other three dark-coloured varieties (brown, maroon and black) (0.20 mm). Seed coat thickness was measured using a pearl chrome-plated micrometer and was not significantly ($p > 0.05$) different for the three dark-coloured varieties [37].

3.2. Seed hardness and rupture strength

Hardness is a parameter that measures the ability of the seed to resist breakage, penetration and scratching [155]. Grain hardness has been related to kernel density and power requirement during the milling process (i.e., dehulling and size reduction), and the physical characteristics and quality of final products [160]. In addition, a correlation was found between seed hardness and seed weight. The role played by seed hardness in the determination of the milling quality of legume seeds is reported to be due to cell wall structure and composition [161]. Further, rupture strength is the force required to initiate seed rupture and it affects milling performance and water absorption of seeds such that seeds with low rupture strength will soften easily during cooking and are easy to handle in flour production. The difficulty in milling of legumes is due to the presence of fibre (cotyledon cell-wall materials) and the strong binding of large amounts of insoluble proteins to starch [162].

3.3. Linear dimensions

Physical dimensions of seeds such as length, width, and thickness are important in designing post-harvest operations of grading and sorting. These linear dimensions determine the particle size of the seed, which is mainly important in determining the required power for size reduction operations and also the quality of the final product [155]. Measuring linear dimensions is important for further determination of geometric average diameter (Dg), sphericity, surface area, volume and porosity. Table 3.4 presents the reported length, width, and thickness of bambara groundnut. The three major perpendicular dimensions of bambara groundnut were measured using a digital Vernier calliper [105, 153] at average moisture contents ranging from (dry basis) 7.2 to 9% [105] and 5 to 35% (wet basis) [153]. From these findings, dimensions increased at higher moisture content and were a function of the moisture content of the seeds. The average dimensions of bambara groundnut seeds were length (11.5 to 12.7 mm), width (9.4 to 10.6 mm) and thickness (9.2 to 10.5 mm). The seed size of the bambara groundnut seeds was graded as large (≥ 10.5 mm), medium (9.50–10.49 mm) and small (< 9.50 mm) [105] The Dg of the seed was generally higher for larger seeds. The Dg was calculated using the $(LWT)^{1/3}$ = Dg formula and ranged from 9.8 to

11.1 mm [105] Germ lengths constituted about 55 to 72% of the total seed length, while germ widths made up 50 to 70% of the seed width [37, 105].

3.4. Volume and surface area of seed

According to Baryeh [153] the volume of bambara groundnut seeds increased with increase in moisture content from 425 mm^3 at 5% moisture content to 900 mm^3 at 25% moisture content [153]. After 25% moisture content, the volume change was reported to be very little [153]. Surface area is an important physical parameter in thermal processing since heat transfer is proportional to surface area. The dimensions of the seed, namely seed surface area and seed volume, increased non-linearly with increase in moisture content. It was observed that on water absorption, the seeds expanded in length, width, thickness and geometric diameter within the moisture range of 5 to 25% (wet basis) and displayed no dimensional change thereafter [153].

3.5. Density of seed

Density of a material expressed in units of mass per unit volume is the amount of that material occupying a certain space [155]. Table 3.4 presents the average values of true density and bulk density. At all seed moisture contents studied, true density was higher than bulk density. The true density decreased proportionally when the moisture content increased from 5 to 35%, indicating a lower seed weight increase in comparison to its volume increase when its moisture content increased. Bulk density can be calculated as the ratio of the bulk weight and the volume of the container (kg/L) [153]. It is a physical property that affects the structural load and is an important parameter in designing drying and storage equipment [153]. Seed density is the ratio of the weight of a single seed to its volume, whereas the bulk density is the defined amount of seeds in a vessel or container that also includes the void spaces between the seeds [153].

3.6. Porosity of seed

Porosity of the seed is the ratio of volume of void spaces in the material over the total volume; its value depends on the value of true density and bulk density. The average values of porosity of bambara groundnut seeds are shown in Table 3.4; porosity variation is not as high as is found in other seeds [153] The porosity of bambara groundnut seeds was reported to increase nonlinearly to 43.8% at a low moisture content (20%) and then decrease nonlinearly to 40.5% at a high moisture content (35%). Porosity is an important measure in bambara groundnut processing as it influences the size reduction properties and drying rate [153]. Porosity permits air and liquids to flow through a mass of seed particles referred to as a packed bed in drying operations [155]. Packed beds of seeds with low porosity (i.e., a low percentage of air space) are more resistant to fluid flow and have low heat transfer, thus they are more difficult to dry, heat and cool.

3.7. Sphericity of seed

Sphericity of the seed is the measure that indicates deviation of the seed from a perfectly round sphere [155]. The average values of sphericity of bambara groundnut seeds are shown in Table 3.4. Higher values of sphericity (> 70%) show less deviation of the shape from a sphere [163]. This parameter is important in determining terminal velocity, the drag coefficient, and the Reynolds number, which are important in dehulling, size reduction, and grading processes. Bambara groundnut seeds are sphere-shaped (oval) and have a high aspect ratio. According to Mpotokwane, Gaditlhatlhelwe [105] the sphericity of bambara groundnut seeds decreased nonlinearly with increase in moisture content. Small-sized seeds had higher sphericity and aspect ratio as compared to large seeds [105]. Seeds that are more spherical occupy more volume. The variation in sphericity is due to inherent seed properties and also the influence of moisture content [163].

Table 3.4 Physical characteristics of bambara groundnut seeds

Parameter	Minimum	Average	Maximum	References
Length (mm)	11.5	11.9	12.7	[37, 105, 107, 153]
Width (mm)	9.4	9.8	10.6	[37, 105, 107, 153]
Thickness (mm)	9.2	9.9	10.5	[37, 105, 107, 153]
Germ length (mm)	6.5	7.1	7.9	[37])
Germ width (mm)	4.7	5.5	6.6	[37]
True density (kg/m3)	1003	1174	1295	[105, 107, 153]
Bulk density (kg/m3)	745	805	895	[105, 107, 153]
Porosity (%)	22.7	32.6	43.8	[105, 107, 153]
Sphericity (%)	85.5	86.9	88	[105, 107, 153]
Geometric diameter (mm)	9.8	10.4	11.1	[105, 107, 153]
Seed coat thickness (mm)	0.11	0.16	0.20	[37]
Test weight (kg/hL)	89	91.1	92.8	[37]
1000 seed weight (g)	543	670	816	[105, 153]

3.8. Water absorption

The extent of controlling the HTC phenomenon in legumes can be determined by water absorption and cooking properties. Water absorption and cooking kinetics of seeds are influenced by their intrinsic (i.e., physical and chemical) properties [107]; thus, bambara groundnut varieties with varying compositions will also vary in cooking times [163]. Research on water absorption and cooking characteristics of bambara groundnut is useful since it allows the evaluation of the process in terms of sustainability, nutritional and sensorial quality of the final product [35]. Mathematical modelling of water absorption and cooking processes is applicable in optimizing these processing operations to reduce cooking time of legumes. The Peleg's, the first order and the sigmoid models are widely used to study the behaviour of legumes during rehydration. A study by Kaptso, Njintang [107] evaluated the physical properties of bambara groundnut and cowpea varieties (2 each). Two varieties of cowpeas (coded GC and WC) and two varieties of bambara groundnuts (coded WB and BB) were purchased from local markets in Ngaoundere (for WB and BB), Garoua (for GC) and Bafoussam (for WC). The study determined the diffusivity of liquid water in the seeds during soaking at different temperatures as well as the required energy of activation. The cowpea varieties (WC and GC) and bambara groundnut seeds (BB and WB) studied had water absorption kinetics that followed the first order, Peleg with a proposed sigmoid model [107]. This means that the absorption curve exhibited a lag phase which was followed by a phase of time–linear relationship water absorption and finally, one of slower rate of absorption.

Substantial varietal variations were observed regarding the physical properties (i.e., water absorption kinetics and effective diffusivity) of the seeds [35, 107]. The saturation water content was higher for the cowpea varieties (1.39 to 1.50 g/g) and lower for the bambara groundnut varieties (0.88 to 1.00 g/g). The proposed sigmoid model significantly described the water absorption kinetics, regardless of the variety and temperature. The effective diffusivity of the seeds was reported to differ in the order of cowpea (GC variety) > bambara groundnut (WB variety) > bambara groundnut (BB variety) > cowpea (WC variety) and increased as the soaking temperature increased from 35 to 45°C. The variation in the effective diffusivity at 25 and 35°C was observed to be linearly correlated ($R^2 > 0.82$; $p < 0.05$) to the percent seed coat, which suggests that seed coat thickness played a major role in water absorption [107]. In addition, the effective diffusivity varied with temperature according to the Arrhenius equation and the resulting activation energy varied from 78.8 kJ mol^{-1} for cowpea (GC variety) to 11.2 kJ mol^{-1} for bambara groundnut (WB variety) [107].

Physical properties responsible for water absorption in cowpeas were studied by Sefa-Dedeh, Stanley [164] who found that inherent seed properties (i.e., seed coat thickness, volume, hilum size) and protein content are of importance depending upon rehydration stage. Additionally, Annan, Plahar [43] reported a significant difference in the rate of water absorption of bambara groundnut varieties with different seed sizes. The same observations were found in sorghum seeds, as smaller seeds had higher rates of water absorption as compared to larger seeds [37]. According to Plahar and Annan [106] for several soya bean cultivars studied, the percent seed coat values had a significant effect on the relative time for maximum water absorption. Additionally, Sefa-Dedeh, Stanley [164] also indicated that seeds with thinner coats have a faster rate of water absorption during the initial soaking period (0-6 h), after which hydration occurred at the same rate. Enwere and Hung [28] observed that maximum water absorption decreased with increase in temperature; for example, when soaking at 25°C, water absorption was 11 h and at 60°C it decreased to 4 h. The water absorption profiles were comparable to those reported for cowpeas [164] with the exception that bambara groundnut took a longer time to reach maximum water absorption.

According to Poulter and Caygill [114] bambara groundnut seeds had a high water absorption during soaking and doubled weight after approximately 36 h; at this stage seed coats became loose and were easily removed. A study by Ojimelukwe [145] observed the changes in textural properties of bambara groundnut during cooking. Additionally, the cooking time was shorter for the cream and brown-coloured cultivars as compared to the red and black-coloured cultivars. Estimation of tannin content of bambara groundnut seeds showed that tannin contents of the red and black seed cultivars (0.96 g CE/100 g and 1.I g CE/100 g, respectively) were considerably higher ($p \leq 0.05$) than the tannin contents of cream and brown seed cultivars (0.68 g CE/100 g and 0.72 g CE/100 g, respectively) [145]. The higher tannin contents of the red and black seed cultivars are hypothesized to cause the lower protein availability of these seeds as a result of the interactions of tannins with proteins, thus leading to prolonged cooking to ensure edibility of legumes [145].

4. Development of hard-to-cook (HTC) phenomena

Legumes are grown, harvested, dried and then stored until consumption [131, 165]. Storage under hot and humid conditions, as encountered in many sub-tropical and tropical African countries, renders legumes prone to a hardening phenomenon characterized by extended cooking time to ensure adequate softening during cooking [47, 131, 135, 166-168]. HTC in legumes is associated mainly with modifications that occur in the cotyledons and seed coats [131, 169-171]. Several intricate factors, external and internal to the tissue, simultaneously contribute to events leading to the HTC phenomenon [172]. Several mechanisms suggested for the HTC phenomenon in legume seeds are shown in Fig 3.1. The factors are categorized as structural (i.e., autolysis of cytoplasmic organelles, weakling plasmalemma integrity, and lignification of middle lamella) and compositional changes (i.e., formation of insoluble pectate, lipid oxidation, and polymerization, phytic catabolism, interactions of proteins and phenolic compounds and polymerization of phenolic compounds, deposition of lignin-like material) [47, 170, 173, 174].

A study by Hincks and Sanley [173] proposed that the HTC phenomenon in legumes proceeds by two mechanisms, namely i) the 'pectin-phytate' and ii) the 'lignification' mechanism, which both occur at high temperatures and humidity.

As such, bean hardening during storage is due to phytate hydrolysis and deposition of lignin-like material, which strengthen the cell walls. Structural components associated with HTC development include: seed coat, cell walls and membranes, middle lamella and starch granules; and compositionally, phenolic compounds, proteins, nonstarch polysaccharides, phytic acid, and lignin [172]. These alterations cause reduced cell separation of HTC legumes during cooking and consequently an extended cooking time [48].

4.1. Microstructure properties in relation to development of hard-to-cook (HTC) phenomena

Scanning electron microscopy provides an in-depth look at the microstructure of plant food materials as affected by changes (i.e., physical and chemical) during post-harvest storage and processing [168, 175]. The HTC phenomenon is characterized by the restricted softening of the cotyledons upon cooking. The relationship between microscopic properties and development of HTC phenomenon was reported [168, 176]. Pirhayati, Soltanizadeh [176] studied the chemical and microstructural changes in HTC pinto bean (*Phaseolus vulgaris)* and easy-to-cook lentil (*Lens culinaris*). The major structural changes observed under the scanning electron microscope were deteriorations in cytoplasmic contents of the cooked cotyledon cells of hard seeds as compared to limited changes in cooked soft beans [176].

The comparison of the structural changes of the seed coats of black beans (*Phaseolus vulgaris*) stored for 2 yr. at ambient conditions (AC) and refrigerated hypobaric conditions (RHC) showed a disruption of the parenchymal cell layers and large intercellular spaces between the cell layers of beans stored under AC [168]. Additionally, the middle lamellae were mostly dissolved in soft beans during cooking, but in hard beans they were intact and binding the cells together [175]. The parenchymal cell layers of the beans stored under RHC exhibited slight disruption of the cell layers. Cotyledons of black beans stored under RHC exhibited many large intercellular spaces typical of normal beans. On the contrary, the beans stored under AC exhibited cotyledon cells with few small intercellular spaces typical of HTC beans [168].

Mafuleka, Ott [177] described the changes occurring in decorticated white and red bean (*Phaseolus vulgaris*) during HTC phenomenon development as elevated phytase activities and slight, but nonsignificant increases in lignin levels in both bean genotypes maintained under adverse storage conditions (8 months). The mechanism involving phytic acid degradation appeared to be the dominant system influencing the HTC phenomenon in the white, and to some extent, the red bean genotypes for the storage period of up to 8 months [177].

4.2. Compositional changes in relation to the development of the HTC phenomenon

Several researchers have described the changes in legume hull, cell wall [178-181] and cotyledon in relation to legume hardening during storage [135, 177, 182]. In addition, changes in phytase were reported in Malawian white and red bean; phytase was also suggested to be an indicator for cookability of common beans [177] Further, phenolic compounds (i.e., tannins and phenolic acids) have been noted relative to HTC development in legumes [169, 183] A study by Shiga, Cordenunsi [184] described the solubilisation pattern of carioca bean hull nonstarch polysaccharides during soaking and subsequent cooking after storage at 30°C and 75% relative humidity (RH) for 8 months. In another study by Shiga and Lajolo [185] and [179] all plant cell wall constituents were reported to have increased during storage (i.e., acid and neutral detergent fibres, lignin, cellulose, and hemicellulose).

4.2.1. Lignification and phenolic compounds

Several studies have reported the changes that occur in lignin, condensed tannins and phytase during storage and their contribution to HTC development in different legumes such as common beans and cowpea [134, 176, 186-189]. The lignification mechanisms hypothesise the migration of aromatic compounds from seed coats to cell wall surfaces where they act as precursors in lignification-like reactions. An investigation was undertaken by Hincks and Sanley [173] to establish the potential contribution of lignification in the HTC phenomenon in common bean (*Phaseolus vulgaris*) using scanning electron microscopy. In their findings, cell wall material from hard beans had a lamellate appearance, not observed in the control; thus, cellulose deposition, a precursor of lignification, was implicated. A study by Molina, Eaten [190] reported an increase in lignified protein in bean cotyledons (*Phaseolus vulgaris*) during storage at ambient conditions (25°C and 70% RH).

This was corroborated by Hincks and Sanley [173] and [183] who reported substantial increases in Klason lignin and lignified protein contents that were correlated to an increase in cooking time. However, Srisuma, Hammerschmdt [183] detected insignificant changes in lignin content during bean hardening and stated a significant increase in free hydroxycinnamic acids, which was hypothetically suggested to be linked with increased hardening.

In a study by Garcia, Filisetti [47] HTC carioca beans (*Phaseolus vulgaris* L. var. Carioca) were reported to have more phenolics (3 times) linked with the soluble-pectic fraction and an increased content of pectates [47]. The researchers proposed that the presence of more hydroxycinnamic acids (i.e., ferulic, *p*-coumaric, ferulic, and sinapic acid) bound to the soluble pectin [191] and their probable involvement in cross-linkages, could contribute to changes in cell adherence. Subsequently, this would alter the cell separation upon cooking of HTC beans. These findings were similar to the earlier findings of Garcia and Lajolo [171] and Machado, FerruziI [191], who observed an increase in the concentration of free phenolic acids in HTC beans, showing that the HTC phenomenon affected potential nutritive properties of dry beans. The analysis of soluble pectin fractions (FT-IR-DRIFTS) by Maurer, Ozen [174] showed that more phenolic compounds were related with the soluble pectin fraction of HTC carioca beans (red and black) as compared to control carioca beans. The consequence of increased phenolics in the HTC beans was thought to be a reduced cell wall separation during cooking, which ultimately would contribute to prolonged cooking time of HTC beans to reach the same tenderness [174].

The relationship of storage temperature and cookability of faba bean (*Vicia faba*) was reported by Nasar-Abbasa, Plummera [192] and showed significant increases in acid detergent fiber and lignin contents with increasing storage temperatures. In addition, considerable reductions in total free phenolics, particularly in the seed coat, were observed at high temperature storage (12 months). A study by Pirhayati, Soltanizadeh [176] evaluated the chemical changes of 'hard-to-cook' pinto bean and small-type lentil. In the study, phytic acid decreased by 36 to 61% and total phenolic content by 43 to 61% during storage, whilst seed hardness increased 3 to 6 times.

4.2.2. Starch alteration in relation to HTC development

A study by Hohlberg and Stanley [167] proposed that compositional and microstructural modifications occur in black bean (*Phaseolus vulgaris*) starch during storage, and that this change is irrespective of the environment. The changes in the starch are one of the contributions in the reduced acceptability of hard beans and a major cause of significant postharvest losses [131]. According to Garcia and Lajolo [171] an important quality indicator for bean consumers in Latin America is the presence of a thick viscous broth in cooked bean. As such, a less thick viscous broth formed in HTC beans during cooking could relate to changes of starch properties induced by the hot and humid storage conditions. HTC phenomena result in prolonged cooking time, and subsequently a reduction in nutritional value and changes in the sensorial quality due to poor properties of the cooking broth [171]. Furthermore, Garcia and Lajolo [171] reported the changes in starch during bean storage to be an end result of hardening and aging, and not as a contributory agent of HTC development. Scanning electron microscopy of starch granules and seed breakages isolated from hard beans revealed granule resistance to amyloglucosidase attack and a higher degree of crystallinity.

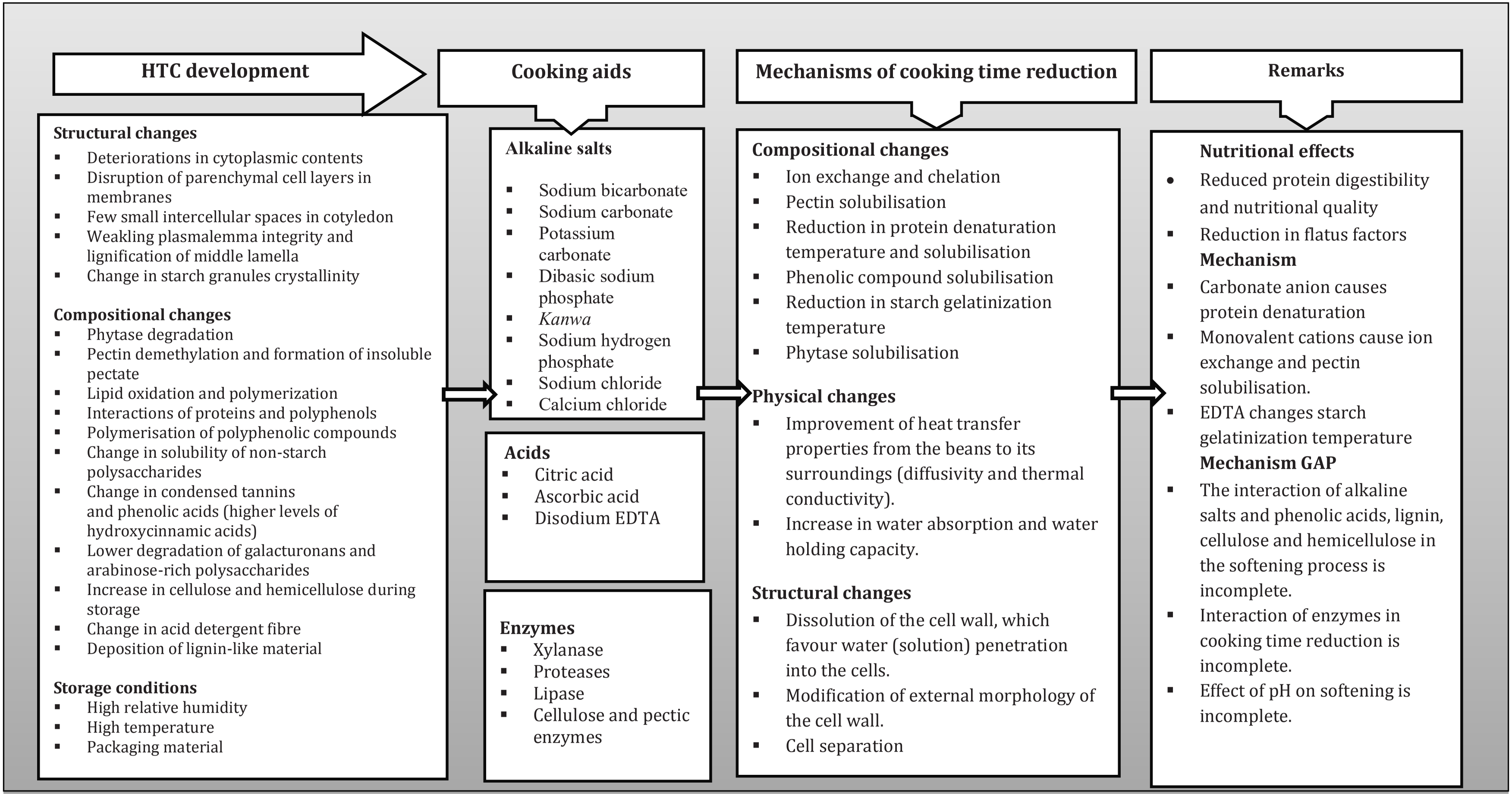

Fig 3.1 Overview of HTC development in legumes and mechanism of cooking time reduction

Additionally, under polarized light microscopy, starch granules of HTC beans had an increased birefringence as compared to starch granules of the control beans [171]. Moreover, an increase of the gelatinization temperature of starch isolated from HTC beans (5 yr. storage) was observed from differential scanning calorimeter (DSC) thermograms, whereas starch isolated from soft bean (control) seeds showed no such change [171]. In a similar study by Hohlberg and Stanley [167] an increase in starch gelatinization temperature during different storage conditions of black beans was not related to the hardening process. Garcia and Lajolo [171] concluded that the changes in the starch of HTC beans could be an outcome of the hardening process rather than a causative mechanism. However, consumers can use starch alteration as a method of screening the cooking quality of common beans and evaluate its acceptance.

4.2.3. Nonstarch polysaccharides (NSP) in relation to HTC

The carbohydrates of bambara groundnut are mainly composed of starch and nonstarch polysaccharides (NSP) (see Table 3.5) with smaller amounts of reducing and nonreducing sugars [25]. In a study by Brough and Azam-Ali [38] approximately 12.8% total NSP found (i.e., resistant to acid and enzyme hydrolysis) were suggested to be lignified seed coat material and low molecular weight phenolic compounds. The ratio of insoluble to soluble fractions of bambara groundnut NSP was 57:43; with cellulose accounting for 36% of the total NSP. Table 3.6 presents the constituent monosaccharides of the individual NSP fractions. The insoluble fraction is predominantly composed of glucose, arabinose, and xylose whereas uronic acids, xylose, and galactose were the components of the soluble NSP of bambara groundnut [38]. NSP are present as arabino-xylans, noncellulosic glucose and xylose as xyloglucans since these are typical hemicellulosic components of seeds. In addition, xylans are reportedly contained in the bambara groundnut seed coats, thus dehulling of seeds may affect the digestibility of the flour produced. Dehulling decreases the proportion of xylose in the insoluble fraction, thereby reducing the amount of material resistant to enzyme and acid hydrolysis [38].

The soluble portion of the cell wall was predominantly composed of pectins consisting of galacturonic acid, rhamnose, arabinose, galactose, and uronic acid and side chain molecules linked to the rhamnogalacturonan and arabinogalactan backbones [38]. Previous researches have shown the influence of NSP in the hardening process of legumes [38]. These researchers attributed the changes in microstructure of legume cell wall and polysaccharides during storage to be the major factor in HTC development [38, 179, 184]. Lower water solubility and lower degradation of galacturonans and arabinose-rich polysaccharides were observed during cooking of aged beans [185]. Additionally, it was proposed that during the cooking process, the pectin in the middle lamella is depolymerized by β-elimination of methyl-esterified polygalacturonic acids, promoting an increase in cell separation and legume softening [176, 182].

4.2.4. Protein alteration in relation to HTC development

A study by Hohlberg and Stanley [167] reported a significant increase in proteins (i.e., small polypeptides and free aromatic amino acids) during storage (10 months) of black beans (*Phaseolus vulgaris*) under different environmental conditions. Small polypeptides and free aromatic amino acids are products of large protein hydrolysis. The concurrence in the increase of these simple proteins and development of HTC in beans suggests a possible link between these phenomena [167]. The suggested mechanism is the probable migration of the small polypeptides and free aromatic amino acids to the middle lamella where they are polymerised and lignified, possibly by the action of mobilized enzymes at elevated temperatures. These findings were corroborated by Hussain, Watts [193] who reported on the changes in electrophoretic pattern of black bean cotyledon proteins during storage.

5. Managing the hard-to-cook phenomenon by legume processing

Storage of legumes at low temperature and humidity prevents the occurrence of the HTC phenomenon in legumes [46-48]. However, such storage conditions are not within reach of the poorest rural communities of Zimbabwe, who lack the infrastructure and resources to implement these. Therefore, effective and efficient processing technologies are required to transform the HTC bambara groundnuts into edible and nutritious foods [194]. The methods of processing HTC legumes are i) chemical treatments (*cooking aids*) (see Figs 3.2, 3.3, 3.4 and 3.5), ii) biological treatments (*germination and fermentation*), and iii) physical treatments (*milling, roasting and canning*) (see Fig 3.6).

5.1. Chemical treatments for managing HTC in legume processing

5.1.1. Effects of cooking aids on cooking time

Previous studies have shown that different salt solutions affect the cooking time of HTC legumes [32, 195, 196]. Soaking of legumes in the presence of both monovalent (Na^+ and K^+) and divalent cations (Ca^{2+} and Mg^{2+}) has been demonstrated to increase the water absorption capacity and subsequently reduce the cooking time of legume seeds [196, 197]. A study by de-Leon, Elias [197] reported that a salt concentration of 0.5% sodium bicarbonate ($NaHCO_3$) and 2.5% potassium carbonate (KCO_3) (w/v) (i.e., a ratio of 8.3:1 of monovalent to divalent cations) was the most effective in increasing bean softening. To optimize the process for bean sensorial properties, the authors suggested the soaking of the beans with a salt solution, thereafter discarding the soaking solution, and cooking with fresh water [197].

Bellidoa, Arntfielda [198] studied the effects of micronization pre-treatments on the physicochemical properties of navy and black beans (*Phaseolus vulgaris* L.) by a mixture of different salts (i.e., sodium bicarbonate, sodium carbonate, and dibasic sodium phosphate (Na_2HPO_4) and a mixture of acids (i.e., citric and ascorbic acid) and disodium EDTA. The mixture of salts was more effective than the other mixtures in reducing the hardness of micronized black beans [198]. There was no reduction in firmness of navy beans due to EDTA, but EDTA decreased the degree of starch gelatinization.

Table 3.5 Composition of nonstarch polysaccharides (NSP) of bambara groundnut [38]

Parameter	**Composition**
Total NSP % DM	12.78 ± 0.32
Insoluble NSP % total	57.42 ± 5.13
Soluble NSP % total	42.58 ± 5.13
NCP % total	53.48 ± 3.41
Cellulose % total	36.04 ± 2.16
Wt NSP % DM	25.62 ± 0.47
Reside % DM	12.84 ± 0.69

Total NSP, insoluble NSP; NCP, noncellulosic NSP; Wt NSP, dry weight of NSP following enzymatic hydrolysis

Table 3.6 Composition of sugar constituents of nonstarch polysaccharides (NSP) of bambara groundnut [38]

Sugar	Total	Insoluble	Soluble	NCP	Cellulose
Rhamnose	1.13 ± 0.08		1.13 ± 0.08		
Arabinose	38.7 ± 1.38	15.54 ± 1.59	23.16 ± 0.08	42.38 ± 3.14	
Xylose	16.69 ± 0.26	9.05 ± 0.98	7.64 ± 1.10	19.15 ± 1.38	
Mannose	1.51 ± 0.22	0.52 ± 0.02	0.99 ± 0.43		
Galactose	5.94 ± 0.18	2.59 ± 0.18	3.35 ± 0.31	5.37 ± 0.18	0.57 ± 0.28
Glucose	50.44 ± 1.81	45.19 ± 2.88	5.25 ± 1.05	3.07 ± 0.70	47.37 ± 1.26
Uronic acids	14.47 ± 0.15	1.09 ± 0.21	13.38 ± 0.25	11.16 ± 0.44	
Total	128.88 ± 4.08	73.98 ± 5.86	54.9 ± 3.30	81.13 ± 5.84	47.94 ±1.54

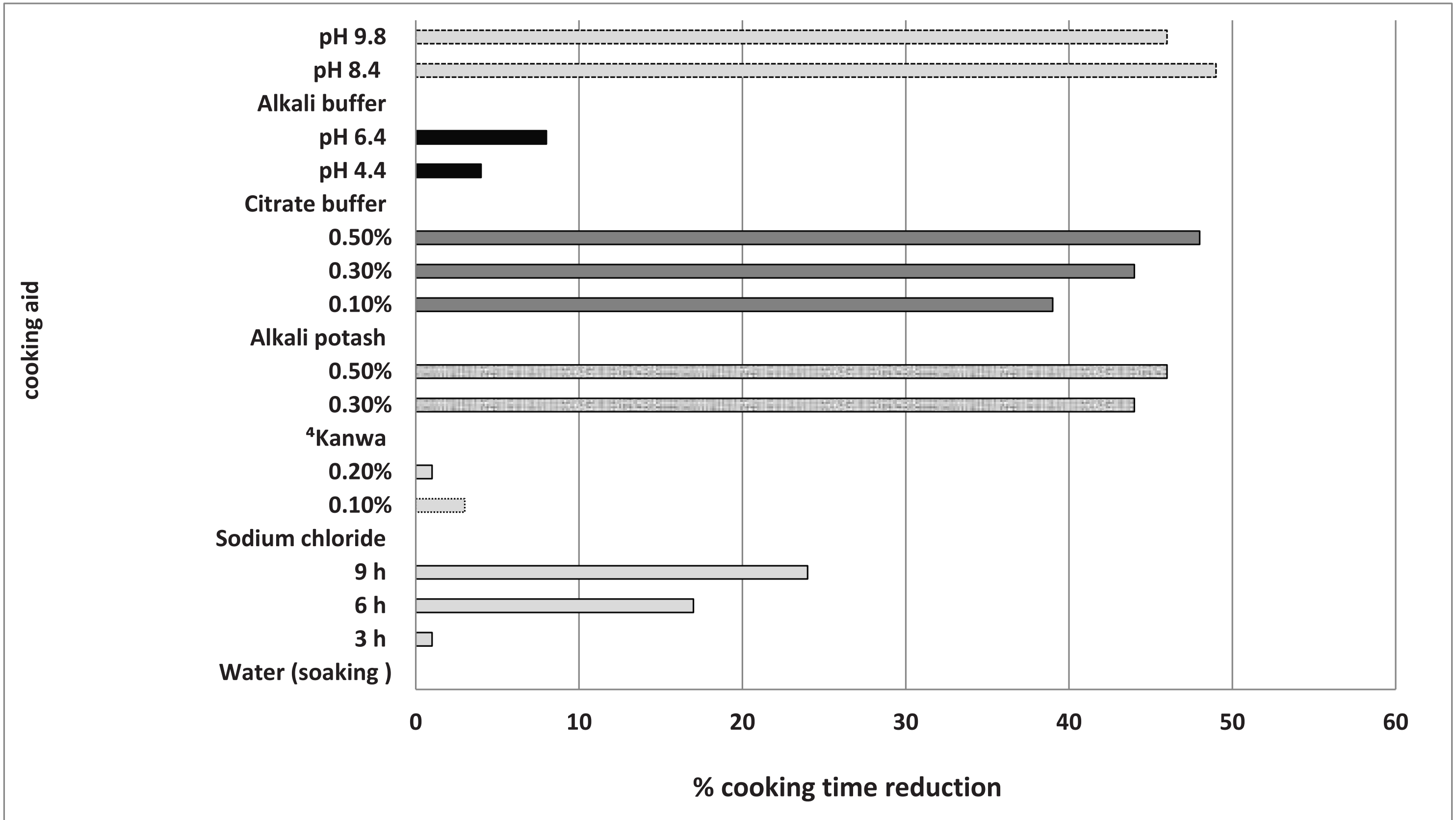

Fig 3.2 Percentage cooking time reduction of cowpeas soaked and cooked in water, cooked in sodium chloride, [4]*kanwa*, alkali potash, citrate buffer, and alkali buffer solutions [129]. [4]*Kanwa* = natural rock salt used as cooking aid in West Africa.

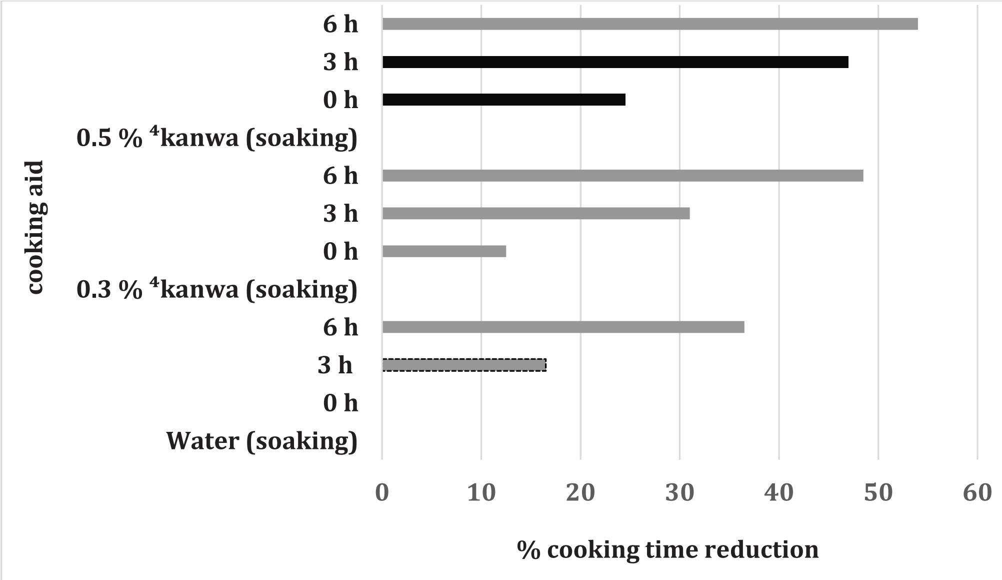

Fig 3.3 Percentage cooking time reduction of bambara groundnut soaked (0, 3, and 6 hours) and cooked in water, 0.3% [4]*kanwa* and 0.5% *kanwa* solutions [32]. [4]*Kanwa* = natural rock salt used as cooking aid in West Africa.

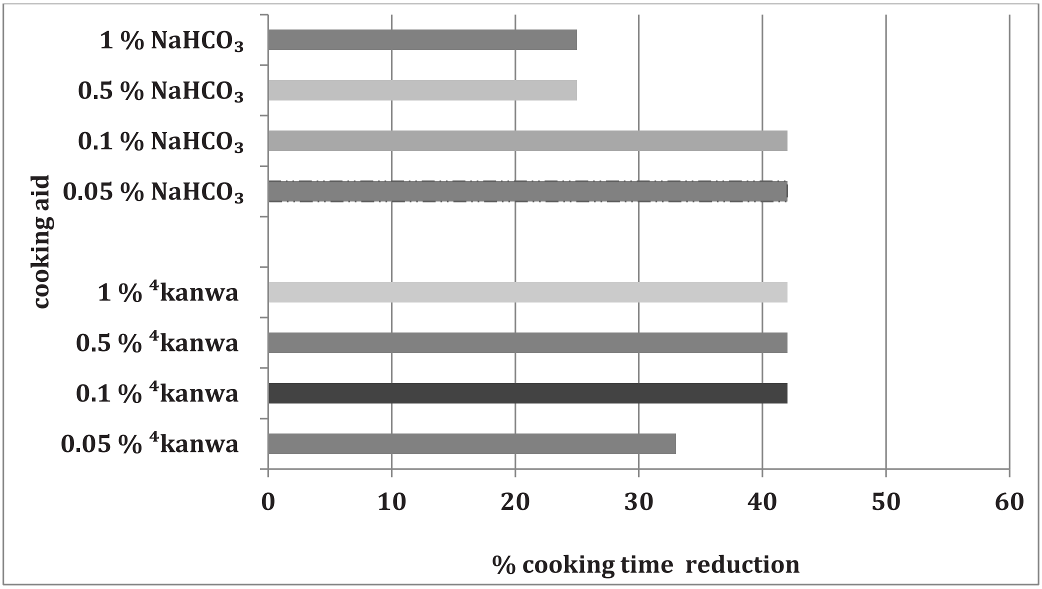

Fig 3.4 Percentage cooking time reduction of cowpeas cooked in sodium bicarbonate and [4]*kanwa s*olutions [109]. [4]*Kanwa* = natural rock salt used as cooking aid in West Africa.

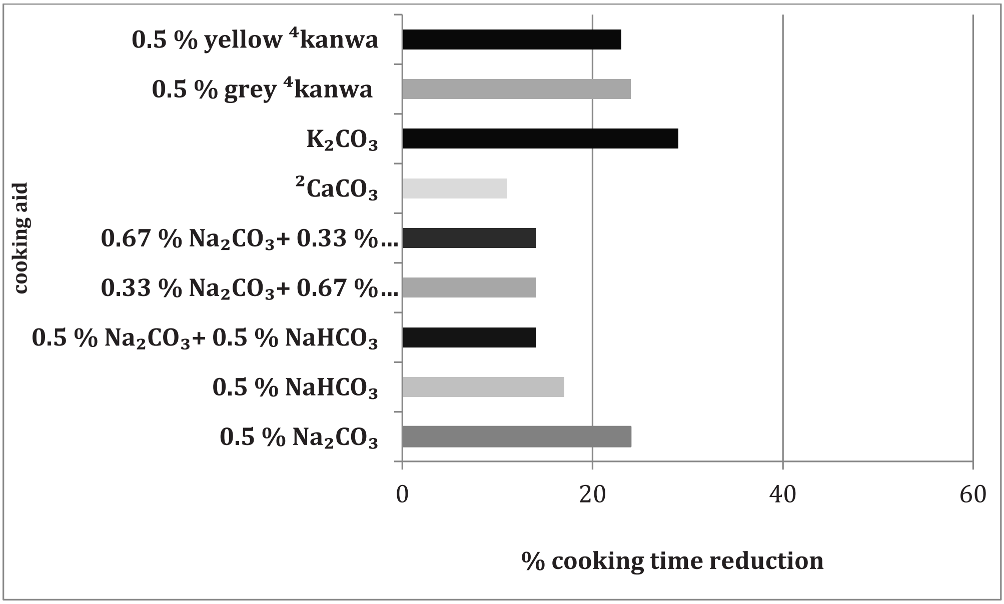

Fig 3.5 Percentage cooking time reduction of cowpeas cooked in [4]*kanwa*, potassium carbonate, calcium carbonate, sodium carbonate, and sodium bicarbonate solutions. [2]$CaCO_3$ = –11% [108]. [4]*Kanwa*= natural rock salt used as cooking aid in West Africa

Additionally, higher levels of gelatinized starch and lower soluble protein levels were significantly associated with a decrease in the hardness of micronized beans [198]. Garcia-Vela, del-Valle [199] described the effects of pH of soaking solutions on the softening of black beans (*Phaseolus vulgaris*); pH of soaking solutions failed to produce significant effects on the softening, but anion type was important in inducing softness. Anion type was effective in the softening process, as follows: carbonate was more effective than EDTA (CO_3^{-2} >$EDTA^{-2}$), and nitrate more effective than sulphate (NO_3 >SO_4^{2}) and lastly Cl^-[199].

Kanwa (also called *trona, kawe, kanwa, potash*) is a naturally occurring alkaline rock salt that features in West African populations (Ghana, Nigeria, and Benin) as food tenderizers, for dry beans and other tough foods, with the aim of reducing cooking time [32, 39, 108, 109, 200]. Other *kanwa* uses include flavouring, preservation and as a prophylactic agent [39]. *Kanwa* is sodium sesquicarbonate (Na_2CO_3,$NaHCO_3$,xH_2O) with trace amounts of minerals (namely Ca, Mg, Fe, Zn, S, Si, P, and K). Its composition, colour and flavor vary significantly according to its origin[39, 200]. *Kanwa* is known as *gowa* in some parts of Zimbabwe, where it is used as a tenderizer in cooking leafy vegetables, common beans and okra [110]. Figs 3.2, 3.3, 3.4 and 3.5 gives an overview of the cooking time reduction of cowpea and bambara groundnut cooked in different concentrations of cooking aids. A cooking time reduction of up to 42% was achieved upon boiling cowpeas in a 0.5% *kanwa* solution [109]. Furthermore, a 24% reduction in cooking time of cowpeas cooked in 0.5% grey *kanwa* and a 29% reduction in 0.5% potassium carbonate solution were also reported [108]. A study by Plahar, Annan [32] showed a significant improvement in the cookability of bambara groundnut after cooking with alkaline salts, with an average cooking time reduction of up to 25% upon boiling bambara groundnut in a 0.5% *kanwa* solution.

Beneficial effects of using salts in cooking have been postulated to be due to both ion exchange and chelation mechanisms occurring between monovalent cations (i.e., Na^+ and K^+) in solution and divalent cations (Ca^{2+} and Mg^{2+}) in pectates of the middle lamella [174]. This hypothesis is based on the fact that divalent cations can form cross-links between adjacent galacturonic acid residues of pectin molecules in the middle lamella leading to stable structures [172, 199, 201]. In addition, the mechanism of salt action during the softening process of legumes has also been attributed to a reduction in the protein denaturation temperature caused by carbonate anions [202]. Further, an assumption is that altered pectates have increased water solubility and thermal conductivity, thus facilitating cell separation during cooking of hardened beans [194].

Moreover, the use of salts was reported to improve the water absorption capacity (diffusivity) between beans and its surroundings [197] and also to increase the water holding capacity of the bean [201]. According to Sefa-Dedeh, Stanley [164] water imbibition in legume seeds is dependent compositionally on protein;

protein and water interact via ionic and polar groups, which imply that pH and ionic strength of the soaking solution can affect water uptake [201]. Alternatively, according to Uzogara, Morton [195], phenolic compound concentration (tannic acid) was reduced substantially (67%) when cowpeas were cooked in alkaline conditions. Moreover, more phytic acid was lost (27-40%) in beans cooked in sodium bicarbonate as compared to beans cooked in *kanwa* (11-29%) [195].

5.1.2. Effects of cooking aids on nutritional quality

An evaluation of protein quality (i.e., protein efficiency ratio and digestibility) of HTC beans cooked in salt solutions (0.3:1 and 9.8:1 monovalent to divalent ion ratios) showed significantly lower protein quality at these ratios [197]. The goal of alkaline salt cooking is not only to reduce cooking time but also to retain the sensorial and nutritional quality of food products [39, 125]. A combination of high temperature and alkali treatment of proteins has been shown to catalyze the formation of cross-linked amino acid side chains such as lysino-alanine, ornithino-alanine and lanthionine [203, 204]. Moreover, transformations of L-isomers of all amino acids to D-isomers through racemization is favored by high pH, long heat exposure and steric properties of the various amino acid side chains [203-205]. The presence of D-amino acid residues and lysino-alanine in the protein structure has been shown to decrease digestibility and nutritional quality [200, 203]. Cooking cowpeas in *kanwa* solution was shown to decrease protein quality (i.e., protein efficiency ratio, net protein ratio and relative net protein ratio) [200].

A study by Madodé, Houssou [108] showed an insignificant loss of amino acids in 0.5% *kanwa* cooked cowpeas, and an insignificant change in available lysine content. Additionally, the high pH (8-10) and temperature reached during boiling (100°C) did not lead to the formation of a detectable amount of lysino-alanine. The amount of *kanwa* added to foods varies with individual preferences and localities and as much as 10% *kanwa* relative to the weight of cowpeas is reportedly used in parts of Northern Nigeria [109]. The chemical composition (viz. crude lipids and water-soluble fractions) of black beans (*Phaseolus vulgaris*) was evaluated after cooking in *kanwa* solution [39]. The cooking resulted in a significant reduction of lipids (palmitic, stearic, oleic or linoleic acids), proteins (essential and non-essential amino acids), and neutral sugars (galactose) [39].

The findings of a study by Uzogara, Morton [109] on the quality of cowpeas after boiling in salt solution (*kanwa* or sodium bicarbonate) were an increased solid leaching, pH and mineral content of the beans and also the occurrence of dark-coloured beans. In comparison, *kanwa* gave greater increases in some minerals and also resulted in a darker coloured product than when cooking in sodium bicarbonate [109]. Pressure cooked beans (in alkaline solutions) produced lighter coloured samples, and also caused a greater reduction in cooking time [109].

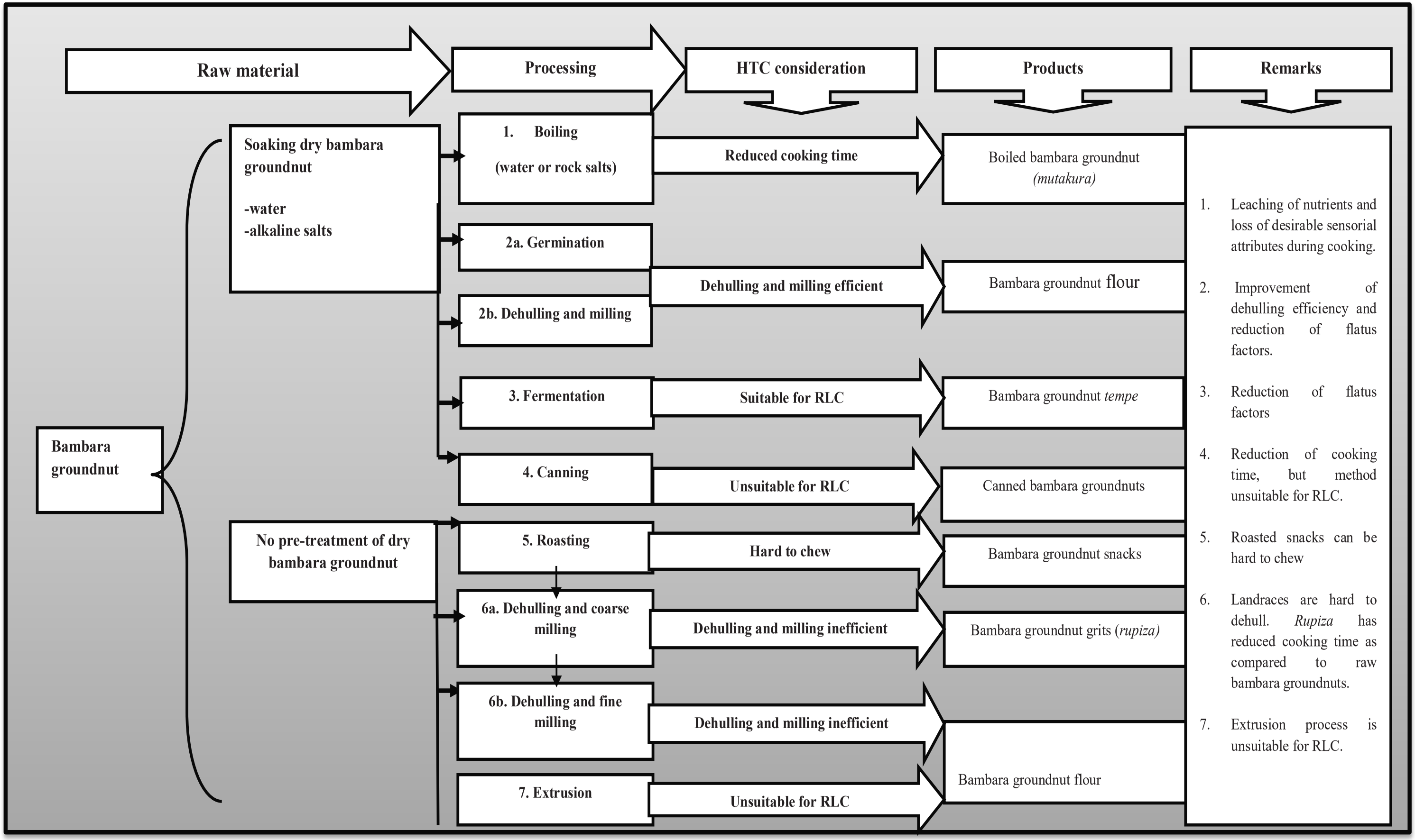

Fig 3.6 Overview of processing techniques for HTC bambara groundnut

The tenderizing effects of the alkali on cowpeas seemed to be dependent on concentration rather than the pH of the alkaline solutions [195]. Furthermore, Uzogara, Morton [195] reported a reduction in the flatus-causing oligosaccharide factors (viz. verbascose, stachyose), which were studied in cooked beans and cowpeas [108, 195].

5.2. Physical treatments for managing HTC in bambara groundnut processing

5.2.1. Milling and roasting

The hardening of bambara groundnuts results in hard-to-mill properties, which are a concern to processors, who find it difficult to find proper dehulling and milling techniques [24, 28, 137]. The hard-to-mill problem is possibly due to the strong attachment between the hulls and cotyledons as a result of the presence of mucilage and gums at the interface [113, 206]. The chemical nature of the mucilage plays an important role in the cooking and milling of bambara groundnut. These mucilage and gums are a network of cellulose microfibrils embedded in a matrix of NSP and proteins [113].

Fig 3.6 outlines different methods of processing of HTC bambara groundnuts to different products. Studies by Enwere and Hung [28] and Alobo [207] discussed the milling properties of bambara groundnut. Enwere and Hung [28] reported that bambara groundnut seeds reached optimum manual dehulling efficiency when they absorbed 54 g of water /100 g seed [28]. After processes of soaking and dehulling, dehulling efficiency, dehulling losses, and the yield of cotyledons were significantly different between the dry samples and the conditioned samples. Dehulling efficiency for manual dehulling raw bambara groundnut sample was zero percent, whereas after mechanical dehulling (by attrition mill), the dehulling efficiency for raw bambara groundnut increased to 70.5%. This value was significantly different from the dehulling efficiencies of the soaked bambara groundnut seeds (81 to 88%). The dehulling efficiencies and yields of dehulled cotyledons increased with increase in temperature of soaking water [28]. Alobo [207] soaked bambara groundnut during the production of legume *akara* pastes and the results showed wrinkled seed coats after 20 min of soaking, but seed coats were still difficult to remove manually even after 10-15 h. The seeds had a relatively low initial rate of water uptake and increased in weight by about 2% after 1 h of soaking. Bambara groundnut seeds had thick seed coats and these appeared to be responsible for the poor water uptake.

The impact of variety on bambara groundnut flour quality was assessed using different varieties of bambara groundnut and three different processing methods [32]. Processing methods studied included i) a traditional method (simple milling), ii) a combination of roasting and milling, and iii) an improved method (heat treatment, dehulling, and milling). For the improved method, cleaned seeds were soaked in water for 30 min, boiled for 25 min, and dried at 60-65 ºC in a hot air dryer for 10 h, and thereafter milled [32]. The study did not evaluate the dehulling and milling efficiency of the flour production processes. Bambara groundnut flour and their protein concentrates produced by roasting were only evaluated for quality (viz. chemical composition and functional properties) [208]. However, there was no evaluation of the effects of roasting temperature on milling and dehulling efficiency of bambara groundnut in the study. A study by Abiodun and Adepeju [29] evaluated the effect of milling (dry and wet) on the chemical and anti-nutritional composition of bambara groundnut flour. Bambara groundnut seeds were processed into flour by i) raw milling and ii) boiling (10 min), removal of seed coats and fine milling of cotyledons. The seed coats were high in fiber when compared to dehulled cotyledon flour samples. Additionally, raw bambara groundnut flour had a higher phytate content, while the dehulled flour had a lower value [29].

5.2.2. Canning

Afoakwa, Budu [121] studied the modelling (viz. response surface methodology and central composite rotatable design for K=3) of bambara groundnut canning by evaluating the combined effects of blanching, soaking and sodium hexametaphosphate salt on cooking indicators (viz. moisture, ash, leached solids, phytates, tannins and hardness). Blanching and soaking of the seeds prior to canning led to increases in water absorption and leaching. In addition, there was a significant decline in phytates, tannins, and hardness. Increase in salt concentration during soaking caused a significant ($p \leq 0.05$) decrease in phytates, tannins and an increase in softening of seeds. Bambara groundnuts have been canned in Zimbabwe and were sold in the more upmarket supermarkets because they were relatively expensive and therefore unaffordable for most low income earners [27, 117].

5.3. Biological treatments for managing HTC in bambara groundnut processing

5.3.1. Soaking and germination

After germination, little effort was needed to remove tough seed coats. Conversely, a significant effort was still required to remove seed coats even after soaking overnight at room temperature. In contrast, improved dehulling properties and reduced soaking time were observed after hot-soaking of bambara groundnut seeds [209]. The contribution of malting to bambara groundnut milling performance and flour yield were studied [137]. Malting increased flour yield of seeds by promoting the loss of the gummy substance between the cells, alterations in cell wall structure, increasing the friability of the seed, and ultimately improving flour extraction during milling. Solar-dried bambara groundnuts produced higher chaff yields, probably because the tenderization of the cotyledons during germination resulted in binding back during the prolonged drying period. Chaff yield is, therefore, a reflection of the effect of the malting and milling processes [137]. Further, malting had the added advantage of decreasing milling energy, reduction in flatus factors, anti-nutritional factors, and lessening of the ‘beany’ flavor, which is unpleasant to certain cultures. However, the sensorial attributes, namely a darker colour and an altered taste of malted flour, were less acceptable to consumers, and these attributes increased with prolonged malting period. A malting period of 1–2 d and drying at 40–50°C was recommended to produce acceptable malted flour [137].

5.3.2. Fermentation

Previous researchers reported changes in composition of bambara groundnut during fermentation [209-212]. According to Fadahunsi and Sanni [210], changes include an increase in crude protein, soluble solids, soluble protein in bambara groundnut tempe after 40 h fermentation. The data obtained during tempe production showed an increase in the activities of the enzymes amylase, lipase, and proteinase as fermentation progressed. Ademiluyi and Oboh [213] reported a change in antioxidant activity and polyphenol distribution in bambara groundnut during fermentation. Amadi, Uneze [214] studied the solid state fermentation of bambara groundnut to produce a *dawadawa* type of product using a starter culture of *Bacillus licheniformis* isolated from naturally fermenting bambara groundnut seeds next to three strains of *Rhizopus* [214]. Sensory evaluation showed that bambara groundnut would be an acceptable food product in the diet as a good protein supplement as its tempe was comparable ($p > 0.5$) in taste and texture, but was rated higher ($p < 0.05$) in colour and flavor than soya bean tempe [215].

6. Conclusion and implications for further research

Constraints to processing and utilization of HTC bambara groundnut still exist in transitional countries such as Zimbabwe. Fig 3.6 shows the potential of bambara groundnut processing methods and an evaluation of their applicability and sustainability for resource limited communities. As the world is moving to the era of convenience and timesaving, processing of the HTC bambara groundnut seeds into different convenient products will increase the utilisation of the legume [215]. Furthermore, food insecurity remains a challenge for transitional countries and according to Clover [1], the solution to food security lies in increasing the availability, accessibility and adequacy of food for everyone. As such, adopting sustainable processing technologies for bambara groundnut can be a source of community resilience to food insecurity. Previously applied methods such as use of cooking aids, physical treatments, and biological treatments are applicable for transitional countries, but sustainability, safety and quality of the products needs appraisal. It is essential to build on these locally developed practises and indigenous knowledge systems to supply culturally acceptable nutritious foods from bambara groundnut.

Essentially, factors that contribute to legume hardening and their interactions with processing treatments need further investigation. In this regard, the mechanism of alkaline salts in legume softening and the contribution of softening indicators, i.e., phenolic compounds, pectin, and protein, in cooking time reduction need further investigation. Further, the potential contribution of cell wall degrading enzymes in reducing legume cooking time need further appraisal. Moreover, since bambara groundnut seeds are highly valued for their nutritional content, it is essential to evaluate the effects of processing on nutrient bio-accessibility, safety and consumer acceptance of products. With consumers in mind, it is also imperative to understand the physical properties that govern preferences for bambara groundnut seeds with the background knowledge that for example consumers in Botswana, Zimbabwe and Ghana prefer different landraces. The motivation behind bambara groundnut landrace preference for cooking and milling needs to be assessed.

7. Acknowledgements

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Chapter 4

Polyphenol profile of hard-to-cook bambara groundnut (*Vigna subterranea* (L.) Verdc.) cooked in alkaline salts

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Mubaiwa J, Fogliano V, Chidewe C, Linnemann AR. Hard-to-cook phenomenon in bambara groundnut (*Vigna subterranea* (L.) Verdc.): the role of phenolic compounds in alkaline cooking

Abstract

Bambara groundnut (*Vigna subterranea* (L.) Verdc.) is an underutilized crop native to sub-Saharan Africa. Its utilisation is limited due to the development of the hard-to-cook (HTC) phenomenon during storage. Various factors have been implicated in the development of the HTC phenomenon. Alkaline rock salts, such as *gowa,* are known to reduce cooking time. In this research, red bambara groundnuts were cooked in deionised water, 0.5% *gowa* and 0.5% $NaHCO_3$. The salts caused 20 and 13% reduction in cooking time, respectively. The decrease of hardness and the kinetics of water absorption by the beans are even more influenced by the alkaline cooking. The comparative effect of $NaHCO_3$ and deionised water on polyphenol profile in the beans and in the boiling water during cooking also showed clear differences among the samples. Catechin and epicatechin were the main polyphenols in bambara groundnuts. They were found in cooking water in all conditions. However, their release in water was faster in alkaline solutions. This study demonstrated that polyphenols are involved in HTC and the potential of alkaline cooking to reduce cooking time. Data indicate that the action of the salts favours polyphenol solubilisation thereby altering the structure of the lamellae and reducing hardness.

Keywords: *bambara groundnut; hard-to-cook phenomenon; cooking aids; alkaline salts, polyphenols.*

1. Introduction

Bambara groundnut is an important component of the human diet in developing countries, where they complement the lack of proteins from cereals, roots and tubers. However, utilisation of bambara groundnut is limited due to the development of the so-called hard-to-cook (HTC) phenomenon during storage at high temperature and relative humidity as commonly experienced in sub-Saharan Africa [70].

Various factors have been implicated in the development of the HTC phenomenon. Several researchers described changes occurring in the legume hull, cell wall [178-181] and cotyledon in relation to legume hardening during storage [135, 177, 182]. Phenolic compounds (i.e. tannins and phenolic acids) have been linked to hard-to-cook (HTC) development in legumes [169, 183]. Srisuma, Hammerschmdt [183] stated a significant increase in free hydroxyl-cinnamic acids, which can be hypothetically linked with increased hardening. In a study by Garcia, Filisetti [47], HTC carioca beans (*P. vulgaris* L. var. Carioca) were reported to have more phenolics (namely three times) linked with the soluble-pectic fraction and an increased content of pectates. These studies all hypothesized that the consequence of increased phenolics in the HTC beans would be a reduced cell wall separation during cooking, which ultimately would contribute to a prolonged cooking time of HTC beans to reach the same tenderness [174]. The researchers proposed that the presence of more hydroxycinnamic acids (i.e., ferulic, p-coumaric, ferulic, and sinapic acid) bound to the soluble pectin, and their probable involvement in cross-linkages, could contribute to increase cell adherence [191]. These findings were similar to the earlier findings of Machado, FerruziI [191], who observed an increase in the concentration of free phenolic acids in HTC beans. The study by Nasar-Abbasa, Plummera [192] on faba bean (*Vicia faba*) revealed considerable reductions in total free phenolics, particularly in the seed coat, at high-temperature storage (12 months). Pirhayati, Soltanizadeh [176] evaluated the chemical changes of HTC pinto bean and a small-type lentil. In their study, phytic acid decreased by 36–

61% and total phenolic content by 43–61% during storage, whilst seed hardness increased 3–6 times.

To solve the problems of long cooking time and ensuing energy expenditure, HTC legumes can cooked using different salt solutions [109, 195, 196, 200, 216]. Soaking of legumes in the presence of monovalent and divalent cations increases the water absorption capacity and subsequently reduces cooking time. Natural alkaline rock salts, known as *kanwa*, have been traditionally used in West Africa as food tenderizers and to reduce the cooking time of HTC legumes [217].

According to the study of del-Valle, Cottrell [202], softening effects of chelating and ion-exchange agents in bean soaking solutions indicate a mechanism based on protein destabilization contributing to softening. Cooking with alkaline salts, such as sodium bicarbonate ($NaHCO_3$) and *kanwa*, have been reported to increase the solubilisation of pectin and proteins, leading to a softer texture [195, 218-220]. After realising that the softening rate of hardened beans was slower than the solubilisation rate of pectic substances, del-Valle, Cottrell [202] suggested that chemical components other than pectates, such as cross-linked phenolic compounds, also may contribute to softening. A positive relationship was reported between the amount of tannins and the length of cooking time; the more tannins present, the longer the cooking time [215].

To date, the scientific knowledge about the way in which salts influence the softening of legumes is incomplete. Following the suggestion of del-Valle, Cottrell [202], that cross-linked phenolic compounds also may contribute to softening, the hypothesis is that -as alkaline salts reduce cooking time of legumes- phenolic compounds that contribute to hardening also contribute to the softening process. Consequently, the interaction of alkaline salts and characterization of changes in a subgroup of phenolic compounds would provide a link to the possible mechanism of softening.

Therefore, in this study the contribution of phenolic compounds to alkaline salt softening effects were investigated. This was achieved by investigating the solubilisation pattern of phenolic compounds of bambara groundnut cooked in alkaline salts in relation to reductions in cooking time. Further, the assessment of changes occurring in the extractability of phenolic compounds of bambara groundnut cooked in alkaline salts in relation to legume-softening mechanism was investigated regarding the salt softening effects.

2. Materials and methods

2.1. Materials

A red-seeded variety of bambara groundnut was procured in Zimbabwe from the Department of Research and Specialist Services (DRSS), where they were grown under hot and dry conditions, harvested for research, stored locally for 2 months at ambient temperatures (~ 25 °C) and then transported to the Netherlands (September 2014) for further research. Once in the Netherlands, they were kept at ~20 °C and treated within 2 months.

Deionised water was obtained from a Veolia water solutions & technologies Netherlands B.V. machine. Alkaline salt (*gowa)* was sourced from Buhera, Zimbabwe. Acidified methanol was made by mixing 69.3% (v/v) methanol, 29.7% (v/v) deionised water and 1% (v/v) formic acid. Methanol, and acetonitrile were obtained from actu-all chemicals, formic acid, trifluoracetic acid were from Merck (Darmstadt, Germany). $NaHCO_3$ was obtained from Sigma-Aldrich. Gallic acid, chlorogenic acid, caffeic acid, ferulic acid, naringenin, catechin, epicatechin, rutine, quercetin-hydrate and hydroxybenzoic acid were all from Sigma Aldrich, as well as myricetin and kaempferol from Fluka.

2.1.1. Analysis of *gowa*

Gowa was degraded by addition of nitric acid and hydrochloric acid followed by microwaving (CEM, MARS-Xpress) to completely solubilize the silicate skeleton. Nitrous vapors were removed by addition of hydrogen peroxide. After that, selected elements (Zn, Na, Cu, Mg, K, and P) were measured using ICP-AES (Thermo, iCAP 6500 duo-dual view ICP-OES) in duplicate.

2.2. Cooking bambara groundnuts in alkaline solutions

The red bambara groundnuts were cooked in deionised water, 0.5% *gowa* and 0.5% $NaHCO_3$ as shown in Fig 4.1. For each cooking treatment, 25 red seeds were selected based on size. Seeds with visible defects were discarded. The seeds were selected and weighed such that every cooking treatment had approximately a similar amount of seeds. Cooking solutions were made by adding 0.5% (w/v) alkaline salt to deionised water. The amount of cooking solution was calculated by taking the ratio of 1:15 seeds/cooking solution. The initial pH of the cooking solution and cooking solution volume were measured before adding the seeds. Thereafter, the samples in the cooking solutions were put immediately in Duran flasks and sampled at 30 min, 60 min, 90 min, 120 min and until cooked. After each sampling interval, the cooked seeds and cooking water were separated. The change in weight of the bambara groundnuts and the pH of the cooking solution were recorded. The separated bambara groundnuts and cooking solution were freeze-dried and stored at -20°C until further analysis. The cooking procedure was done in triplicate for each cooking solution.

2.2.1 Measuring the degree of softening of bambara groundnut

The degree of softening was determined at time intervals by the traditional method of squeezing cooked beans between fingers [145, 221, 222] as well as by a texture analyser (Stable Micro Systems Ltd, Surrey, UK). The analysis employed was the return-to-start method, measuring force under compression with a 2 mm cylindrical probe (P2), recording the peak of maximum force. P2 is the probe recommended for assessing bean hardness because its small area affects the tegument and could help to differentiate similar samples, even when they possess soft cotyledons but a hard tegument [223]. Whole beans were axially compressed to 50% of their original height. Force-time curves were recorded at a speed of 2 mm/s. The results corresponded to the average of about 20 measurements of individual cooked beans expressed in Newton (N).

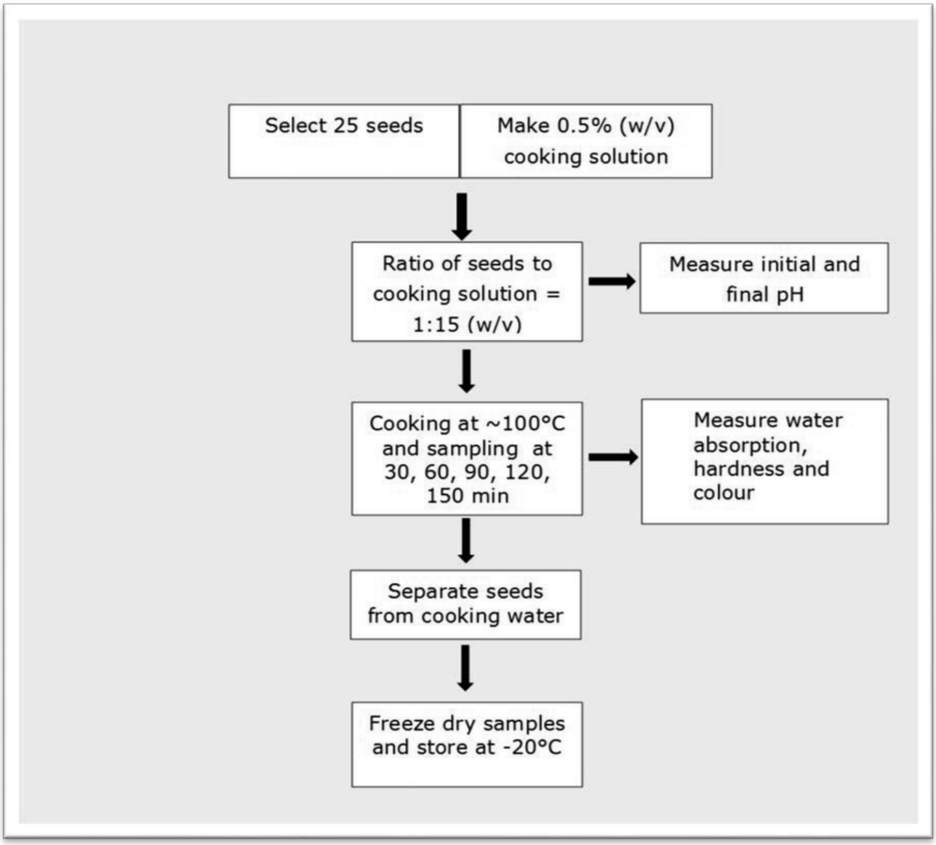

Fig 4.1 Design of bambara groundnut cooking procedure in different alkaline salts

2.3. Extraction and analysis of polyphenols

Freeze-dried, cooked and raw bambara groundnuts were milled using a Ball mill (MM400, Retch, Germany) at a frequency of 30/s for 2 and 3 min, respectively, and passed through a 500 μm sieve. The freeze-dried cooking water was not milled. Extraction of polyphenols from bambara groundnut powders was according to Ojwang, Dykes [224], with a small modification. Three gram of powder was mixed with 15 ml of acidified methanol. Thirty ml of acidified methanol was added to freeze-dried cooking solution (ratio bambara groundnut powder/acidified methanol was 1:5 (w/v), ratio freeze-dried cooking solution/acidified methanol was 1:10 (w/v)). The samples were incubated for 18 h at 4 °C. Thereafter the samples were put for 4 h in a shaking water bath at 37 °C. Then the samples were centrifuged for 10 min at 4500 rpm at 4 °C. The extracts were filtered using 0,20 μM ptfe filters and stored for further analysis at -20 °C. Standard solutions (5 ppm) in 0.5 % $NaHCO_3$ were heated in a water bath at 100 °C for an hour and also stored for further analysis.

2.4.2. Identification and quantification of polyphenols

Series of calibration curves of quercetin di-hydrate, kaempferol, myricetin (all from Fluka) and naringenin, (+-)-catechin, (-)- epicatechin, rutin hydrate, kaempferol (from Sigma-Aldrich) were used for identification and quantification. Extracts were analysed by RP-HPLC equipment and Xbridge Shield RP 18 3 x 100 mm 3.5μm. The mobile phase consisted of a solution of deionised water + 0.1% formic acid as A and B: acetonitrile + 0.1% formic acid. The flow rate was 0.3 ml/min, which started with a mixture of 90% A and 10% B, raised to 20% B and 20% A during 7 to 9 min, turned back to 90% A until the end of the 15 min run. Ten μL of sample was injected in the column and analysed in the negative mode. General MS settings were 2000 V spray voltage, a vaporizer temperature of 200°C, capillary temperature of 250°C, sheath gas pressure (60), ion sweep gas pressure (4) and aux gas pressure (30). The polyphenols in the sample were scanned according to the mass, tube lens and collision energy shown in Table 4.1 at a wavelength range of 220–370 nm. The results were analysed using the Xcalibur software.

Table 4.1 Flavonoids and phenolic acid parent mass with their fragment mass, tube lens offset and collision energy

Name	Parent mass m/z $[M\text{-}H]^-$	Other ions	Tube lens offset	Collision energy
Quercetin	301	151	110	24
		179	110	21
Catechin	289	203	113	22
		245	113	17
Myricetin	317	137	105	28
		151	177	25
Kaempferol	285	93	124	39
		185	124	28
Naringenin	271	119	111	25
		151	111	20
Epicatechin	289	203	113	22
		245	113	17
Rutin	609	300	158	37
Caffeic acid	179	135	59	18
Ferulic acid	193	134	55	17
		178	55	17
p-coumaric acid	163	119	28	17
p-hydroxybenzoic acid	137	93	27	17
Protocatechuic acid	153	109	31	17
Gallic acid	169	125	40	16

3. Results and discussion

3.1. Softening of bambara groundnut seeds as influenced by alkaline cooking

The softening of bambara groundnut by cooking aids, i.e. alkaline salts, was measured by water absorption profiles and changes in seed hardness as cooking progressed (Figs 4.2 and 4.3), respectively. Changes in hardness as indicated by lower required compression [145] show the rate of softening brought about by alkaline salts whereas a high water absorption profile is also related to a higher rate of softening. According to Rockland, Zagarosa [225], water absorption, reactions of components responsible for hardness, structural changes such as the breakdown of the middle lamellae, are all factors that contribute to softening.

Raw seeds are known to be hard and brittle with more compact cell arrangement, but during cooking, entrance of water into the intracellular spaces causes the disruption of cell to cell adhesion resulting in seed elasticity and less resistance to compression [226, 227]. The significant effect of different cooking solutions on deformation force from 60-75 min cooking time on is in line with Ojimelukwe [145], who reported significant differences from 0-75 min cooking time of different bambara groundnut cultivars. Softening as measured by the texture analyser does not give an entire picture of doneness. Therefore, softening of bambara groundnut was also monitored by a sensory test of squeezing the cooked beans between fingers; when minor or no hard particles were present, bambara groundnuts were presumed ready [145, 221, 222].

The influence of alkaline salts on cooking time of the seeds and the percentage cooking time reduction are shown in Table 4.2. The use of 0.5% (w/v) *gowa* and 0.5% (w/v) $NaHCO_3$ decreased cooking time of red bambara groundnut with approximately 20% and 13%, respectively, in comparison with cooking in deionised water. However, if we define the physical index of doneness to be 10 N compression, by extrapolation on the graphs, *gowa* and $NaHCO_3$will have a cooking time reduction of 35% and 15%, respectively. After 10 N, the time taken to reach doneness as determined by finger compressing is impartially different; this could be the time for completion of starch gelatinization and protein denaturation, which give the smooth texture of fully cooked beans [227]. As such, *gowa* required 45 min, $NaHCO_3$ and water, 40 min and 35 min, respectively. According to Varriano-Marston and De Omana [219], alkaline salts can elevate the gelatinization temperature of starch cellular structures or the inherent structural characteristics of the bean starch limiting starch swelling. This implies that alkaline salts can limit starch gelatinization.

Gowa had an initial pH ~10.6 and the final cooking water was the most dark with a pH ~8.2. Elements found in gowa included ; Na^+ (3971 mg/ 100g),

Ca^{2+} (0.18mg/100g), K^{+} (2 mg/ 100g), Mg^{2+} (0.1 mg/ 100 g) and Fe^{2+} (0.1 mg/ 100 g). Cooking water with 0.5% (w/v) $NaHCO_3$ had an initial pH ~8.2, which increased to pH ~9.5, when the water had a light brownish colour. The effect of salt on cooking time reduction and the influence of pH on softening was reported in the studies of Uzogara, Morton [217], de-Leon, Elias [197] and del-Valle, Cottrell [202]. According to de-Leon, Elias [197] increasing the ratio of monovalent to divalent cations decreased the cooking times of common beans. The average L-value which represents the lightness of cooking water with added alkaline salts was stable over time for $NaHCO_3$, but increased for water. This is an indication that polyphenols, among other compounds, could have leaked into the cooking water at a faster rate than when cooking in water. Colour differences were observed in the cooking water during cooking of bambara groundnuts. In deionised water the solution was light brown, whereas, when an alkaline salt was added, colour changed to reddish brown. Changes in colour of cooking water to reddish brown can be attributed to the presence of tannins in bambara groundnuts [215, 228].

Table 4.2 Cooking time reduction of red bambara groundnut

	Cooking time (min)	Cooking time reduction (%)	pH	
			Before	After
Deionised water	150±2.55^{c}		5.3	6.3
Gowa	120±5.03^{a}	20	10.6	8.2
$NaHCO_3$	130±2.31^{b}	13	8.4	9.8

Different superscript letters (a, b, c) in a column indicate means that are significantly different

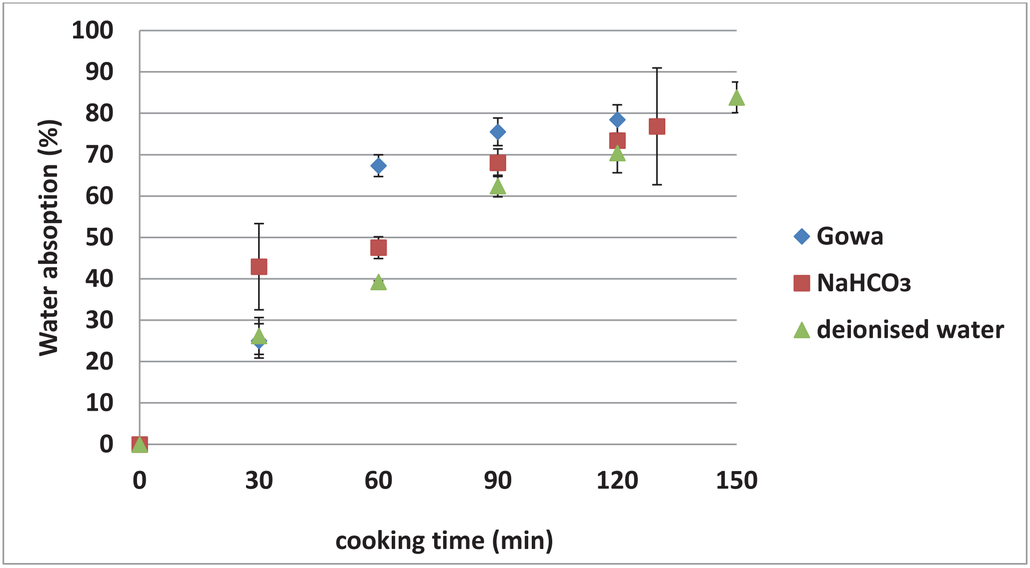

Fig 4.2 Water absorption of bambara groundnuts cooked in deionised water, $NaHCO_3$ and *gowa* in relation to cooking time

3.2. Role of polyphenols in the softening action of salts

3.2.1. Phenolic compounds identified in raw and cooked red bambara groundnut

The phenolic compounds of raw and cooked bambara groundnut were identified based on authentic standards and MS/MS spectra obtained in both positive and negative mode using their fragmentation patterns, data published in phenol-explorer.eu and literature. Channel A presented a wavelength of 290 nm, channel B a wavelength of 330 nm and channel C a wavelength of 520 nm. Compounds expected at 290 nm, 330 nm and 370 nm include phenolic acids whereas at 520 nm flavonoids and anthocyanins were projected [224].

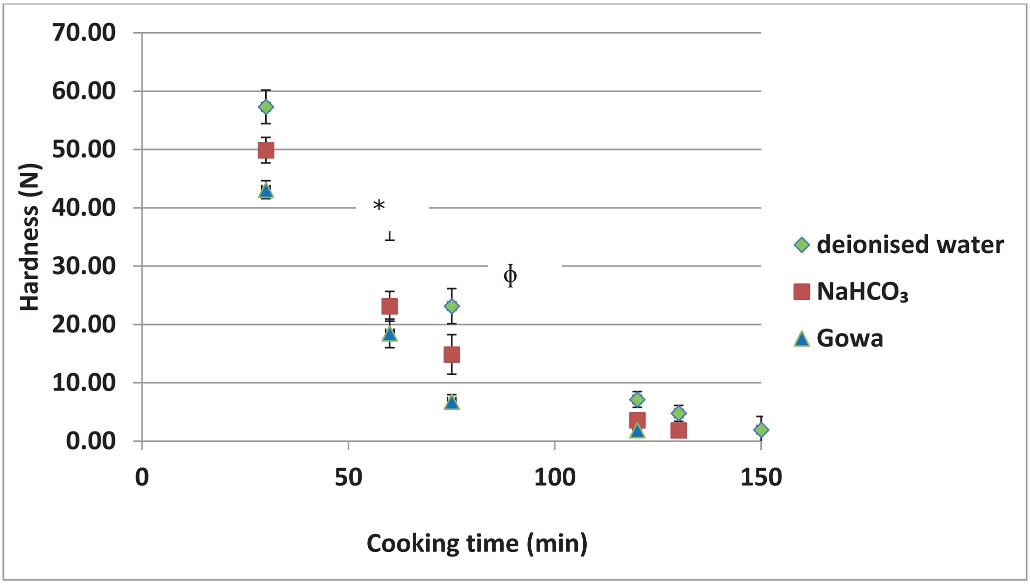

Fig 4.3 Change in hardness of red bambara groundnut cooked in deionised water, $NaHCO_3$ and *gowa* in relation to cooking time.

*Significant differences in hardness at 60 min (*gow*a and $NaHCO_3$ significantly different from deionised water).
ϕSignificant differences in hardness at 90 min (*gowa* significantly different from $NaHCO_3$ and deionised water).

In our targeted experiments, we looked for flavonoids, phenolic acids and anthocyanins in raw and cooked bambara groundnut. The flavonoids searched for were quercetin di-hydrate, kaempferol, myricetin, naringenin, catechin, epicatechin and rutin. We succeeded to identify epicatechin, myricetin, quercetin di-hydrate, myricetin and kaempferol in raw seeds. As for the identification of rutin, a peak appeared and the mass under the peak was found to be $[M-H]^+$ 611 and with a molecular weight of 610. Comparison with Nyau [229] indicated that this compound could be quercetin-3-O-rutinoside (rutin) as was found in red bambara groundnuts in their study. However, after spiking with the rutin standard, it was confirmed that this compound was not rutin. No peaks corresponding to keracyanin, delphinidin, petunidin and malvidin (both glucosides) were found. Therefore, the colour of the red variety is likely due to other unidentified anthocyanin compounds.

3.3.1. Variations in phenolic acid content during cooking with deionised water and $NaHCO_3$

Table 4.3 shows the phenolic acid content of bambara groundnut before and after cooking in deionised water and $NaHCO_3$. Caffeic acid and gallic acid were found in raw seeds, whilst p-coumaric, protocatechuic and p-hydroxy-benzoic acid were not detected, but appeared after cooking. Gallic acid decreased after cooking with $NaHCO_3$, whilst an increase was observed after cooking in deionised water. Nyau [229] reported the occurrence of *t*-ferulic, p-coumaric and salicylic acid in red bambara groundnut. The differences in phenolic acids present could be due to differences in variety and analytical methods. According to Sosulski and Dabrowski [230], phenolic acids present in legume hulls (e.g. cowpea) in the soluble esters included protocatechuic acid, syringic acid, gallic acid, p-coumaric and *t*-ferulic. After cooking, Nyau, Prakash [231] tentatively identified caffeic acid in red bambara groundnut, whilst phenolic acids such as p-coumaric and *t*-ferulic acid were identified after alkaline hydrolysis of cowpea [230].

Fig 4.4 shows the changes in two hydroxy-benzoic acids, protocatechuic acid and gallic acid, in bambara groundnut seeds during cooking in deionised water and $NaHCO_3$. Protocatechuic acid increased significantly in bambara groundnut cooked in $NaHCO_3$ as compared to the increase found in deionised water. Moreover, the concentration of protocatechuic acid also increased in cooking water of both cooking solutions. This suggest that hydroxy-benzoic acid derivatives are less likely to diffuse to the cooking water when $NaHCO_3$ is present or possibly form other compounds.

This might be due to the difference in pH between cooking water and bambara groundnut. Complex polyphenols exist in bound form with other natural compounds within the cell such as cell wall bound phenolics as monomeric, dimeric, or oligomeric compounds esterified to the cell components (carbohydrates, lignin, pectin and proteins) [232].

Table 4.3 Phenolic acids in raw and cooked bambara groundnut

	Phenolic acid [µg/100 g dry weight]					
Sample	caffeic	p-coumaric	ferulic	p-hydroxy-benzoic	protocatechuic	gallic
Raw	2.1 ± 1.6	ND	ND	ND	ND	30.0 ± 3.2
$NaHCO_3$	5.6 ± 1.2	53.7 ± 3.3	45.4 ± 10.4	34.1 ± 6.1	196.5 ± 23.0	24.8 ± 2.7
Deionised water	2.8± 2.2	37.0 ± 3.0	29.6 ± 14.8	22.0 ± 3.2	138.0 ± 15.8	47.0 ± 8.0

Table 4.4 Changes in two hydroxy-cinnamic acids, namely ferulic acid and p-coumaric acid, in bambara groundnut seeds cooked in deionised water and $NaHCO_3$

Sampling time (min)	ferulic acid		p-coumaric acid	
	$NaHCO_3$	water	$NaHCO_3$	water
0	ND	ND	ND	ND
30	21.4 ± 11.9	27.0 ± 4.3	21.4 ± 0.2	24.9 ± 3.5
60	21.9 ± 7.5	33.4 ± 1.5	33.6 ± 4.1	32.6 ± 3.7
90	27.4 ± 6.3	23.2 ± 1.2	40.0 ± 2.5	37.7 ± 5.8
120	32.9 ± 9.5	18.2 ± 6.4	45.0 ± 2.4	34.4 ± 2.9
130/150	45.4 ± 10.4	29.6 ± 15.0	53.7 ± 3.3	36.9 ± 2.8

These cell components may undergo various changes during the cooking process, resulting in the increase in polyphenol concentration caused by the release of bound polyphenols. Thus, an increase of the benzoic acid derivatives in the cooked seeds and also in cooking water is expected because of leakages. Table 4.4 shows the changes in two hydroxy-cinnamic acids, i.e. ferulic acid and p-coumaric acid, in bambara groundnut seeds during cooking in deionised water and $NaHCO_3$. The concentrations of hydroxy-cinnamic acid derivatives for the bambara groundnuts in both cooking solutions were almost similar except for ferulic acid, which recorded higher concentrations in seeds cooked in deionised water. Apparently the extraction of the polyphenols is better when the bambara groundnuts have been cooked for a longer time, thus the matrix of bambara groundnut seeds is changed aiding extraction.

3.3.1. Variations in flavonoid content during cooking with deionised water and $NaHCO_3$

Flavonoids found in raw bambara groundnut were naringenin, quercetin, myricetin and kaempferol as shown in Table 4.5. Epicatechin was the most abundant flavonoid found, whilst catechin was not detected, contrary to the findings of Nyau [229], who reported the occurrence of catechin in raw red bambara groundnut. Catechin was only detected after cooking in deionised water and $NaHCO_3$, agreeing with Nyau, Prakash [231]. Cooking changed the content of flavonoids in seeds. Kaempferol decreased in cooking solutions and was not detected in seeds cooked in deionised water. An outstanding increase in catechin followed by epicatechin in cooked seeds agrees with Shadkami, Estevez [233], who reported the assumption that catechin, epicatechin, epigallocatechin and gallocatechin are the main monomeric units present in condensed tannins. Thermal processes have a large influence on the availability of phenolic compounds in food, regardless of the method used [234]. In these situations, an increase of temperature improves the extraction of phenolic compounds from foods.

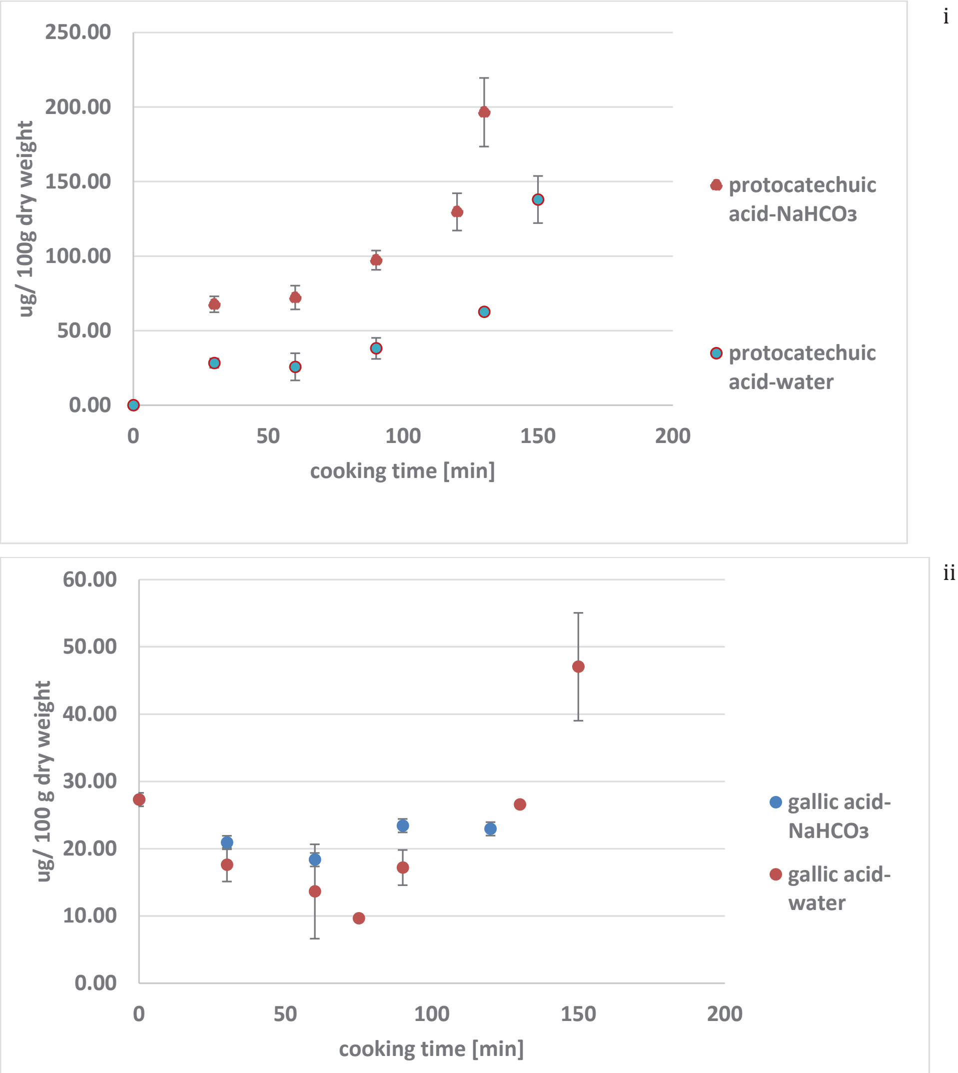

Fig 4.4 Changes in two hydroxy-benzoic acids, namely (i) protocatechuic and (ii) gallic acid, in bambara groundnut seeds cooked in deionised water and $NaHCO_3$

Fig 4.5 and Table 4.6 show the variations in flavonoids during cooking in deionised water and $NaHCO_3$. Changes in catechin and epicatechin shows the variation in extractability of these polyphenols as influenced by cooking in an alkaline salt and water. Catechin decreases after 90 min and after 120 min another increase is observed. These findings indicate that catechins leach out of the bambara groundnuts more easily when cooked with $NaHCO_3$ or react faster to other components that were not measured. Moreover, another possibility is that the extractability of catechins is facilitated by a change in the bambara groundnut matrix during prolonged cooking. The same trend of a better extractability of flavonoids was observed for kaempferol, rutin, myricetin and naringenin. The only outlier was quercetin, which showed better extractability in deionised water than in $NaHCO_3$. Since quercetin is an aglycone of rutin, perhaps the neutral pH of water favoured the aglycone.

Changes in the concentration of individual phenolic compounds after cooking were explained by Cheynier [235] in two ways: firstly, the bound phenolics present are released during heating due to changes of the components to which they bind as illustrated in Fig 4.6. Secondly, phenolic compounds that exist as oligomers and polymers (condensed tannins or proanthocyanidins) may disintegrate to release different constitutive units when heated.

Table 4.5 Flavonoids in raw and cooked bambara groundnut

	Flavonoid [µg/100 g dry weight]						
Sample	Quercetin	Catechin	Myricetin	Kaempferol	Naringenin	Epicatechin	Rutin
Raw	1.6 ± 0.0	ND	3.2 ± 0.0	1.5 ± 0.0	3.6 ± 0.0	5.3 ± 0.0	0.3 ± 0.0
$NaHCO_3$	2.8 ± 0.2	501 ± 73	1.7 ± 0.6	0.1 ± 0.1	4.2 ± 0.6	153.4 ± 45.5	1.3 ± 0.3
Water	6.5 ± 3.1	2234 ±1408	3.6 ± 2.1	ND	5.3 ± 3.3	646.4 ± 334.3	1.5 ± 0.3

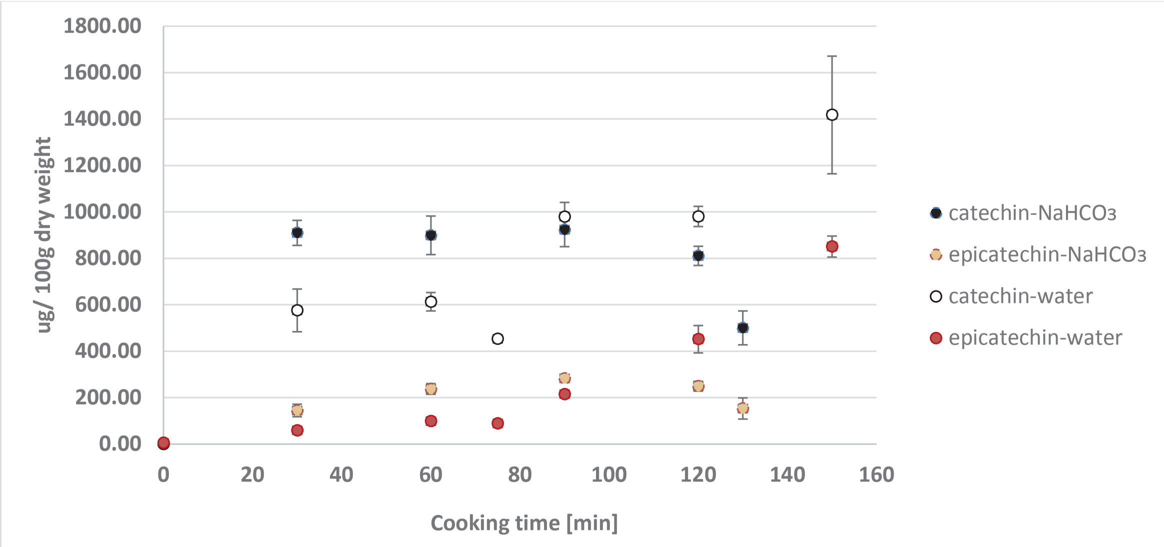

Fig 4.5 Changes in epicatechin and catechin in bambara groundnuts during cooking in deionised water and $NaHCO_3$.

Table 4.6 Changes in quercetin and rutin in bambara groundnuts during cooking in deionised water and $NaHCO_3$

Flavonoid [μg/100g dry weight]				
Time (min)	Quercetin		Rutin	
	$NaHCO_3$	water	$NaHCO_3$	Water
0	1.6 ± 0.0	1.6 ± 0.0	0.3 ± 0.0	0.3 ± 0.0
30	3.2 ± 0.6	3.5 ± 1.6	2.4 ± 0.5	2.5 ± 1.6
60	3.0 ± 0.5	4.1 ± 2.5	1.6 ± 0.3	1.8 ± 0.0
90	2.9 ± 0.3	4.1 ± 1.4	1.9 ± 0.4	1.5 ± 0.1
120	2.8 ± 0.3	6.5 ± 4.2	1.7 ± 0.1	1.8 ± 0.9
130/150	2.8 ± 0.2	6.5 ± 3.1	1.3 ± 0.3	1.5 ± 0.3

4. Conclusions

The study shows a substantial decrease in cooking time when using cooking aids such as the rock salt *gowa* and $NaHCO_3$. Different polyphenol behaviour is seen in the bambara groundnuts cooked in $NaHCO_3$ and in deionised water: their release in the boiling water is faster in alkaline cooking conditions, confirming the involvement of polyphenols in HTC development and softening. Analysis of data shows protocatechuic acid, catechin and epicatechin as indicators of softening in relation to the use of sodium bicarbonate in cooking water, contributing to the ion exchange theory of salt action. Even though the cooking time reduction due to alkaline salts is not very prominent, the results from the study improve the understanding of the mechanisms of hardening and softening of legume seeds. However, as shown by texture measurement results, the mechanism of salt action appears to be more on the cell wall components, triggering easy deformation. Since, this easy deformation did not entirely translate to the readiness of seeds, this implies the need for further studies on effects of salts on other cell components, such as starch, in relation to legume softening. Moreover, further studies on the role of catechins and hydroxy-benzoic acids and the impact of alkaline salts on polyphenols are recommended using differently coloured varieties of bambara groundnut and model systems.

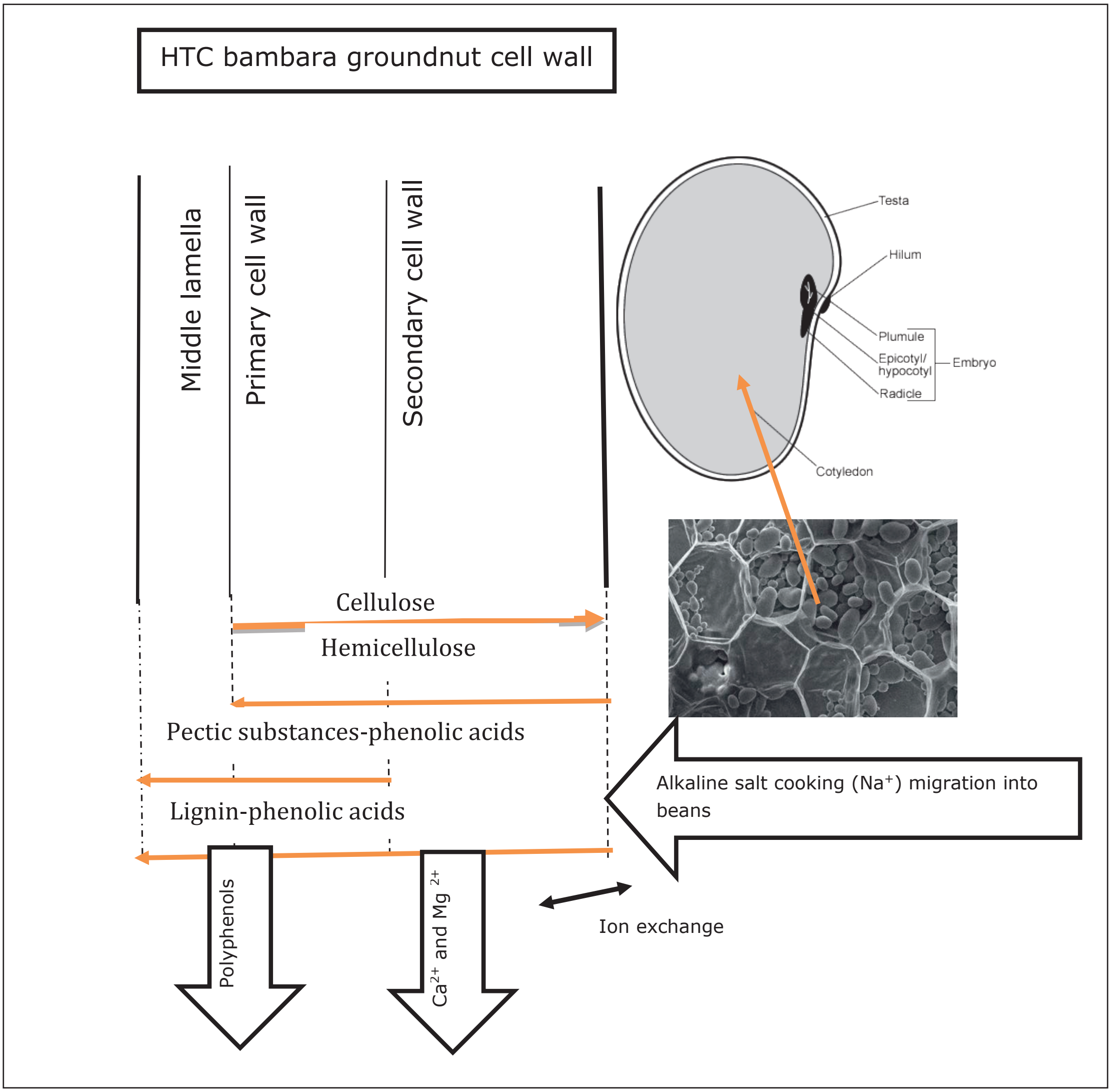

Fig 4.6 Schematic overview of the impact of alkaline salts on parenchyma cell walls of seed cotyledons. Monovalent cations migrate from alkaline salts to cell walls and interact with pectic substances and polyphenols through ion exchange with divalent cations resulting in softening. Adapted from de-Leon, Elias [197], Bourne [236].

Chapter 5

Processing strategies to address the hard-to-cook phenomenon in legumes exemplified by bambara groundnut (*Vigna subterranea* (L.) Verdc.)

Submitted as:

Mubaiwa J, Fogliano V, Linnemann AR. Processing strategies to address the hard-to-cook phenomenon in bambara groundnut (*Vigna subterranea* (L.) Verdc.) for food and nutrition security

Abstract:

The utilization of bambara groundnut (*Vigna subterranea* (L.) Verdc.), Africa's third legume, is limited due to the hard-to-cook (HTC) phenomenon and the lack of adequate processing and cooking techniques. To improve use, the study evaluates the comparative effects of traditional boiling and alternative (grit) processing methods on mineral bioaccessibility and *in vitro* protein (IVPD) and starch digestibility (IVSD) of red and brown varieties. Processing aptitude and consumer acceptance of products were also assessed. Data showed that grit production is an efficient way of circumventing the HTC phenomenon. Different methods of grit processing had a similar dehulling efficiency with no significant varietal influence. Both traditional boiling and grit production improved IVSD, IVPD and mineral bioaccessibility. Based on average values for both varieties, dry roasted grits had the lowest IVPD (42%), followed by the combined soaking and roasting (45%), soaking (48%) and boiling (68%). Concerning starch, boiling of seeds and soaking of grits brought better IVSD performance in both varieties compared to other methods. Additionally, grit production was superior in improving mineral bioaccessibility, i.e. Zn, K, P and Mg. As to consumer acceptance, dry roasted grits were preferred. Overall, processing of dry roasted grits is recommended as an alternative way of circumventing HTC while simultaneously contributing to the protein, starch and mineral recommended daily intake (RDI) for young children and adults.

Keywords: *Vigna subterranea, hard-to-cook, domestic processing, INFOGEST, digestibility, bioaccessibility.*

1. Introduction

Grain legumes are commonly cultivated for their agronomic and nutritional benefits [165]. They are important for supplying cheap dietary protein and other essential nutrients. The development of textural defects known as hard-to-cook (HTC) and hard-to-mill (HTM) phenomena poses a drawback to the optimal use of legumes [75]. The defects develop during post-harvest storage in hot and humid as well as temperate conditions [131]. The HTC phenomenon is a global grain legume textural shortcoming that has been reported as early as the 3rd century B.C [131]. It is characterized by an extended boiling time needed to ensure adequate softening prior to consumption, whilst the HTM phenomenon makes dehulling and grinding difficult [28]. The consequence of the HTC phenomenon is reduced processing and utilization leading to forfeiture of nutrients that could have eased food insecurity problems as well as economic losses throughout the food chain [76].

Bambara groundnut (BG) (*Vigna subterranea* (L.) Verdc.) is an underutilized indigenous crop cultivated by subsistence women farmers throughout tropical and sub-tropical countries in sub-Saharan Africa and some parts of Latin America and Asia [25]. BG has a carbohydrate (60-63%), fat (6.5%), protein (18-24%) and mineral content that fulfils the nutritional requirements for an almost complete diet (FAO 2011). In Africa, BG is ranked third in importance after groundnut (*Arachis hypogea*) and cowpea (*Vigna unguiculata*) in terms of production and consumption. BG is a suitable crop for rural populations who live in sub-Saharan Africa (SSA) semi-arid regions where intensive cropping of maize is unfavorable [79]. The importance of BG stems from its resistance to drought, pests, and the ability to produce a reasonable yield on poor soils. As BG is extensively grown by rural populations, the group suffering from HTC phenomenon is large. The HTC problem may not seem severe for people living in the developed world, who have energy resources and state-of-the-art techniques to utilize HTC legumes. However, in developing countries, boiling HTC bambara groundnuts is challenging, especially for those of a lower socio-economic status, who rely on firewood to provide energy for cooking and heating [131, 132]. Through a survey in Zimbabwe [237] and previous reports [70], soaking and or roasting prior to milling of BG into grits and flour were disclosed as pre-treatment methods to circumvent the HTC and HTM problem. BG grits take approximately 45 min of boiling prior to consumption, equaling boiling time of freshly harvested BG pods. Thus, grit production partly solves the problem of long boiling time with a 75% reduction as compared to a 25% reduction when boiling BG in alkaline salts [70]. Processing involved in grit production is expected to alter protein content and quality. In the view that simple nutrient analysis will give a deceptively high/low indication of nutritional quality, yet the nutrient might be resistant to enzymatic hydrolysis.

This paper compares traditional boiling of BG with alternative methods of processing that circumvent HTC phenomena to determine if the latter efficiently yield nutritious foods. Assessment criteria include processing efficiency, consumer acceptance as well as digestibility of starch and proteins and mineral bioaccessibility. To our knowledge, no studies have evaluated the effects of these alternative processes on nutritional quality of this important nutritional source.

2. Materials and Methods

2.1. Sample collection and preparation

A red (*manna*) and a brown-seeded variety (*kazuma*) of BG were procured from the Director of Research and Specialist Services, Zimbabwe. The procured BG seeds were grown in the 2015-2016 farming season and were harvested and stored at ambient temperatures. Batches of 2 kg seeds each underwent different pre-treatment steps: i) boiling, ii) soaking, iii) soaking followed by dry roasting and iv) dry roasting (Fig 5.1). Soaked seeds were prepared by immersing them in distilled water for 24 h at 25 °C followed by drying in an oven for 48 h at 50°C. Dry roasted seeds were prepared by roasting seeds using Hot top Coffee bean roaster (KN-8828-2K, Pullman Espresso Accessories, Australia) programme 6 roasting cycle for 10 min. This roaster was chosen to standardize the roasting process as it was a critical control point. In programme 6, each temperature range was maintained for 1 min (73-70 °C, 70-80 °C, 80-90°C, 90-106 °C, 106-120 °C, 120-132 °C, 132-145 °C, 145-162 °C, 162-167 °C, 167-179 °C), followed by cooling for 5 min. For combined soaking and roasting treatment, seeds were soaked as in ii) and roasted as in iv). Next, all samples were mechanically dehulled using a SATAKE-TMO-5C dehuller to make grits (particle size ~2 mm). Dehulling efficiency (DE) was according to Enwere and Hung [28]. Subsequently, 200 g of grits was boiled with deionized water at a 1:4 ratio using a Thermomix (Thermomix TM5, Vorwerk) at 100 °C for 45 min with minimum stirring. Boiling and cooking processes were done in duplicate. Boiled BG grits were freeze-dried and milled to powder (Retch, MM400, Germany) (particle size ~ 0.5 mm). Powders were kept in sealed plastic bags at -21 ºC for further analysis.

2.1.1. Measuring BG processing aptitude

The aptitude of BG processing methods (from raw material to finished product) was assessed through scoring for different indicators as shown in Table 5.1. In coming up with the scoring system, self-anchoring of each index was carried out. Overall processing aptitude was obtained by adding all scores of the indicators, as such, the smaller the overall score, the better the processing method.

2.1.2. Measuring colour of cooked seeds and grits

Colour was measured using Hunterlab Colourflex EZ and differences in colour were determined by calculating chroma, hue and ΔE^*_{ab} [238].

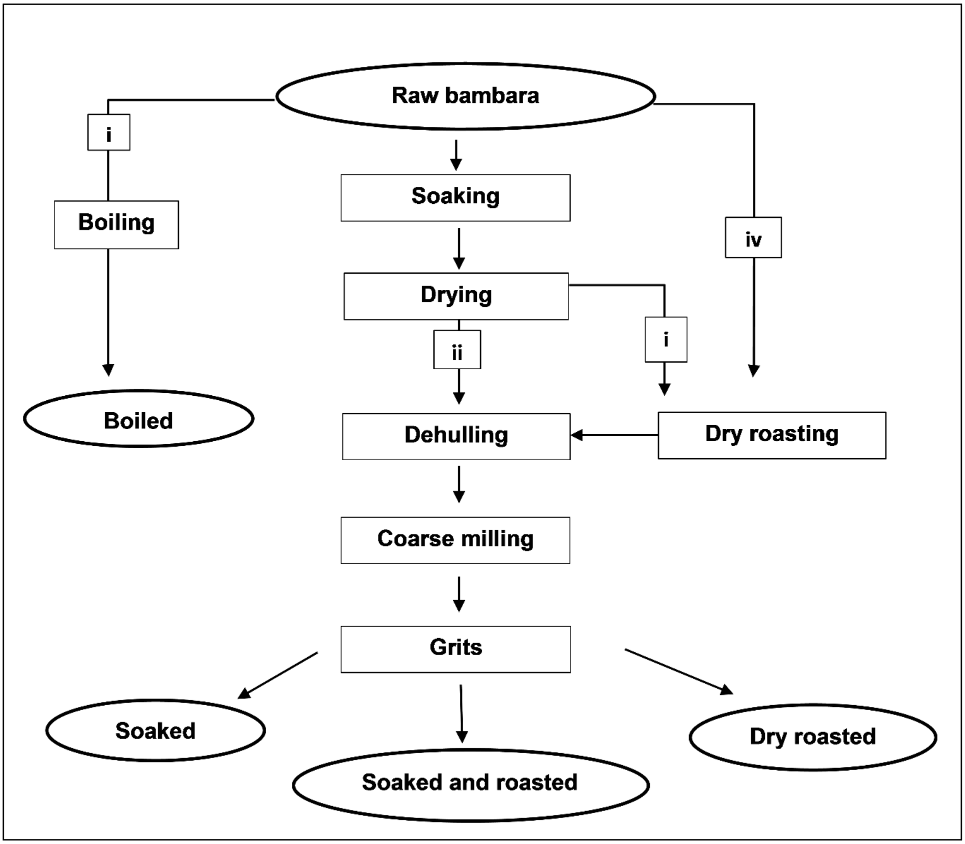

Fig 5.1 Processing of bambara groundnut into grits and boiled seeds

2.2. *In vitro* digestion

In vitro digestion analyses were performed in duplicate for each sample according to the static INFOGEST digestion method described by Minekus, Alminger [239], modified by excluding salivary amylase, but included simulated salivary fluid (SSF). The intestinal phase was demonstrated with pancreatin instead of individual enzymes. At oral phase, a 2.5 g freeze-dried powder (particle ~ 0.5 mm) was mixed with 2.5 ml of deionized water and 4 ml of SSF electrolyte stock solution for 30 s in a Waring blender to obtain a paste-like consistency. A blank was prepared with 2.5 ml deionized water. After gastric and intestinal phase, samples were cooled in an ice water bath for 15 min, followed by centrifugation at 4000 rpm for 15 min. Aliquots of digested and centrifuged samples were stored for future analysis: samples for amyloglucosidase incubation were mixed with absolute ethanol in a ratio of 1:4, samples for total phenol analysis were mixed with 70% methanol (ratio 1:1) and samples for protein analysis were snap frozen with liquid nitrogen. All samples were stored at -20 °C until analysis.

Table 5.1 Indicators for processing aptitude of bambara groundnut products

Processing aptitude indicator	Description	Scoring key
Firewood use	Time required to heat the products during processing (from raw seeds to finished product)	1 h = 1
Pre-processing time	Time needed for pre-processing of products (e.g. from raw seeds to grits)	24 h = 1
Boiling time	Time taken to boil the seeds or grits to edible products.	1 h = 1
Pre-processing water use	The use of water during pre-processing is indicated by yes or no (e.g. from raw seeds to grits)	yes = 1 no = 0
Water use during boiling	This was measured in relation to the time needed for boiling of the products	1 h = 1
Dehulling	Need for dehulling during pre-processing (yes or no)	yes = 1 no = 0
Product storage	Storability of intermediate products e.g. grits and seeds	1 = easy 2 = difficult
Overall process flexibility	This measures the overall aptitude of the particular food processing method	1 = easy 2 = difficult

2.2.1. Amyloglucosidase incubation

Amyloglucosidase incubation of intestinal phase samples was adapted from Monro, Mishra [240]. Aliquots previously combined with absolute ethanol were rested for 30 min prior to starting amyloglucosidase incubation. Ethanoic solutions were shaken in a vortex mixer for 10 s and centrifuged at 4500 g for 15 min. A 0.1 ml of supernatant was placed in tubes containing 0.5 ml of amyloglucosidase solution in acetate buffer (0.1 M) of pH 4.8. Amyloglucosidase activity in 0.6 ml (enzyme solution + sample) was 27.16 U/ml. Samples were incubated at 37 °C for 1 h. To stop the reaction, samples were incubated at 100 °C for 10 min, cooled in an ice water bath for 15 min and snap frozen using liquid nitrogen. Amyloglucosidase incubation of each intestinal phase sample was done in duplicate.

2.3. Chemical analysis

2.3.1. Folin-Ciocalteu assay for total phenol content (TPC)

Extraction and analysis of polyphenols of BG products was based on method of Nyau, Prakash [241], with a small modification. About 3 g of sample was mixed with 15 ml of acidified methanol (70%). The mixture was shaken for 30 min at room temperature and sonicated for 30 min at 25 ºC. Thereafter, extracted samples were centrifuged for 15 min at 4500 rpm at 4 °C and stored at -20 °C. Digested samples were mixed with 70% acidified methanol (ratio 1:1) before storing at -20 °C for further analysis. After Folin-Ciocalteu assay, gallic acid equivalents (GAE) were calculated based on calibration curve.

2.3.1. Total protein by Dumas method

BG samples were analyzed in duplicate according to AOAC method 993.13 using a Flash EA-1112 protein analyzer (Thermo Scientific, Netherlands). Methionine (ACROS Organics 227210250, 99% purity) was used as nitrogen calibration standard and cellulose (Sigma-Aldrich 310697) as blank. Total protein content was obtained using 5.7 as Nitrogen: Protein conversion factor (N:P) [242].

2.3.3. Amino acid analysis by O-phthaldialdehyde (OPA)

Acid hydrolysis of amino acids (TAA) was according to Maehre, Edvinsen [243]. For in *vitro* digested samples, 2 ml of sample was centrifuged at 14 000 rpm, 4ºC for 15 min before starting dilutions for OPA measurements. Free amino acids (FAA) in non-digested samples were extracted using Phosphate Buffered Saline

(PBS) in a ratio of 2 g of sample for 10 ml of buffer. After shaking for 2 h, the mixture was centrifuged for 15 min at 4700 rpm and supernatant was collected for further analysis. Free amino acids were determined using the improved OPA method described by Nielsen, Petersen [244]. For standard curve, 2.6 mg of L-leucine (ReagentPlus, ≥99% (TLC), Sigma-Aldrich) was dissolved in 1 ml PBS buffer. Dilutions were made from 10 mM to 0.078 mM. *In vitro* protein digestibility (IVPD) was calculated based on formula 1.

$$\mathrm{IVPD} = \frac{\text{digested amino acids} - \text{buffer extracted free amino acids}}{\text{total acid hydrolysed amino acids in processed sample}} * 100 \qquad (1)$$

2.3.4. Total starch content

Total starch was measured using the improved AACC-76-13.01/AOAC 996.11 methods (Megazyme K-TSTA-50A/K-TSTA) [245]. IVSD was calculated as total starch before digestion / digested starch *100.

2.3.5. Mineral analysis by ICP-OES

Freeze-dried non-digested samples were degraded by addition of nitric acid and hydrochloric acid followed by microwaving (CEM, MARS-Xpress) to completely solubilize the silicate skeleton. Nitrous vapors were removed by addition of hydrogen peroxide. After that, selected elements (Zn, Mg, K, and P) were measured using ICP-AES (Thermo, iCAP 6500 duo-dual view ICP-OES) in duplicate. Each mineral bioaccessibility was calculated as: mineral content before / mineral content after digestion *100.

2.4. Consumer acceptance of boiled BG grits

Consumer preference of BG products was assessed according to the method of Nnam [246] to test for taste, flavor, texture, colour and general acceptability of boiled grits. Thirty untrained participants who were regular consumers of boiled BG were selected through random sampling from students of Chinhoyi University of Technology, Zimbabwe. Boiled seeds and grits, which were coded (RC, RS, RSR, RDR, BC, BS, BDR and BSR), were presented to each panelist in a Thermos flask (20 ml of sample). Panelists were not aware of the product they were given to evaluate. Each panelist was given eight transparent dessert bowls and plastic teaspoons for use during sensory test. A column for each sample in the hedonic instrument was coded to correspond with sample code.

2.5 Statistical analysis

Results were analyzed and expressed as mean and standard deviations of duplicates or triplicates. Two-way ANOVA statistical analysis was performed to determine significant differences amongst means. When significant differences ($p < 0.05$) were found, results were compared using a post-hoc test (Tukey). All statistical analyses were run using SPSS v 23.0 software.

3. Results and discussion

3.1. BG processing efficiency

Boiling BG to sufficiently soften it for consumption commonly takes 3 h. This process causes notable expenditures of scarce energy, water and time. In comparison to Western consumers who spend less time on general food preparation (~ 40 min) [247], 3 h of boiling means that 4.5 x more time is spent on legume preparation. However, when BG is pre-processed into grits, and subsequently made into a porridge, boiling is shortened to 45 min. An assessment of aptitude of processing methods shows that processing of grits is far more efficient as compared to boiling of seeds (Table 5.2). The dry roasting process is more efficient (overall score of 7.36) followed by soaking (score of 10), combined soaking and roasting (10.36) and boiling with a score of 13.5. Dehulling efficiency (DE) in grit production ranged between 81-84% (Table 5.3) and there was an insignificant effect of both variety and pre-treatment method ($p > 0.05$), implying the diversity in processing grits and the applicability of both varieties.

Table 5.2 Processing aptitude of bambara groundnut grits (locally known as *rupiza*) and boiled seeds (so-called *mutakura*). The smaller the score, the better the processing aptitude

Aptitude indicator	Boiling	Soaked grits	Dry-roasted grits	Soaked + roasted grits
Flexibility	2	1	1	1
Pre-processing time	0	3	0.18	3.18
Boiling time	2.5	1	1	1
Firewood use	4	1	1.18	1.18
Water use during cooking	3	1	1	1
Product storage	2	1	1	1
Pre-processing water use	0	1	1	1
Cost of dehulling	0	1	1	1
Total scores	13.5	10	7.36	10.36

3.2. Colour of BG products

Table 5.3 shows distinct ΔE*ab, chroma and hue values of BG products. The ΔE*ab values show close resemblance between raw and soaked grits (1.6 and 2.7) of both varieties. Roasting had the greatest effect on ΔE*ab in red variety (26.7), while cooked brown variety had 20.3. Overall, difference in colour between roasted, combined soaked and roasted and control samples is easily perceptible and can even be perceived as different colour. Close resemblance of both chroma and hue of raw seeds and cooked seeds as well as soaked grits was observed in both varieties. Further, just like ΔE*ab trends, processing caused significant differences in chroma ($p = 0.000$), and the dry roasting effect resulted in higher chroma values than other processes. Roasting decreased hue values in both varieties, however, raw and soaked seeds values were similar. Colour development during roasting is ascribed to Maillard reactions occurring during roasting, the significance of these reactions will be visible in consumer acceptance of products as previously reported by Nti [248].

3.3. Total phenol content (TPC) of raw and cooked products

High polyphenol content is suggested to interfere with digestion and absorption of nutrients [249]. The found TPC of raw seeds i.e., 100-110 mg/100 g DW (Table 5.3) agrees with 109-138 mg/100 g found by Nyau [229], but lower than 217 mg/100g DW reported by Yagoub and Abdalla [250]. Red variety products had a significantly higher TPC (p = 0.000) than brown variety. Boiling increased TPC of both varieties as already found also by Nyau [229]. However, the increase after boiling is contrary to the findings of Siddhuraju and Becker [251]. Conversely, all grit processing methods lowered TPC inclining with Nti [248] for dehulled and roasted BG seeds and Siddhuraju and Becker [251], for soaked, roasted and dehulled dry beans. Moreover, significant reduction of TPC during soaking followed by thermal processing has also been observed in dry beans and mung-bean [252]. The dehulling as well as soaking effect in reducing polyphenols was reported by Nti [248].

3.4. Protein digestibility of BG grits as influenced by variety and processing conditions

3.4.1. Total protein before and after pre-treatment and boiling

Protein content of raw BG seeds, i.e. 20.1 and 20.6% (Table 5.4) concur with Nti [248], Mazahib, Nuha [253]. Observed varietal differences is consistent with Nti [248], who reported the same inclinations in maroon and brown varieties. Differences within varieties are ascribed to cultivation conditions e.g. soil and climatic conditions [254]. Current protein content is higher than 18 g/100 g reported by Amarteifio and Moholo [149], but lower than 25 g/100 g reported by Brough, Azam-Ali [255]. BG contains lower protein content than 21-25% for raw cowpea (*Vigna unguiculata* L. Walp.) [256].

Processing had diverse effects on protein content, as such, cooking decreased protein content, whereas an increase was observed after grit production. Effect of variety was significant (p = 0.001), agreeing with Nti [248] that protein content differ between varieties and their response to processing also vary. In relation to grit production techniques, brown variety grits showed superior protein content than red variety. Overall, effect of processing method on protein content was significant (p = 0.000), demonstrating its bearing on protein quantity.

Decrease in BG protein content after soaking and boiling is reported by Mazahib, Nuha [253], after soaking, boiling and roasting by Yagoub and Abdalla [250] and Yusuf, Ayedun [257]. Similar decreases in protein after cooking were also observed in cowpea [258]. Decrease in protein content after cooking is attributed to denaturation of protein during heating [259].

Slight increase in protein content after grit production and boiling is ascribed to positive effect of dehulling [29, 248]. An increase in protein content after soaking was observed by Hassan, Osman [260] for lupin seeds (*Lupinus mutabilis*) and was attributed to reduction of anti-nutritional factors.

Table 5.3 The DE (%), colour and total phenol content of red and brown bambara groundnut products

Variety	Processing method	Dehulling efficiency (%)	Chroma (C*)	Hue (h°)	ΔE*ab	[2]TPC [GAE mg/100g DW]
Red	Raw seeds	< 15	$10.9^{a} \pm 0.1$	$1.44^{d} \pm 0.00$	Control	$110.4^{bc} \pm 1.1$
	Cooked seeds	[1]ND	$13.8^{a} \pm 0.1$	$1.09^{a} \pm 0.01$	20.3	$140.3^{d} \pm 2.9$
	Dry roasted grits	$83.8^{a} \pm 1.9$	$29.7^{b} \pm 7.0$	$1.21^{abc} \pm 0.07$	26.7	$98.2^{ab} \pm 1.9$
	Soaked grits	$84.2^{a} \pm 2.5$	$12.0^{a} \pm 0.2$	$1.49^{d} \pm 0.04$	1.6	$89.7^{ab} \pm 2.6$
	Soaked + roasted grits	$83.1^{a} \pm 4.1$	$25.6^{ab} \pm 7.7$	$1.27^{abc} \pm 0.04$	16.8	$93.4^{ab} \pm 1.8$
Brown	Raw seeds	< 15	$12.0^{a} \pm 0.0$	$1.41^{cd} \pm 0.00$	Control	$100.5^{ab} \pm 1.4$
	Cooked seeds	ND	$15.9^{ab} \pm 1.1$	$1.12^{ab} \pm 0.14$	14.7	$122.5^{c} \pm 2.2$
	Dry roasted grits	$81.5^{a} \pm 4.8$	$25.8^{ab} \pm 3.7$	$1.31^{abc} \pm 0.03$	14.6	$81.4^{a} \pm 1.2$
	Soaked grits	$83.4^{a} \pm 4.7$	$12.5^{a} \pm 1.4$	$1.47^{d} \pm 0.06$	2.7	$81.1^{a} \pm 16.5$
	Soaked + roasted grits	$82.2^{a} \pm 3.4$	$23.4^{ab} \pm 5.9$	$1.33^{bc} \pm 0.04$	11.8	$81.7^{a} \pm 1.5$

[1]ND = not done. [2]TPC = Total phenol content

Similar superscripts in columns (a, b, c and d) indicate means that are not significantly different ($p > 0.05$).

Table 5.4 Total protein, acid hydrolysed amino acids (TAA), enzyme hydrolysed amino acids (FAA), IVPD (%) of raw seeds, boiled seeds, and boiled grits from red and brown bambara groundnut.

Variety	Processing method	Total protein g/100g DW	Acid hydrolysed amino acids (TAA) g/100g DW	Enzyme hydrolysed amino acids (FAA) g/100g DW	³IVPD (%)
Red	Raw seeds	$20.1^{abc} \pm 0.1$	$15.7^{bc} \pm 0.0$	$6.0^{ab} \pm 1.3$	$38.5^{ab} \pm 8.4$
	Boiled seeds	$19.4^{ab} \pm 0.1$	$11.0^{a} \pm 0.6$	$7.6^{ab} \pm 0.4$	$68.8^{c} \pm 3.3$
	Dry roasted grits	$21.2^{cd} \pm 0.2$	$18.3^{c} \pm 0.3$	$7.5^{ab} \pm 0.2$	$40.8^{ab} \pm 0.8$
	Soaked grits	$20.3^{abc} \pm 0.2$	$18.4^{c} \pm 1.1$	$9.3^{b} \pm 1.0$	$50.9^{bc} \pm 5.4$
	Soaked and roasted grits	$20.6^{bcd} \pm 0.4$	$17.8^{bc} \pm 1.1$	$6.6^{ab} \pm 0.3$	$37.3^{ab} \pm 1.9$
Brown	Raw seeds	$20.6^{cd} \pm 0.9$	$18.1^{c} \pm 0.2$	$4.8^{a} \pm 1.0$	$26.4^{a} \pm 5.7$
	Boiled seeds	$19.0^{a} \pm 0.0$	$13.8^{ab} \pm 0.1$	$7.7^{ab} \pm 0.6$	$56.1^{bc} \pm 4.4$
	Dry roasted grits	$22^{d} \pm 0.4$	$18.2^{c} \pm 0.8$	$8.0^{ab} \pm 1.3$	$43.9^{ab} \pm 7.3$
	Soaked grits	$21.9^{d} \pm 0.3$	$18.0^{bc} \pm 0.6$	$8.4^{b} \pm 1.1$	$45.3^{ab} \pm 5.7$
	Soaked and roasted grits	$21.8^{d} \pm 0.5$	$16.3^{bc} \pm 2.8$	$8.5^{b} \pm 0.1$	$52.1^{bc} \pm 0.8$

³IVPD = *in vitro* protein digestibility.

Similar superscripts in columns (a, b, c and d) indicate means that are not significantly different ($p > 0.05$).

3.4.2. Acid hydrolyzed amino acids (TAA) before digestion

Table 5.4 shows TAA after acid hydrolysis of BG varieties. The observed decrease in TAA after boiling of seeds is consistent to inclinations in total protein. Grit production significantly increased TAA ($p = 0.000$) than boiling treatment, whereas variety had no significant effect ($p = 0.186$). TAA was slightly lower for combined soaking and roasting (17.8 and 16.3%) as compared to separate treatments of either soaking or roasting (18.0-18.4%).

TAA differences in raw and processed samples are ascribed to discrepancies in protein hydrolysis brought by processing. Denatured proteins are usually easy to hydrolyze by acidic treatment, since during processing, it is possible to alter protein-starch complexes thereby improving hydrolysis [261]. Alternatively, limited degree of unfolding limits hydrolysis of raw proteins [262], therefore, an underestimation occurs.

3.4.3. *In vitro* protein digestibility (IVPD) of BG products

Several factors causing disparities in protein enzyme hydrolysis and digestibility include process induced structural changes that hinder or promote enzyme hydrolysis [263] and presence of starch-protein-polyphenol complexes [264]. In addition, binding of ligands to sites on a protein, are also known to affect susceptibility to hydrolysis [261]. Intrinsically, protein denaturation may be beneficial for the hydrolysis of protein by protease, while protein aggregation may inhibit hydrolysis reaction [265].

Enzyme hydrolyzed FAA varied for raw and cooked products (Table 5.4). Boiled seeds and grits had higher FAA content after digestion (6.6-10%) as compared to digested raw seeds (4.8 and 6%). Digested products showed mutual inclination of increased FAA, but this difference was only prominent for soaked grits (both varieties) and for combined treatment of brown variety. Nevertheless, variety had no significant effect on enzyme hydrolyzed FAA, only processing had ($p = 0.003$). The lower enzyme hydrolyzed FAA of raw seeds is predictable as raw seed proteins are expected to be less digestible compared to structurally changed proteins of cooked seeds and grits. Increase of enzyme hydrolyzed FAA after grit production is attributed to polyphenols reduction after seed coat removal [251].

IVPD of all BG products ranged from 26-68%. Increase of IVPD after processing was prominent in boiled red and brown BG seeds with 69% and 56% IVPD, respectively. Differences in IVPD between red (38-51%) and brown variety (26-56%) of BG were found to be significant (p = 0.027), assenting with Chitra, Vimala [252], who reported variation in IVPD (from 60-74%) for pigeon pea varieties and (from 65-79%) for chickpea varieties. Moreover, a significant difference in IVPD between processing methods (p = 0.003) was observed, such that, dry roasted BG had the lowest IVPD (42%). The IVPD for boiled BG is higher than 51% reported by Yagoub and Abdalla [250], and comparable to 69% boiled chickpea [266]. Inversely, results reveal a lower digestibility value than 87% for boiled BG reported by Mazahib, Nuha [253] and 79% reported for cowpea [267]. Furthermore, after roasting Yagoub and Abdalla [250], recorded 42% IVPD, which is comparable to 43-46% obtained in the current study (though currently, seeds were roasted prior to boiling). Conflicting effects of roasting on IVPD are also stated by Chitra, Singh [268] and Yagoub and Abdalla [250]. According to Chitra, Singh [268], combined roasting and dehulling caused a slight increase in IVPD e.g. mung bean (from 70 to 73%) and soya bean (from 63-65%). However, according to Yagoub and Abdalla [250], IVPD for roasted BG decreased (from 78-42%). The positive effect of soaking, roasting and dehulling cowpea on IVPD was reported by Plahar, Annan [269]. Heat processing was reported to increase protein digestibility of grain legumes by denaturing globulin proteins, that are highly resistant to proteases in their native state [270].

3.5. Starch content and digestibility of BG as influenced by variety and processing method

3.5.1. Starch content in raw and processed BG products

Total starch content of raw and processed BG products ranged from 29 to 39% (Table 5.5). Starch content in both varieties (*viz.* 29.2 and 29.5 %) is comparable to the 33% in *cultivar* 63 from Ghana, but lower than 39-50% reported for other cultivars (e.g. A23-cream-grey hilum) by Poulter [142] and 42.8% [271]. This variation in starch content is attributed to different agricultural conditions and method of starch analysis [272]. In comparison to other legumes, BG total starch was analogous to the 31-35% in common beans [273], but lower than 38% in raw cowpea [274].

Boiling of seeds increased total starch content in both varieties to 33.4 and 35.5 %. Even though starch content for grits was higher than for boiled seeds, the differences between processing methods were insignificant ($p > 0.05$). This implies that starch gelatinization is almost complete in grits [275], in practice, this means that, by producing grits, there is a guarantee of optimal bioaccessibility of starch for use in metabolic functions. Conversely, brown BG had a slightly higher starch content as compared to red variety and the difference was significant ($p = 0.002$). Increase of starch after boiling agrees with Yagoub and Abdalla [250] and Mazahib, Nuha [253] but disagrees with Rehman and Shah [276]. Total starch content of boiled BG seeds was comparable to starch content (31-35%) in boiled black bean and boiled cowpea (36-38%) [277].

3.5.2. *In vitro* starch digestibility (IVSD) of BG products

Digested starch content in all products ranged from 15.7 to 31.2% and was in all cases lower than total starch content (Table 5.5). All processing treatments increased digested starch content, however, no significant difference in starch content were observed between treatments ($p = 0.976$). IVSD of all BG products was between 48.7 and 84%. The increase in IVSD of processed BG products agrees with Yagoub and Abdalla [250] on BG, Preet and Punia [278] on cowpea and Rehman and Shah [276] on chickpea, lentil, red kidney beans. Current IVSD is comparable to 70-78% for cooked lentil, red kidney beans and chickpea [266], higher than 69% reported for cooked cowpea [279]. The slightly better IVSD of boiled seeds as compared to dry heated samples is consistent with Siddhuraju and Becker [251]. The slightly lower IVSD of grit samples as compared to boiled seeds can be ascribed to less boiling time given to grits (as their cooking time is shorter. Overall, an insignificant effect of variety and processing method were found on IVSD ($p > 0.05$), implying that all processing methods have the same effect on IVSD, in practice this broadens diversity potential.

Table 5.5 Total starch content, digested starch content and IVSD of raw seeds, boiled seeds, and boiled grits from red and brown bambara groundnut.

Variety	Processing method	Total starch g/100g DW	Digested starch g/100g DW	[4]IVSD (%)
Red	Raw seeds	$29.2^{a} \pm 1.0$	$18.8^{a} \pm 0.0$	$59.3^{ab} \pm 0.1$
	Boiled seeds	$33.4^{b} \pm 0.9$	$29.0^{b} \pm 2.2$	$80.3^{c} \pm 6.2$
	Dry roasted grits	$34.5^{b} \pm 1.1$	$30.2^{b} \pm 1.4$	$81.1^{c} \pm 3.7$
	Soaked grits	$36.4^{bc} \pm 1.1$	$29.9^{b} \pm 0.7$	$77.5^{c} \pm 1.8$
	Soaked and roasted grits	$34.9^{b} \pm 1.7$	$29.6^{b} \pm 0.5$	$78.7^{c} \pm 1.3$
Brown	Raw seeds	$29.5^{a} \pm 1.0$	$15.7^{a} \pm 1.3$	$48.7^{a} \pm 4.0$
	Boiled seeds	$35.5^{bc} \pm 0.8$	$31.2^{b} \pm 0.5$	$83.2^{c} \pm 1.3$
	Dry roasted grits	$36.8^{bc} \pm 0.0$	$29.6^{b} \pm 2.9$	$77.3^{c} \pm 7.6$
	Soaked grits	$36.7^{bc} \pm 0.0$	$29.3^{b} \pm 2.0$	$74.9^{bc} \pm 5.0$
	Soaked and roasted grits	$38.9^{c} \pm 0.3$	$29.6^{b} \pm 2.0$	$72.6^{bc} \pm 5.0$

[4]IVSD = *in vitro* starch digestibility.
Similar superscripts (a, b, c and d) in columns indicate means that are not significantly different ($p > 0.05$).

3.6. Mineral bioaccessibility as influenced by variety and processing conditions

Tables 5.6a and b show mineral content (i.e. Zn, Mg, K, and P) of raw and processed BG samples before and after *in vitro* digestion process. Zn content of raw BG before digestion (Zn-B), i.e. 3.1 and 3.3 mg/ 100 g DW, was higher than 1.1-2 mg/ 100 g DW reported by Abiodun and Adepeju [29] and Amarteifio, Karikari [26]. Raw BG seeds had a comparable Zn-B content to several varieties of raw lentil (2.6-3.8 mg/ 100 g DW) [280], but a lower Zn-B content than cowpea

(4.4 mg/ 100 g DW) [258]. Boiling of seeds decreased Zn-B in both varieties agreeing with Wang, Hatcher [280] and Uzogara, Morton [258]. Grit production also decreased Zn-B, markedly, in red variety. Zn-B in brown variety was significantly higher than red variety ($p = 0.035$). Even though processing was not a factor in Zn-B ($p = 0.376$), red variety grits had noticeably lower content compared to brown variety grits.

Digested products had a lower Zn content (Zn-D) (1.1-2.6 mg/ 100 g DW) as compared to undigested samples (2.1-3.3 mg/100 g DW). Effect of variety on digested Zn-D content ($p = 0.226$) and processing method ($p = 0.067$) was insignificant. Grits had a superior Zn bioaccessibility (61-106%) than cooked seeds, inferring a positive effect of grit production on Zn bioaccessibility than boiling. The recommended daily intake (RD1) of Zn depends on age such that children from 7 months to five yr., for instance, require 3 mg/day, and those from 18 yr. and above require on average 10 mg/day [281]. Zn bioaccessibility results show that for example, consumption of 100 g DW dry roasted brown BG contributes for 32.5% to overall requirement of Zn by adults from 18 yr. onwards.

Mg content in undigested samples (Mg-B) ranged from 143 to 174 mg/100 g DW and was within range reported by Amarteifio, Karikari [26]. Mg-B content in raw red and brown BG of 147 and 161 mg/ 100 g DW, respectively, was higher than in raw lentil (99-110 mg/100 g DW) [280] and cowpea (128 mg/ 100 g DW). Mg-B content increase after boiling of seeds agrees with Uzogara, Morton [258]. Brown variety products had a significantly superior Mg-B content as compared to red variety ($p = 0.000$). Grit production had a positive effect on Mg-B content in brown variety, whilst no substantial changes were observed in red variety. After digestion, Mg content (Mg-D) for all products varied from 122 to 162 mg/ 100 g DW. Effects of processing on Mg-D content was significant ($p = 0.006$), such that cooking decreased Mg-D content, whilst an increase was observed after grit production. Grits had a higher Mg bioaccessibility (90-94%) of as compared to cooked seeds (75 and 83%), however, the differences were not significant (p =

0.09). In practice, any processing method is adequate in meeting RDI for young children (4-8 yr. RDI of 80 mg/day) [282].

P content before digestion (P-B) i.e., 448-486 mg/100 DW was higher than 296 mg/100 DW [149] and 267-323 mg/100 DW reported by Nti [248]. Boiling of seeds decreased P-B content, whilst an increase in P-B content after grit production is consistent with Nti [248]. The positive effect of dehulling was also reported for lentils [280]. The differences in P-B amongst processing methods were significant ($p = 0.000$), entailing processing influence, conversely, varietal effects were insignificant ($p = 0.204$). A slight decline P content (P-D) after digestion was observed.

Grits had a higher P (94-100%) bioaccessibility than cooked seeds (76 and 89%), but varietal and processing differences were insignificant ($p > 0.05$). This suggest that all processing options are adequate in optimizing P bioaccessibility and accordingly, bio-accessible P from would be adequate to meet the RDI for children (young children (1-8 yr.) is between 460-500 mg/day) [281].

K content (K-B) of BG seeds (i.e. 1679 and 1708 mg/100 g DW) was higher than the findings of Amarteifio, Karikari [26]. All processes decreased K-B content agreeing with Uzogara, Morton [258]. Significant differences in K-B content were found between processing methods ($p = 0.000$), conversely no varietal effect were observed ($p = 0.231$). The same trend was observed on K after digestion (K-D). Grits had a higher K bioaccessibility (92-101%) compared to cooked seeds. There was no effect of both variety and processing on K for young children and adults is the same, namely 3510 mg/day. The results show that bio-accessible K from the products e.g. 100 g DW dry roasted brown BG would contribute 54% of the RDI for children and adults.

Table 5.6 Mineral content (mg/100 g DW) and mineral bioaccessibility (BA) (%) of raw seeds, boiled seeds and boiled grits

a)

Variety	Processing method	Zn-B[5] mg/100g DW	Zn-D[6] mg/100g DW	Zn- BA[7] (%)	K-B mg/100g DW	K-D mg/100g DW	K-BA (%)
Red	Raw seeds	$3.1^{a} \pm 0.8$	$2.6^{a} \pm 0.1$	$85.0^{a} \pm 17.1$	$1679^{abc} \pm 32$	$1714^{a} \pm 124$	$102^{a} \pm 5$
	Cooked seeds	$2.9^{a} \pm 0.4$	$1.5^{a} \pm 0.5$	$51.9^{a} \pm 23.5$	$1431^{a} \pm 21$	$1314^{a} \pm 90$	$92^{a} \pm 8$
	Dry roasted grits	$2.4^{a} \pm 0.5$	$1.4^{a} \pm 0.5$	$61.8^{a} \pm 34.1$	$1922^{c} \pm 165$	$1840^{a} \pm 156$	$96^{a} \pm 0$
	Soaked grits	$2.1^{a} \pm 0.4$	$2.2^{a} \pm 0.0$	$106.1^{a} \pm 16.5$	$1838^{abc} \pm 117$	$1698^{a} \pm 63$	$92^{a} \pm 2$
	Soaked and roasted	$2.0^{a} \pm 0.5$	$1.8^{a} \pm 0.1$	$88.4^{a} \pm 16.2$	$1852^{bc} \pm 204$	$1809^{a} \pm 179$	$98^{a} \pm 1$
Brown	Raw seeds	$3.3^{a} \pm 0.9$	$2.1^{a} \pm 0.3$	$66.9^{a} \pm 28.7$	$1708^{abc} \pm 34$	$1476^{a} \pm 236$	$86^{a} \pm 12$
	Cooked seeds	$2.8^{a} \pm 0.0$	$1.1^{a} \pm 0.3$	$37.4^{a} \pm 10.7$	$1508^{ab} \pm 10$	$1176^{a} \pm 200$	$78^{a} \pm 14$
	Dry roasted grits	$2.7^{a} \pm 0.1$	$2.6^{a} \pm 0.7$	$97.5^{a} \pm 31.8$	$1925^{c} \pm 86$	$1900^{a} \pm 219$	$99^{a} \pm 16$
	Soaked grits	$2.8^{a} \pm 0.3$	$2.6^{a} \pm 0.6$	$95.3^{a} \pm 30.0$	$1961^{c} \pm 78$	$1898^{a} \pm 238$	$97^{a} \pm 16$
	Soaked and roasted	$2.9^{a} \pm 0.4$	$2.4^{a} \pm 0.4$	$86.7^{a} \pm 27.0$	$1917^{bc} \pm 103$	$1916^{a} \pm 307$	$101^{a} \pm 21$

b)

Variety	Processing method	Mg-B	Mg-D	Mg-BA (%)	P-B	P-D	P-BA (%)
		mg/100g DW	mg/100g DW		mg/100g DW	mg/100g DW	
Red	Raw seeds	$147^{a} \pm 2$	$135^{ab} \pm 4$	$91^{a} \pm 3$	$486^{ab} \pm 7$	$515^{bc} \pm 52$	$106^{a} \pm 12$
	Cooked seeds	$147^{a} \pm 3$	$122^{a} \pm 5$	$83^{a} \pm 2$	$425^{a} \pm 14$	$380^{ab} \pm 4$	$89^{a} \pm 2$
	Dry roasted grits	$153^{a} \pm 14$	$139^{ab} \pm 6$	$91^{a} \pm 4$	$592^{bc} \pm 43$	$556^{c} \pm 3$	$94^{a} \pm 6$
	Soaked grits	$143^{a} \pm 7$	$130^{a} \pm 2$	$91^{a} \pm 6$	$593^{bc} \pm 21$	$592^{c} \pm 3$	$100^{a} \pm 3$
	Soaked and roasted	$143^{a} \pm 13$	$134^{cb} \pm 7$	$94^{a} \pm 4$	$598^{c} \pm 59$	$590^{c} \pm 73$	$99^{a} \pm 2$
Brown	Raw seeds	$161^{a} \pm 3$	$134^{ab} \pm 8$	$83^{a} \pm 4$	$448^{a} \pm 5$	$393^{ab} \pm 37$	$88^{a} \pm 7$
	Cooked seeds	$165^{a} \pm 0$	$122^{a} \pm 11$	$74^{a} \pm 7$	$437^{a} \pm 4$	$330^{a} \pm 36$	$76^{a} \pm 9$
	Dry roasted grits	$167^{a} \pm 6$	$152^{ab} \pm 11$	$91^{a} \pm 10$	$579^{bc} \pm 12$	$574^{c} \pm 44$	$99^{a} \pm 10$
	Soaked grits	$174^{a} \pm 12$	$162^{b} \pm 10$	$94^{a} \pm 12$	$576^{bc} \pm 24$	$579^{c} \pm 38$	$101^{a} \pm 11$
	Soaked and roasted	$169^{a} \pm 10$	$152^{ab} \pm 9$	$90^{a} \pm 11$	$570^{bc} \pm 29$	$559^{c} \pm 29$	$98^{a} \pm 10$

B[5]= before digestion, D[6] = after digestion, BA[7] = bioaccessibility.
Similar superscripts (a, b, c and d) in columns indicate means that are not significantly different ($p > 0.05$).

3.7. Consumer acceptance of boiled BG seeds and grits

Mean sensory scores for boiled seeds and grits prepared by different processing techniques using both red and brown varieties of BG are given in Table 5.7. The general acceptability of products was influenced by organoleptic attributes such as taste, flavor, texture and colour. The scores indicate that both variety and processing method affected the various sensorial attributes and overall acceptability of BG products. Boiled seed varieties scored high on all sensorial attributes and were better accepted than grit products. This is attributed to cultural environment, specifically traditions, beliefs and patterns as explained by Meiselman, Frewer [283], which favor a commonly processed product than a uncommon alternative.

Comparison of grit colour showed that dry roasted grits of both varieties were the best choice for panelists. Soaked grits of both varieties and combined soaked and roasted grits from the brown variety were slightly liked. There was no significant effect of variety on colour preference, but the effect of processing was significant ($p = 0.000$). This demonstrates the importance of Maillard reactions that cause the characteristic brown colour and flavor of roasted products [248]. Concerning flavor, Maillard reactions occurring in dry roasted red grits contributed to the superior flavor exhibited. Results showed a significant effect of processing method p = (0.000) on flavor preference between panelists. As for taste, dry roasted grits from the brown variety were superior to red-based grits and taste preferences were influenced by processing method ($p = 0.000$). The same trend was also noticeable in texture results.

General acceptability results showed a significant effect of processing method p = (0.049) on the preference of BG products. Conventionally boiled seeds were superior followed by dry roasted products, combined soaked and roasted products and lastly soaked grits. Hence, in practice, the choice of the processing method will affect acceptability of end products.

Table 5.7 Sensory properties of boiled grits from brown and red bambara groundnut

Variety	Processing method	Colour	Flavour	Taste	Texture	Overall acceptability
Red	Boiled seeds	$7.9^{e} \pm 1.0$	$7.8^{c} \pm 1.3$	$8.0^{d} \pm 1.2$	$7.9^{d} \pm 1.1$	$8.1^{d} \pm 1.0$
	Soaked grits	$5.3^{a} \pm 1.6$	$4.0^{a} \pm 1.5$	$4.5^{ab} \pm 1.8$	$4.9^{ab} \pm 1.8$	$4.6^{a} \pm 1.4$
	Dry roasted grits	$6.4^{bc} \pm 1.2$	$5.8^{b} \pm 1.5$	$5.5^{bc} \pm 1.8$	$6.1^{bc} \pm 1.3$	$6.2^{bc} \pm 1.3$
	Soaked and roasted grits	$6.1^{ab} \pm 1.9$	$4.8^{ab} \pm 1.9$	$4.2^{ab} \pm 1.4$	$5.0^{ab} \pm 2.1$	$5.4^{ab} \pm 1.5$
Brown	Boiled seeds	$7.5^{de} \pm 1.2$	$7.6^{c} \pm 1.1$	$7.9^{d} \pm 1.2$	$7.4^{d} \pm 1.2$	$7.8^{d} \pm 1.2$
	Soaked grits	$5.0^{a} \pm 1.7$	$4.2^{a} \pm 1.6$	$4.4^{ab} \pm 1.7$	$5.0^{ab} \pm 1.7$	$4.7^{a} \pm 1.6$
	Dry roasted grits	$6.9^{bcd} \pm 1.3$	$5.9^{b} \pm 1.9$	$6.0^{c} \pm 1.8$	$6.8^{cd} \pm 1.4$	$7.0^{cd} \pm 1.4$
	Soaked and roasted grits	$5.9^{ab} \pm 1.9$	$4.5^{a} \pm 1.6$	$4.1^{a} \pm 1.6$	$4.9^{a} \pm 1.6$	$4.8^{a} \pm 1.7$

Similar superscripts (a, b, c and d) in columns indicate means that are not significantly different ($p > 0.05$).
Scores are based on a point hedonic scale: 9 – Like extremely 8 – Like very much 7 – Like moderately 6 – Like slightly 5 Neither like nor dislike 4 – Dislike slightly 3– Dislike moderately 2 – Dislike very much 1 – Dislike extremely

3.8. Conclusions

Producing BG foods from grits proved to be an efficient way -in terms of labor, time and water use- of circumventing HTC phenomenon as compared to traditional boiling of seeds. Making dry roasted grits was most efficient since the process omits soaking and drying stages incorporated in combined soaking and roasting processes. All grit processing methods had a similar dehulling efficiency with no significant varietal influence.

Before making conclusive remarks on IVPD and IVSD found in the study, it is imperative to consider the *in vitro* digestion method used when comparing with data from previous studies. The current *in vitro* digestion Infogest method is harmonized to support production of more comparable data in the future [239]. Therefore, digestibility data obtained by the protocol are hard to compare with other methods. Nevertheless, comparable IVSD were found for boiled seeds and all grits from different varieties. However, overall, boiling of seeds and dry roasting of grits brought better results in IVSD compared to other methods. Both boiling and grit production improved IVPD, though boiling yielded better results. Nevertheless, boiling remains unfavorable in circumventing HTC phenomenon in BG processing. Mineral bioaccessibility results showed that consumption of processed grits contributes in meeting the RDI for the young children and adults. In conclusion, with consumers in mind and the need to circumvent the HTC phenomenon, grit production combined to roasting appears to be a viable option that needs further optimization to meet the RDI of nutrients. Moreover, since the only disadvantage of grit production to conventional boiling is the slightly lower protein digestibility and unconvincing consumer preference, solutions to improve protein digestion and sensorial attributes need to be further formulated.

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Conflict of interest

The authors declare that they have no conflict of interest.

Chapter 6

Bambara groundnut flour: a functional ingredient to favour the use of an unexploited sustainable protein source

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Abstract

Variability in dehulling efficiency, colour, chemical composition and selected functional properties of raw and pre-treated bambara groundnut (BG) flour from red and black-eye varieties were studied. Functional properties were water and oil absorption, gelation, pasting, emulsification and foaming capacity. Pre-treatment of seeds (i.e. soaking, roasting and combined soaking and roasting) improved dehulling efficiency of BG varieties. Protein content of flour ranged from 15.6-19.6%, starch from 47.8-52.0% and sucrose from 1.9-5%. An improvement was observed for protein and ash content of pre-treated flour compared to raw flour. Heat treatments increased onset gelatinization temperature of flour. Black-eye BG flours that had higher starch content, also had better gelation capacity than red BG flours. All pre-treatment methods decreased flour emulsification capacity and stability. Dry-roasting caused a greater decline than other methods, whereas soaking had little effect on emulsion stability. Further, soaking increased foaming capacity, whilst a decline was observed in roasted flour. All pre-treatment methods increased oil absorption capacity of both BG flour varieties. Overall, soaked and combined soaked and roasted flour is recommended for BG flour to be incorporated in food products.

Keywords: *hard-to-cook, hard-to-mill, functional properties, food security, Zimbabwe*

1. Introduction

Impact analyses in sub-Saharan Africa (SSA) indicated that indigenous legume crops can reduce vulnerability of rural households to food and nutrition insecurity [9]. One such legume is bambara groundnut (BG) (*Vigna subterranea* (L.) Verdc.), which features in subsistence farming systems throughout semi-arid regions of SSA [118]. Bambara groundnut is an important source of affordable protein in the diets especially in regions where animal protein is comparatively expensive. The crop is richer in essential amino acids than other legumes and has a higher protein score (80%) than soya bean (74%) and cowpea (64%) [284]. This means that bambara groundnut has relatively more protein available for human metabolism than the other common legumes in Africa [63]. However, like other legumes, BG lacks sulphur containing amino acids [285, 286]. Thus, blending bambara groundnut with a staple food, such as maize, which contains higher levels of cysteine and methionine, is a recommended nutritional strategy [64].

Although BG is a crop with great nutritional and agronomic potential, it remains underutilized. Drawbacks to use BG and other legumes are the hard-to-cook (HTC) and hard-to-mill (HTM) phenomena [75]. The HTC phenomenon in legumes is characterised by an extended cooking time required to ensure adequate softening prior to consumption. In rural areas where BG is of significance, the predominant energy source for cooking is firewood. Due to limited firewood supply and the long time required for boiling, consumption of BG is hampered [76], thus warranting the need for alternative processing methods [70]. A recent survey performed by our group Mubaiwa, Fogliano [237], revealed that soaking and or roasting are applied by some households as pre-treatment methods prior to milling of BG seeds into flour in an effort to circumvent the HTC problem (Fig 6.1). In previous studies, soaking [28], germination [209] and roasting are also employed to bypass the HTM phenomenon.

BG flour has several applications in households to prepare porridge, soups and baked products. However, successful performance of BG flour as a food ingredient depends on the functional characteristics and sensory qualities it imparts to products. Functional properties are intrinsic physico-chemical characteristics that affect behaviour of foods during pre-treatment and storage, e.g. solubility, foamability, gelation and emulsification.

A study by Onimawo, Momoh [36] reported low water binding capacities of raw BG flour as compared to cowpea and soya bean flours. In addition, low foaming properties and stability were also reported, suggesting unsuitability of BG flour for cakes and bread. In a study by Yagoub and Abdalla [143], combined soaking and cooking of BG seeds as well as roasting resulted in the least solubility of nitrogen, whereas soaking led to better solubility. Further, according Olapade and Adetuyi [287], foaming capacity was highest for a cold-water soaked flour (22%) while 13% was reported for roasted flour. Low foamability of roasted flour was attributed to ordered globular molecules due to the high temperature (190°C) employed during roasting [287].

To improve the use of BG flour as a food ingredient, the functional properties and the characteristics imparted to food stuffs need to be assessed. Eventually, consumption of BG can be stimulated by processing seeds into a flour, easing the utilisation and providing more diversity in local diets. Improving the use of BG would mean an increase in food and nutrition security in SSA, while complying with local food preferences and habits. The aim of the paper is to investigate processing effects on chemical composition and functional properties of BG flour from different varieties. Such knowledge allows to decide if varietal differences should be accounted for and which pre-treatment results in the best flour for a particular application.

2. Materials and methods

2.1. Sample characteristics and flour production

A red and a black-eye seeded variety of BG were procured in Zimbabwe from the Director of Research and Specialist Services (DRSS) and Dee Spice Private Company, respectively. The varieties were grown in the 2016-2017 farming season, harvested and stored at ambient temperatures. Batches of 2 kg seeds each underwent different pre-treatments: i) no pre-treatment (raw), ii) soaking, iii) soaking followed by dry roasting and iv) dry roasting (Fig 6.1). Soaked seeds were prepared by immersing in excess deionised water for 24 h at 25°C followed by drying in an oven for 48 h at 50°C. Dry-roasted seeds were prepared by roasting in a Hot top Coffee bean roaster (KN-8828-2K, Pullman Espresso Accessories, Australia), following programme 6 for 10 min to standardize the roasting process. In programme 6, subsequent temperature ranges were maintained for 1 min (73-70°C, 70-80°C, 80-90°C, 90-106°C, 106-120°C, 120-132°C, 132-145°C, 145-162°C, 162-167°C, 167-179°C), followed by 5 min cooling. For the combined soaking and roasting treatment, seeds were soaked as in ii) and roasted as in iii). Next, all samples were mechanically dehulled using a SATAKE-TMO-5C dehuller. Dehulling efficiency (DE) was determined according to Enwere and Hung [28]. Next, pre-treated and raw seeds were coarse milled using a Rotormill (Condux Werk, Germany) to a flour that passed through a 1.5 mm sieve. Thereafter, about 25 g of coarse flour was fine milled using an IKA blender (Model A 11B S000, Germany) for 30 s before sieving through a 180-µm sieve to obtain the samples shown in Fig 6.2. Milling efficiency (%) was determined by calculating the yield before and after fine milling and sieving.

2.1.1. Gravimetric properties of raw and pre-treated seeds

Bulk density was determined by filling a 1000 ml container with kernels from a height of about 15 cm, striking the top level and then weighing the contents [153]. The seed true density was by the water displacement method according to

Karababa [288]. The porosity of bulk seed was computed from the values of true density and bulk density according to Mohsenin [289].

2.1.2. Image analysis

Image analysis of raw and pre-treated bambara groundnut seeds was by X-ray computer Tomography (XRT / CT), allowing non-invasive 3D imaging of internal structures using GE/Phoenix v[tome]x m X-ray microfocus and nanofocus CT scanner.

2.1.3. Particle size distribution of flour

Flour was dispersed in ethanol and sonicated according to Kaptso, Njintang [107] before measuring particle size distribution with a Malvern MSS laser diffraction system (Malvern Instruments Ltd, Malvern, England). The Fraunhofer diffraction model, assuming a standardized spherical shape, was used for the analyses [290].

2.1.4. Colour measurements of raw and pre-treated flour

Colour was measured using Hunterlab colourflex EZ. Differences were determined by calculating chroma, hue and ΔE^*.

2.2. Chemical composition of flour

Dry matter, fat and ash content of BG flour were determined in duplicate according to methods described by Association of Official Analytical Chemists [291]. Analysis of protein content was according to the Dumas method using a Flash EA 1112 protein analyser (Thermo Scientific, Netherlands). Protein content was obtained using 5.7 as conversion factor [242]. Total starch was measured using AACC-76-13.01/AOAC 996.11 method (Megazyme K-TSTA-50A/K-TSTA) [245].

2.2.1. Quantification of carbohydrate content in flour

Flour (2.5 g) was dispersed in 25 ml Milli-Q/ethanol mixture (50-50% (v/v)) and centrifuged (10 min, 3000 rpm). The supernatant was filtered (RC HPLC filter, RC Minisart Satorius, Germany) and centrifuged (15 min, 14,000 rpm). A calibration curve was made for D-fructose (Merck) and D-sucrose (Sigma Aldrich). Quantification of carbohydrates (sucrose and fructose) was by HPLC using an Evaporative Light Scattering Detector (ELSD) [292] and the Alltech prevail Carbohydrates ES 5u 250*4.60 mm column. Flow rate was 0.8 ml/min for 35 min using 100% acetonitrile and deionised water as eluents.

2.3. Determination of the functional properties of flour

2.3.1. Thermal properties

Thermal properties of flour were analysed using a Differential Scanning Calorimeter (DSC) equipped with a thermal analysis data station (Perkin-Elmer Corp Norwalk. USA) according to Evageliou, Richardson [293]. Flour (10-15 mg) was dispersed in distilled water (1:3 w/v) in hermetically sealed stainless steel capsules and incubated for 4 h to equilibrate moisture. Sample and reference pans (balanced to within ± 0.5 mg) were loaded at ambient temperature, cooled to 10°C, and held for 2 min before scanning to 120°C. Samples were scanned at a heating rate of 0.5°C/min using a Seteram microcalorimeter. Temperatures of characteristic transitions and enthalpy (ΔH) of transitions were recorded.

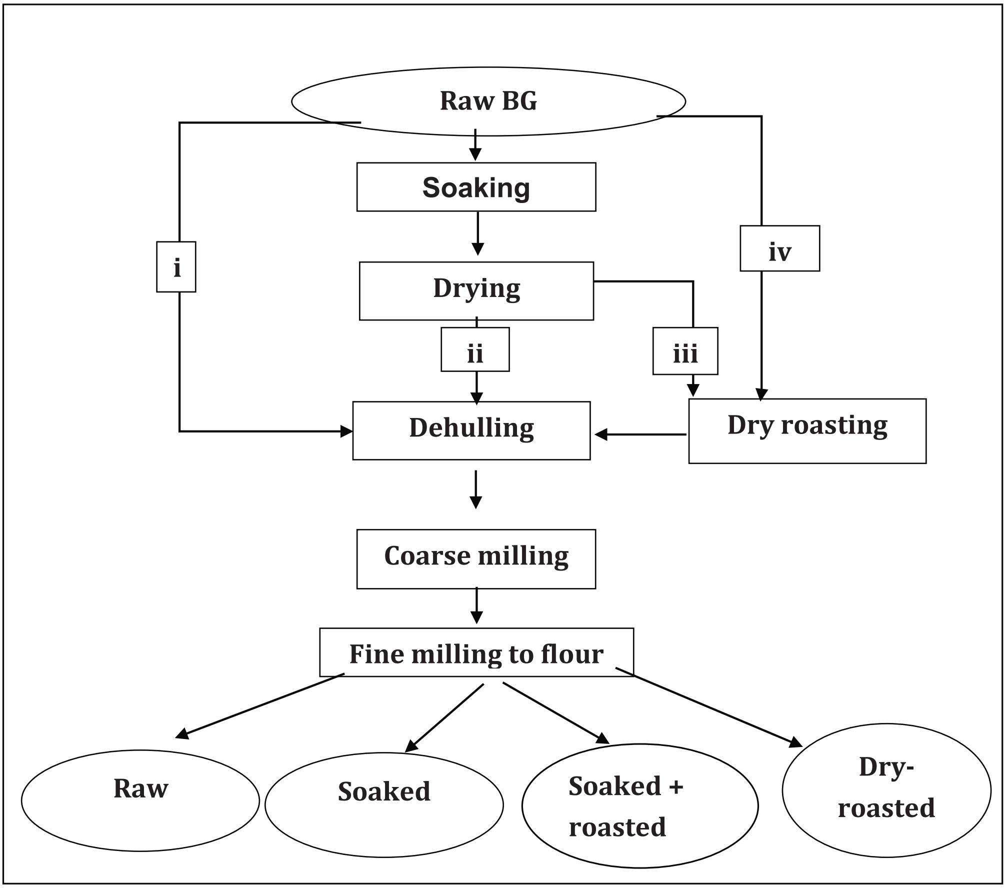


Fig 6.1 Pre-treatments of bambara groundnut before coarse and fine milling to flour

2.3.2. Least gelation concentration

Least gelation concentration (LGC) was determined in triplicate according to Coffmann and Garcia [294].

2.3.3. Pasting properties

Pasting properties were determined according to Afolabi [295] using a Rapid Visco Analyser (RVA 4500 Perten instruments, SIN 214 31208-45A, Australia). A suspension of 3 g of flour in 25 ml distilled water was subjected to controlled heating and cooling cycle under constant shear. During this cycle samples were held at 50°C for a minute, heated from 50 to 95°C at 6°C/min, held at 95°C for 5 min, cooled to 50°C at 6°C/min, and held at 50°C for 5 min. The pasting temperature, peak viscosity, trough viscosity, breakdown viscosity, final viscosity and setback viscosity (SB) values were obtained from the RVA curves and viscosity was expressed as centipoise units (Cp).

2.3.4. Foaming capacity and stability

Foaming capacity (FC) and stability (FS) were determined in triplicate as whip-ability of flour dispersed in water according to Coffmann and Garcia [294]. Flour (5 g) was dispersed in 100 ml of deionised water and blended for 5 min using a Waring Laboratory blender at high speed. The blended mixture was poured into a 250 ml graduated cylinder and total height and height of the emulsion layer were measured immediately and after 1, 2, 4 and 6 h of room temperature incubation. FC and FS were calculated according to Eltayeb, Ali [296].

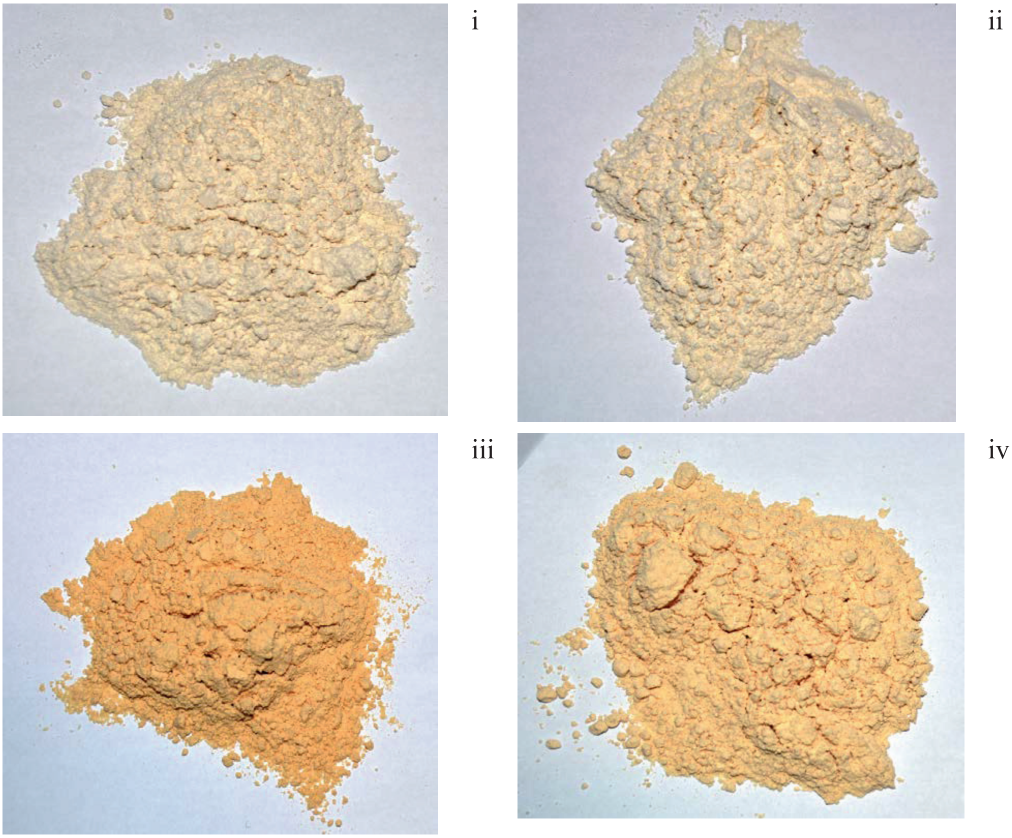


Fig 6.2 Bambara groundnut flour produced from a red variety after i) no pre-treatment (raw), ii) soaking, iii) soaking followed by dry roasting and iv) dry roasting.

2.3.5. Emulsification capacity and emulsion stability

Emulsification capacity (EC) and emulsion stability (ES) were determined according to Chaparro Acuña, Gil González [297] with some modifications. Flour samples (0.4 g), 20 ml of maize oil (0.9 ml/g) and 20 ml water (1.0 ml/g) (resulting in a 1% (w/v) mixture) were homogenized for 1 min using a Waring blender at low speed. Thereafter, the mixture was centrifuged for 10 min at 1600 rpm and the height of the total content (TC) and the height of the emulsion layer

(ELH) were measured. EC was determined by heating the sample at 80°C for 30 min.

2.3.6. Water and oil holding capacity

Water and oil holding capacity (WAC and OAC) were determined using the method of Diedericks and Jideani [298].

2.4. Statistical analysis

Results were analysed and expressed as mean values with standard deviations. Two-way ANOVA statistical analysis was performed to determine significant differences amongst means. When significant differences ($p < 0.05$) were found, results were compared using a post-hoc test (Tukey). All statistical analyses were run using SPSS v 23.0 software.

3. Results and discussion

3.1. Effect of variety and pre-treatment on milling properties, colour and chemical composition of flour

3.1.1. Gravimetric and milling properties of raw and pre-treated seeds

Table 6.1 shows the variation of gravimetric and milling properties of raw pre-treated BG seeds. All pre-treatment methods decreased both the bulk and true density. This can be attributed to a higher rate of increase in seed volume than weight [288, 299]. Porosity of seeds ranged between 41-51%; in both varieties, soaking decreased seed porosity significantly agreeing with Sreerama, Sashikala [300], whereas insignificant porosity variation was found in dry roasting and combined soaking and roasting treatments. According to Malik and Saini [299], a decrease in moisture content of seeds should be correlated to the decline in porosity as shown by the decline in moisture in all pre-treated seeds. However, an exception was in dry roasted red BG. Data of porosity are important to determine size reduction properties and the resistance to airflow during aeration and drying procedures such that a low porosity means a low heat transfer [153]. The significance of the observed results on porosity is that the raw and pre-treated seeds will differ in size reduction properties, which will affect homogeneity of particle size and the functional properties of flour.

Raw seeds are very difficult to mill (HTM properties) as shown by a DE (%) of less than 15%, which increased to 83-88% when a dehulling pre-treatment was adopted. Fig 6.3 shows the images of raw and treated seeds, which display the differences in cotyledon and seed coat attachment. The low DE (%) of raw seeds is because the seed coat is strongly attached to the cotyledon, which makes removal difficult without pre-treatment [287]. However, treatment causes important changes. An insignificant effect of variety and pre-treatment ($p > 0.05$) on DE (%) found suggests that all pre-treatment methods were equally useful in managing the HTM characteristic. The positive effect of soaking on DE (%) in the current study agrees with the 81-88% reported by Enwere and Hung [28].

Milling efficiency of raw coarse milled seeds increased after pre-treatment of seeds from 65% to 70-75% showing little distinction between varieties and methods, implying the applicability of all pre-treatments in circumventing HTM properties. Fig 6.4 shows the variation in particle size distribution of raw and pre-treated flour whereby a bi-modal distribution was evident in some red variety flours, agreeing with [301]. From the distribution curve, parameters d_{10}, d_{50} and d_{90}, which represent the diameter of 10, 50 and 90% of the population of the particles, are represented in Table 6.1. Ten percent of all samples had a diameter between 7.1-11 µm, 50% between 30-51 µm and 90% between 125-175 µm. As there were insignificant differences in 90% of the particle size, we expect a negligible effect of particle size on the characteristics imparted to the food products.

3.1.2. Colour of raw and pre-treated flour

Table 6.2 also shows ΔE^*_{ab}, chroma and hue values of flour made from red and black-eye varieties using different pre-treatment methods. Colour changes during roasting are ascribed to Maillard reactions occurring during roasting [37], influencing ΔE^*_{ab}, chroma and hue values of flour. The ΔE^*_{ab} specifies differences between colour of control sample (raw) and pre-treated flour [302]. The ΔE*ab (0.14) of black-eye seeded raw and soaked flour shows that differences between flour were not perceptible by human eye. However, the ΔE*ab (1.2) of red seeded raw and soaked flour shows that differences between flour were perceptible through close observation. Exclusive roasting, combined soaking, and roasting processes are shown to have an effect on the colour of flour in both varieties such that colour differences from raw flour were perceptible at a glance. Even though soaking prior to roasting reduced ΔE*ab of flour of both varieties, differences in colour between exclusively roasted and combined soaked and roasted flour were still easily perceptible (ΔE*ab, 4.2-4.7).

Chroma indicates the degree in which a colour differs from the neutral colour of the same value whilst hue is defined as perception of colour of an object (i.e. red, orange, green, blue) [302]. Just like ΔE*ab trends, pre-treatments caused significant differences in chroma and hue ($p > 0.05$). Dry roasting resulted in higher chroma values than other processes whereas an opposite trend was observed for hue, with roasting decreasing hue values in both varieties. Colour differences are relevant as they affect consumer acceptability of products.

Table 6.1 Gravimetric and milling properties of bambara groundnut flour made from a red and a black-eye variety.

Variety	Pre-treatment method	Bulk density	True density	Porosity ε	Dehulling	Milling	D_{10}	D_{50}	D_{90}
		(g/cm³)		(%)	Efficiency (%)		Particle size diameter (µm)		
Red	Raw	0.63 ± 0.01^{d}	1.23 ± 0.16^{ab}	48.5 ± 6.1^{a}	< 15%	66.0 ± 2.8^{a}	10.4 ± 0.3^{c}	36.3 ± 1.3^{ab}	134.2 ± 14.1^{a}
	Soaked	0.58 ± 0.02^{bc}	1.04 ± 0.20^{ab}	42.4 ± 13.2^{a}	84.2 ± 1.9	73.2 ± 4.3^{b}	7.1 ± 0.3^{a}	30.5 ± 1.4^{a}	129.1 ± 8.9^{a}
	Dry roasted	0.58 ± 0.02^{ab}	1.21 ± 0.20^{ab}	51.1 ± 10.5^{a}	83.8 ± 2.5	72.1 ± 2.3^{ab}	9.7 ± 0.6^{bc}	43.3 ± 2.6^{bcd}	146.9 ± 23.1^{a}
	Soaked + roasted	0.56 ± 0.01^{ab}	1.05 ± 0.17^{ab}	45.6 ± 8.8^{a}	83.1 ± 4.1	74.3 ± 2.9^{b}	10.6 ± 1.4^{c}	48.6 ± 8.6^{cd}	174.1 ± 51.8^{a}
Black-eye	Raw	0.65 ± 0.02^{d}	1.36 ± 0.16^{b}	51.6 ± 5.0^{a}	< 15%	65.9 ± 4.2^{a}	8.5 ± 0.2^{ab}	31.8 ± 0.8^{a}	125.0 ± 1.8^{a}
	Soaked	0.54 ± 0.01^{a}	0.92 ± 0.02^{a}	41.4 ± 2.6^{a}	88.0 ± 6.0	72.3 ± 2.6^{ab}	10.9 ± 0.6^{c}	39.2 ± 2.6^{abc}	152.3 ± 29.3^{a}
	Dry roasted	0.62 ± 0.01^{cd}	1.16 ± 0.02^{ab}	46.7 ± 1.6^{a}	85.7 ± 3.6	70.5 ± 0.8^{ab}	9.8 ± 1.6^{bc}	44.3 ± 11.1^{bcd}	164.3 ± 39.5^{a}
	Soaked + roasted	0.57 ± 0.01^{ab}	1.19 ± 0.12^{ab}	51.4 ± 5.2^{a}	85.4 ± 4.0	72.3 ± 1.8^{ab}	10.8 ± 1.2^{c}	51.3 ± 5.4^{cd}	152.3 ± 30.7^{a}

Similar superscripts in columns (a, b, c and d) indicate means that are not significantly different ($p > 0.05$).

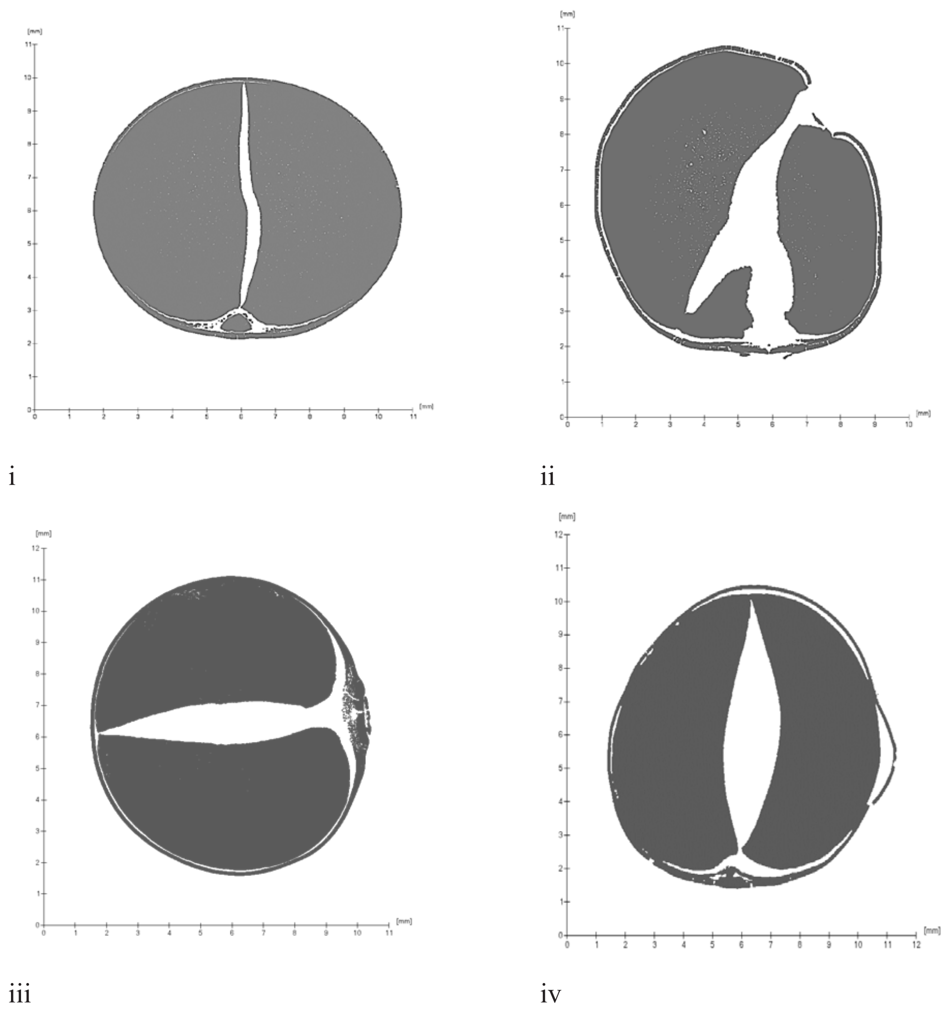
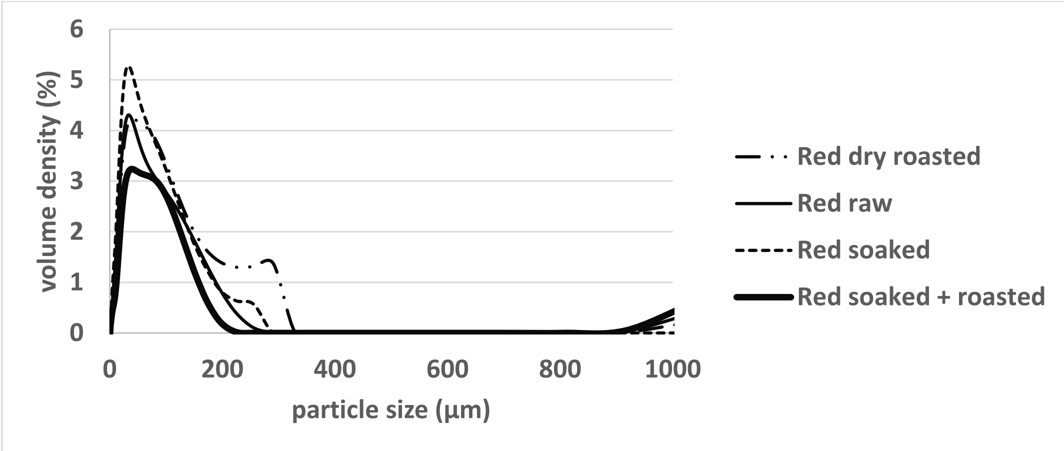


Fig 6.3 Image analysis of raw and pre-treated black-eye seeded bambara groundnut seeds (i) raw, (ii) soaked, (iii) dry roasted, and (iv) soaked and roasted. The image shows the distinction in the attachment of seed coat to the cotyledon after pre-treatment. In (i) raw seeds, the seed coat and cotyledon are intact as compared to ii) soaked and (iv) soaked and roasted.

(i)



(ii)

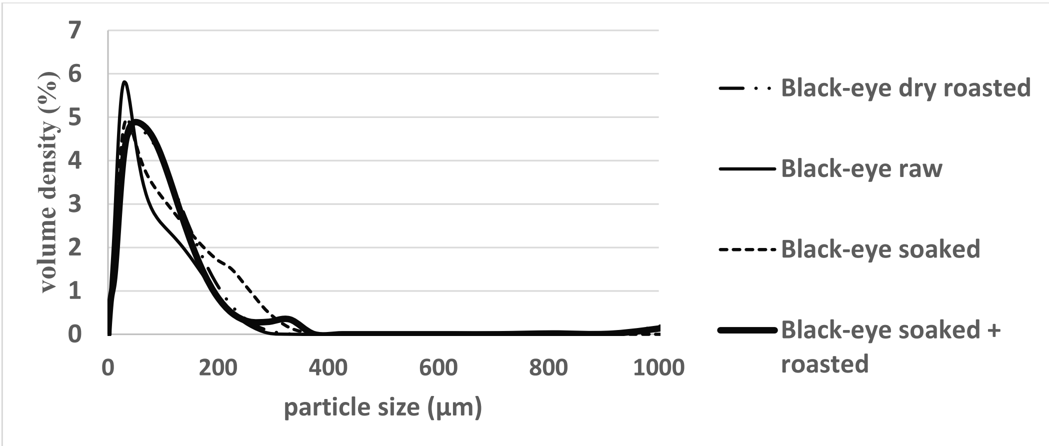


Fig 6.4 Particle size distribution of raw and pre-treated bambara groundnut flour from (i) a red and (ii) a black-eye variety

3.1.3. Chemical composition of raw and pre-treated flour

Table 6.3 shows the chemical composition of flours from raw and pre-treated red and black-eye varieties. Pre-treating seeds decreased moisture content of flour, as also reported by Yusuf, Ayedun [208]. Moisture content of flour from red and black-eye seeds, i.e. 7.7 and 9.1%, respectively, was lower than the 11.3-11.6% reported by Kaptso, Njintang [303], but higher than the 4.3% reported by Yusuf, Ayedun [208].

Table 6.2 Colour of bambara groundnut flour made from red and black-eye seeded varieties

Variety	Pre-treatment method	Chroma (C*)	Hue (h°)	[1]ΔE*ab
Red	Raw	10.4^{a}	1.51^{e}	control
	Soaked	11.5^{a}	1.55^{f}	1.2
	Dry roasted	21.1^{e}	1.39^{b}	12.6
	Soaked + roasted	17.8^{c}	1.45^{d}	8.3
Black-eye	Raw	12.6^{b}	1.57^{g}	control
	Soaked	12.7^{b}	1.56^{g}	0.14
	Dry roasted	22.8^{f}	1.37^{a}	13.3
	Soaked + roasted	19.4^{d}	1.44^{c}	8.6

[1]ΔE*ab colour interpretation: < 1 means not perceptible by the human eye, 1-2 means perceptible through close observation, 2-10 means perceptible at a glance, 11-49 means colours are more similar than opposite and 100 means colours are exact opposites. Similar superscripts in columns (a, b, c, d, e. f and g) indicate means that are not significantly different ($p > 0.05$).

Protein content of flour from both varieties ranged from 15.6-19.6 g/100 g DW using a factor of 5.7 to convert nitrogen to protein. In previous studies 6.5 was used [242, 304]. The general use of 6.25 as N:P conversion factor is criticised because this disregards variations in non-protein nitrogen and variable percentages of nitrogen in individual proteins [304]. Yet the protein content of raw BG in this study is in line with the 17.8-19.7 g/100 g DW [149, 303], but lower than the 25 g/100 g reported by Brough, Azam-AIi [206]. The protein content of the flour of the red variety was significantly higher than that of the black-eye variety ($p = 0.00$), implying that choice of variety matters [37]. Moreover, pre-treatments significantly increased the protein content of flour of both varieties ($p = 0.001$). However, as expected, no significant differences between pre-treatments were observed ($p = 0.98$) as thermal treatments do not change the amount of proteins.

The fat content of flour, which ranged from 7.0 to 8.6 g/100 g DW, agrees with the 6.0-10.4 g/100 g reported by Yusuf, Ayedun [208]. Fat content of the flour of the black-eye variety was significantly higher than that of the red variety ($p = 0.027$). As expected, no differences in fat content due to pre-treatments ($p = 0.153$) were observed. The low fat content in flour of raw seeds is ascribed to the larger amount of hulls as a result of poor dehulling efficiency, which lowered the fat content as hulls contain nearly no fat [305].

The starch content in flour from raw red and black-eye seeds, i.e. 50.4 and 49.8 g/100 g DW, respectively, is comparable to the 39-50% reported by Poulter [142], but lower than the 56.9-58.3 g/100 g DW reported by Deshpande, Sathe [306]. This dissimilarity is attributed to varietal differences [142], cultivation conditions [272] and analytical methods [143]. In comparison to other legumes, total starch content was comparable to the 41-44% in raw lentil, chickpea and red kidney beans [266], but higher than the 31-38% in raw cowpea [274].

The starch content of the red variety decreased significantly ($p = 0.000$) due to pre-treatment contrary to trends in pre-treated black-eye flour. The exhibited opposite behaviour in varieties is attributed to differences in the rate of starch hydrolysis due to presence of fibre, possible presence of natural enzyme inhibitors during analysis and inherent differences in starch structure and composition [307, 308]. Insignificant differences in starch content between pre-treatments ($p = 0.792$) were found, implying that differences observed in starch after pre-treatment were only due to varietal differences.

Fructose and sucrose contents ranged from 0.18 to 0.33 g/100 g DW and 1.9 to 5.0 g/100 g DW, respectively. Soaking decreased sucrose in both varieties, but the effect was more pronounced in the black-eye variety, which initially had a higher sucrose content. The current findings agree with Adebowale, Awolala [144], who also observed a decrease in carbohydrate content by soaking as well varietal differences. Longland, Barfoot [309] found that soaking affected both fructose and sucrose concentrations, but only sucrose in a significant manner. Significant differences in sucrose content between varieties ($p = 0.021$) were observed as opposed to insignificant effects on fructose ($p = 0.145$). Conversely, a significant difference was present between pre-treatments regarding sucrose and fructose contents ($p > 0.05$).

The ash content, which ranged from 2.5 to 3.2 g/100 g DW, agrees with the 2.8 g/100 g and 3.6-3.8 g/100 g DW reported by Abiodun and Adepeju [29] and Kaptso, Njintang [303], respectively. All pre-treated flours had a higher ash content than the flour from raw seeds, agreeing with Nti [37], who reported an increase in ash content after dehulling. The effect of pre-treatment on ash content was significantly higher in the red variety than in the black-eye variety ($p = 0.000$). Within pre-treatments, only the roasted and combined soaking and roasted flour had comparable ash contents. The flour from soaked seeds had a lower ash content.

3.2. Effect of variety and pre-treatment on functional properties of flours

3.2.1. Thermal properties

Gelatinization temperatures and enthalpies of flours are presented in Table 6.4. According to Krueger, Knutson [310] and Tester [311], gelatinization temperatures are related to characteristics of the starch granule, such as the degree of crystallinity, starch composition and molecular structure of amylopectin. Gelatinization describes the irreversible disruption of molecular order within a starch granule when heated in excess water. The (T_0) of raw flour, i.e. 77.1 and 76.9°C, was comparable to 76.8°C reported by Sirivongpaisal [312], but higher than the 67.4-71.2°C reported by Kaptso, Njintang [303]. The substantial differences observed indicate differences in the starch granule, such as a more rigid granular structure in the red variety [313]. Lower onset (T_0) and peak (T_p) temperatures were obtained in the study as compared to cowpea (T_p= 86°C) [314]. Enthalpy of gelatinization (ΔH) of flour from raw seeds of the two varieties (4.1 and 4.8 J/g) was lower than the 6.0-9.7 J/g reported by Sirivongpaisal [312] and Kaptso, Njintang [303].

Table 6.3 Chemical composition of differently processed flours of a red and a black-eye bambara groundnut variety

Variety	Flour type	Moisture	Protein	Fat	Starch	Sucrose	Fructose
					g/100g DW		
Red	Raw	7.7 ± 0.0^{cde}	17.1 ± 0.1^{a}	7.0 ± 0.0^{a}	50.4 ± 0.6^{ab}	3.09 ± 0.38^{ab}	0.31 ± 0.02^{a}
	Soaked	7.7 ± 0.5^{cde}	19.4 ± 0.3^{b}	7.9 ± 0.1^{ab}	48.3 ± 0.6^{a}	2.24 ± 0.09^{a}	0.30 ± 0.00^{a}
	Dry roasted	6.1 ± 0.3^{abc}	19.6 ± 0.1^{b}	8.2 ± 0.0^{b}	48.3 ± 0.6^{a}	3.63 ± 0.12^{bc}	0.32 ± 0.02^{a}
	Soaked and roasted	5.0 ± 0.2^{a}	19.5 ± 0.4^{b}	8.5 ± 0.1^{b}	47.8 ± 0.3^{a}	2.35 ± 0.07^{a}	0.23 ± 0.01^{a}
Black-eye	Raw	9.1 ± 0.2^{e}	15.6 ± 1.4^{a}	7.6 ± 0.7^{ab}	49.8 ± 0.4^{ab}	4.42 ± 0.71^{c}	0.23 ± 0.07^{a}
	Soaked	8.0 ± 0.2^{de}	17.1 ± 0.0^{a}	8.3 ± 0.0^{b}	52.0 ± 0.7^{b}	1.94 ± 0.03^{a}	0.26 ± 0.01^{a}
	Dry roasted	6.9 ± 0.9^{bcd}	17.0 ± 0.2^{a}	8.6 ± 0.3^{b}	51.4 ± 0.5^{b}	4.65 ± 0.23^{c}	0.32 ± 0.01^{a}
	Soaked and roasted	5.9 ± 0.5^{ab}	17.2 ± 0.0^{a}	8.6 ± 0.0^{b}	51.6 ± 1.3^{b}	2.14 ± 0.08^{a}	0.27 ± 0.01^{a}

All values are means ± standard deviations of duplicate analysis . Similar superscripts in columns (a, b, c and d) indicate means that are not significantly different ($p > 0.05$).

Pre-treatments increased gelatinization temperatures, indicating alterations in starch granule characteristics. In all cases, a significant effect of variety on gelatinization temperatures ($p > 0.05$) was observed. Basically, flour from the red variety had higher gelatinization temperatures than flour from the black-eye variety. Furthermore, a significant effect of pre-treatments on gelatinization temperatures ($p > 0.05$) was revealed. Pre-treatments resulted in similar values peak (T_p) temperatures for both varieties, indicating that heat treatment hardly affected (T_p). Pre-treated flour increased enthalpy of gelatinization (ΔH) and the same statistical trend as for gelatinisation temperatures was observed.

Gelatinization improves stiffening abilities of flour. In food applications, good gelatinization properties are important for thickening of soups and porridge [315]. During pre-treatment, lower gelatinization temperatures are therefore desirable, because of the lower energy requirements. However, differences in gelatinization temperature were fairly small, indicating a low variability in thermal properties of molecules, including starch granules that make up each variety [303]. Furthermore, differences between the onset and end temperature (T_e-T_0) were small, reducing the importance of this flour characteristic for food applications.

3.2.2. Least Gelation Concentration (LGC)

Table 6.4 shows the Least Gelation Concentration (LGC) of flour, which is defined as the lowest concentration of flour to form a self-supporting gel [75, 294]. Flour with a lower LGC has a greater gelling capacity. Gelation occurs due to protein denaturation, causing formation of hydrogen and ionic bonds stabilizing the gel and gelatinization of starch with other factors [293, 316]. Current LGC values, which varied from 6 to 10%, were comparable to the 8% reported by Eltayeb, Ali [296], but lower than the 12, 16 and 28% previously reported [208, 317, 318]. In comparison to other legumes, LGC of BG was higher than the 4% in groundnut [319], but lower than the 17% in cowpea [320].

Generally, black-eye flours had the least LGC values as compared to the red variety flours. This is credited to thee higher starch content of flours from the black-eye variety. Moreover, differences are also ascribed to variations in the relative ratio of protein and lipids and the interaction between these components [321]. In both varieties, roasting had a negative effect on LGC, but the effect was more pronounced in the red variety. The higher LGC in roasted samples is attributed to protein denaturation and dissociation because of the high roasting temperature (179°C). Protein subunits resulting from dissociation might not be favourable to form hydrogen and ionic bonds [322] required for gelation. Occurrence of Maillard reactions may have induced insoluble complexes that can result in reduced solubility [323].

Relative to simple sugars, Evageliou, Richardson [293] showed that the sucrose concentration has a marginal effect on LGC. In the current study, sucrose is the only factor that was changed by soaking, explaining why LGC of soaked flour does not differ much from raw flour. Gelation is important in creating texture in many food products, such as yogurt, processed meats and gelatin-based products [324]. All BG flours would do adequately in these products due to their low LGC, with roasted BG being the poorest performer.

3.2.3. Pasting properties

Pasting properties of raw and pre-treated bambara groundnut varieties are shown in Fig 6.5. Pasting includes the changes that occur after gelatinization upon further heating. These consist of further swelling of granules, leaching of molecular components such as amylose from the granules and eventual disruption of granules [325]. The properties of the swollen granules and the soluble materials leached from the granules control the viscosity parameters during pasting [326]. All pre-treatments decreased peak viscosity, except in combined soaking and roasting of the black-eye variety.

Peak viscosity indicates the water-binding capacity of the starch whereby the gelatinized starch reaches its maximum viscosity during heating in water

[327]. Currently, insignificant differences were observed, implying that different treatments did not influence peak viscosity. High peak viscosity maybe suitable for products requiring high gel strength and elasticity. Moreover, a high peak viscosity indicates thermal stability of the flour, implying potential use in products requiring sterilization [328]. Trough viscosity measures the ability of the paste to withstand breakdown during cooling. It is the minimum viscosity value in the constant temperature phase of the Rapid Visco Analyser (RVA) pasting profile. Trough viscosity decreased in flours of the red variety, whereas an insignificant increase was recorded for the black-eye variety. High trough viscosity implies that the flour has the ability to remain undisrupted when subjected to a hold period of constant high temperature and mechanical stress by rapid and continuous mixing [327]. The breakdown viscosity in the pasting profile indicate the degree of disintegration of granules or paste stability. Less stable starch paste is commonly accompanied with a high value of breakdown. The higher the breakdown value, the lower the ability to withstand heating and shear stress during cooking. As low breakdown values are associated with stable gruels, soaked flour of both varieties resulted in stable pastes, whilst flours from the combined soaking and roasting pre-treatment resulted in unstable pastes for both varieties.

The final viscosity indicates the ability of the starch to form a viscous paste or gel after cooling. Final and setback viscosity decreased significantly in both varieties due to roasting, while an insignificant decrease was recorded in soaked flour of both varieties. Low final viscosity implies that flour will form a low viscous paste rather than a thick gel on cooking and cooling. Nutritionally, this means a high calorific density for a low volume [327]. The setback viscosity indicates the syneresis of starch upon the cooling of the cooked starch pastes [326]. High setback values are associated with a cohesive paste. Therefore, the higher the setback viscosity, the lower the retrogradation during cooling and the lower the starting of retrogredation for a product made from the flour.

Table 6.4 Gelatinization, LGC and pasting properties of differently processed flours of a red and a black-eye bambara groundnut variety

Variety	Flour type	Onset T (°C)	Peak T(°C)	End T (°C)	ΔH (J/g)	LGC (%)	Peak	
							Time	Temperature
Red	Raw	77.1 ± 0.7^{ab}	81.3 ± 0.7^{ab}	85.7 ± 0.5^{a}	4.8 ± 0.3^{ab}	8	6.98 ± 0.04^{c}	84.3 ± 0.5^{a}
	Soaked	78.4 ± 0.6^{bc}	82.6 ± 0.5^{bc}	87.4 ± 0.3^{abc}	4.5 ± 0.4^{ab}	7	7.00 ± 0.00^{c}	83.8 ± 0.4^{a}
	Dry roasted	78.8 ± 0.1^{c}	83.0 ± 0.0^{c}	88.0 ± 0.2^{bc}	5.2 ± 0.2^{ab}	10	5.36 ± 0.15^{a}	83.4 ± 0.5^{a}
	Soaked + roasted	78.3 ± 0.1^{bc}	82.8 ± 0.1^{c}	88.8 ± 0.2^{c}	5.6 ± 0.0^{b}	6	5.25 ± 0.04^{a}	83.8 ± 0.5^{a}
Black-eye	Raw	76.9 ± 0.0^{a}	81.0 ± 0.2^{a}	85.7 ± 0.6^{a}	4.1 ± 0.5^{a}	6	6.98 ± 0.04^{c}	84.0 ± 0.1^{a}
	Soaked	77.1 ± 0.1^{ab}	81.6 ± 0.3^{abc}	86.6 ± 0.3^{ab}	4.1 ± 0.5^{a}	6	7.00 ± 0.00^{c}	83.6 ± 0.5^{a}
	Dry roasted	78.6 ± 0.4^{c}	82.5 ± 0.1^{bc}	87.6 ± 0.5^{abc}	5.1 ± 0.0^{ab}	8	6.31 ± 0.54^{b}	73.9 ± 16.8^{a}
	Soaked + roasted	77.9 ± 0.1^{abc}	81.8 ± 0.5^{abc}	87.6 ± 0.8^{abc}	5.0 ± 0.0^{ab}	6	5.15 ± 0.04^{a}	72.8 ± 17.9^{a}

All values are means + standard deviations of duplicate analysis for gelatinization and triplicate for LGC, peak time and peak temperature.
T_0 is gelatinization onset temperature, T_p is gelatinization peak temperature, T_e is end of gelatinization temperature, and ΔH is enthalpy of gelatinization.
Similar superscripts in columns (a, b, c and d) indicate means that are not significantly different ($p > 0.05$).

Pasting temperature provides an indication of the minimum temperature required to cook a flour (Table 6.4). High pasting temperatures indicate a high water-binding capacity, gelatinization tendency, and lower swelling property of a starch-based flour due to a high degree of association between starch granules. Pasting temperature did not change much in the flours of the red variety, but decreased in both varieties. Peak time was decreased in dry roasted and combined soaked and roasted flour of both varieties, whilst soaking slightly increased it.

Table 6.5 Functional properties of differently processed flours of a red and a black-eye bambara groundnut variety

Variety	Pre-treatment method	EC (%)	ES (%)	FC (%)	FS (%)
Red	Raw seeds	49.1 ± 2.7^{d}	47.9 ± 1.0^{cd}	10.8 ± 1.9^{bcd}	79.0 ± 11.1^{cd}
	Soaked seeds	46.5 ± 1.4^{cd}	46.5 ± 1.6^{cd}	18.3 ± 1.9^{ef}	79.1 ± 10.9^{cd}
	Dry roasted	40.7 ± 0.7^{b}	31.9 ± 0.7^{b}	3.3 ± 3.1^{a}	14.7 ± 4.8^{a}
	Soaked + roasted	48.8 ± 3.0^{d}	45.8 ± 3.4^{cd}	7.5 ± 2.5^{abc}	87.4 ± 3.8^{d}
Black-eye	Raw seeds	50.2 ± 1.4^{d}	45.2 ± 1.1^{c}	17.1 ± 1.9^{def}	63.0 ± 8.4^{bc}
	Soaked seeds	48.7 ± 0.0^{cd}	50.0 ± 0.6^{d}	22.9 ± 1.4^{f}	73.6 ± 5.7^{bcd}
	Dry roasted	29.7 ± 2.8^{a}	15.6 ± 2.2^{a}	5.8 ± 2.9^{ab}	0.0 ± 0.0^{a}
	Soaked + roasted	43.4 ± 0.7^{bc}	35.1 ± 0.8^{b}	12.9 ± 3.1^{cde}	57.2 ± 3.7^{a}

All values are means + standard deviations of triplicate analysis. Similar superscripts in columns (a, b, c and d) indicate means that are not significantly different ($p > 0.05$).

3.2.4. Emulsification properties

Emulsification capacity (EC) of raw and pre-treated flour ranged from 29 to 50% (Table 6.5). EC and emulsion stability (ES) are indices to evaluate emulsifying properties of flours. EC measures the amount of oil that can be emulsified per unit of flour, whereas ES measures the ability of the emulsion to resist changes to its structure over a defined period [75]. EC is mainly determined by the solubility of the proteins, but insoluble proteins play a role as well, as do polysaccharides

[329]. Protein can emulsify and stabilize an emulsion by decreasing the surface tension of the oil droplet and providing electrostatic repulsion on the surface of the oil droplet [330, 331]. EC of raw flours, i.e. 49.1 and 50.2%, was lower than the 65-69% of raw BG reported by Adebowale, Awolala [144]. In comparison to other legumes, EC was comparable to the 50% reported for pigeon pea [332].
ES of flours from raw seeds, i.e. 47.9 and 45.2%, were lower than the 70% reported for soaked BG flour by Adebowale and Lawal [317]. All pre-treatments significantly decreased EC and ES ($p > 0.05$), with roasting causing a greater decline, while soaking had little effect. Adebowale, Awolala [144] reported contrasting results on effects of soaking on EC of flour from black and cream BG varieties. Cold soaking decreased EC of cream variety flour, whereas an increase was observed in black variety flour. Currently, considering the varietal effect on EC, differences between combined soaking and roasting (46%), soaked flour (48%) and raw flour (50%) were small. Decreases in both EC and ES after roasting agree with Obatolu, Fasoyiro [333], who reported EC values ranging from 50.7% for raw to 20% for roasted beans and reported that processing resulted in significant reductions in EC for all treatments.

Good emulsification properties are important in many fat-containing food products, such as sausages, vegetable milk and milk-based products, as well as cake batters [331]. The negative effect of roasting on EC capacity and ES is ascribed to denaturation and dissociation of proteins and exposing hydrophobic regions, which increase surface tension [331]. Even though roasting reduced emulsification properties of BG flour, soaking prior to roasting seemed to mitigate the negative roasting effect. Soaking changes physical properties of flour, thereby decreasing the effect of heat treatments. The positive effect of soaking is ascribed to a change in thermal conductivity [334].

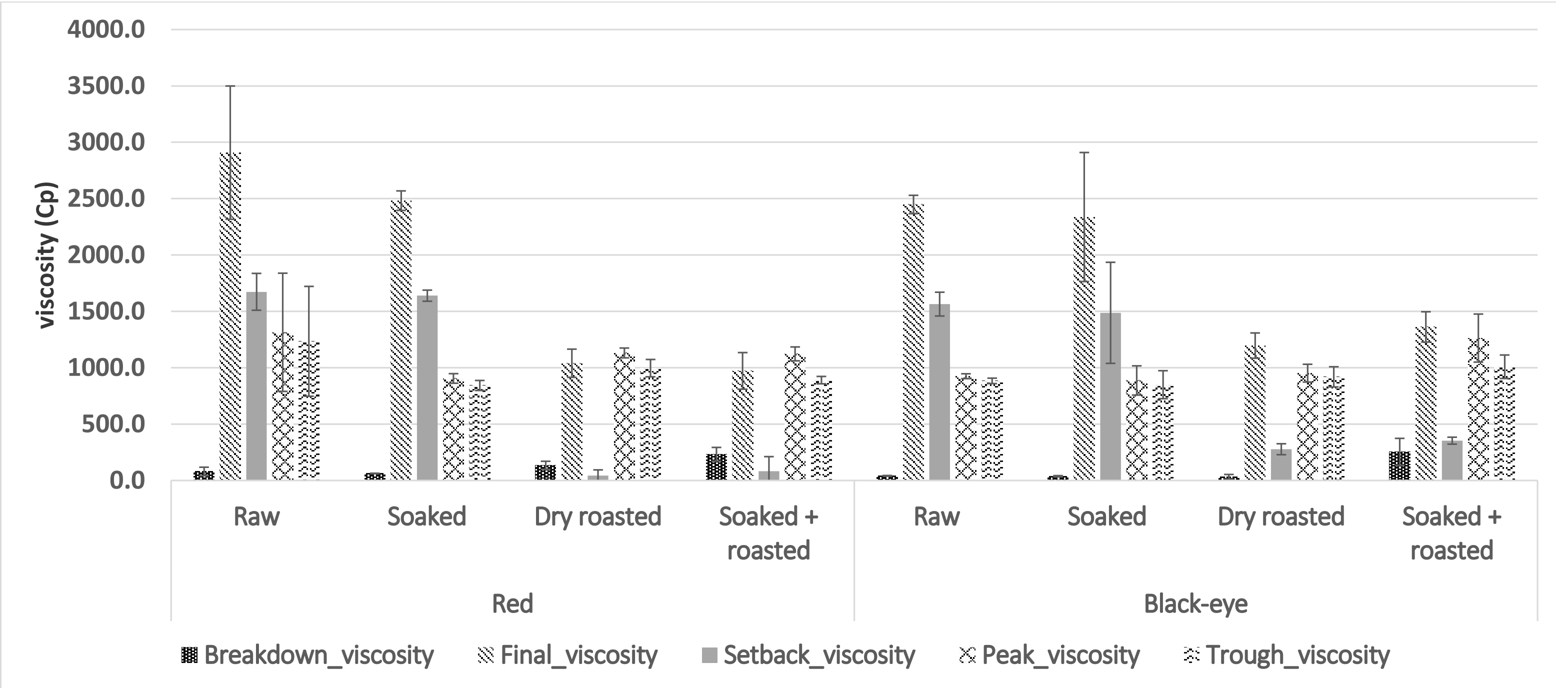


Fig 6.5 Viscosity properties of raw and pre-treated flours of a red and a black-eye bambara groundnut variety

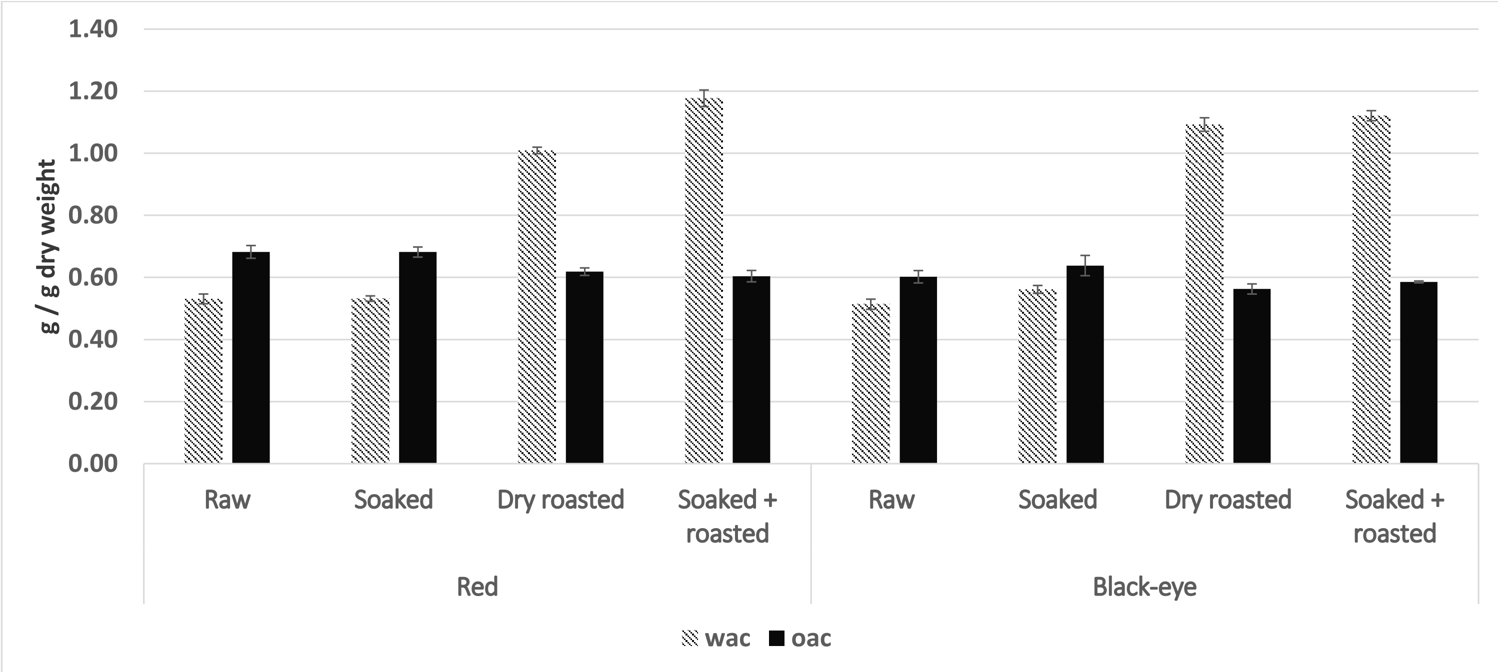


Fig 6.6 WAC and OAC properties of raw and pre-treated flours of a red and a black-eye bambara groundnut variety

3.2.5. Foaming properties

Foams can be defined as a colloidal dispersions in which gas is the dispersed phase and liquid is the continuous phase [329]. Foaming in flours is induced by trapping air in water and stabilized by a decrease of surface tension by proteins [331]. Foaming capacity (FC) of raw and pre-treated flours ranged from 3.3 to 22.9% (Table 6.5). FC of raw red and black-eye varieties, i.e. 10.8 and 17.1%, respectively, agrees with the 17-18% reported by Adebowale, Awolala [144]. In comparison to other legumes, FC was lower than for cowpea flour (40%) [256].

FC of the black-eye variety was significantly higher than of the red variety. FC was increased by soaking, whilst a decline was observed for roasting, agreeing with Obatolu, Fasoyiro [333] for roasted yam bean. Soaking prior to roasting counteracted the effects of roasting significantly in the black-eye variety, but not in the red variety. The effect of soaking on roasting is ascribed to the difference in heat transfer during roasting caused by soaking [335]. FS was comparable to the 80% after 1 h (with a FC of 70%) reported by Yusuf, Ayedun [208] and the 30% after 2 h [296]. FS of raw and soaked samples after 2 h was higher than for cowpea flour (71%) [256]. Roasting significantly decreased FS compared to soaked and raw flour. Soaking prior to roasting reduced the negative effect of roasting.

FC has been related to the amount of protein, with native protein having better foaming abilities than denatured protein [304]. This is due to the fact that proteins should be soluble in the aqueous phase, which happens most often at the isoelectric point [331]. Roasting is suggested to bring more hydrophobic areas of proteins to the surface, decreasing solubility. FC is important in food products such as cakes, soufflés and foams. Raw or soaked samples would be best for the production of this kind of products [331]. However, milder pre-treatment (70 – 80 °C) has also been reported to improve FC and FS by promoting denaturation to the extent that some hydrophobic regions of proteins come to the surface and resist reabsorption into the aqueous phase, making the protein film more dense [336].

3.2.6. Water and oil absorption

Water absorption capacity (WAC) of raw and pre-treated flours varied from 0.51 g/g to 1.12 g/g DW (Fig 6.6), which is lower than the 1.6 ml/g - 2.8 ml/g DW previously reported [296, 298, 317]. In comparison to other legumes, WAC of BG flour was lower than the 2.1 g/g reported for roasted cowpea flour [256]. Soaking and dry roasting in the current study increased WAC, in line with Yusuf, Ayedun [208] for BG and [256] for cowpea. A high WAC in flour is attributed to denaturation and dissociation of proteins during roasting, which leave more polar binding sites than native protein [337]. A higher WAC enables bakers to add more water to doughs, improving handling and maintaining freshness in bread [338]. When considering the average WAC for both varieties, differences between raw and soaked flour are marginal (0.52 and 0.54 g/g, respectively), and the same trend appears for the dry roasted and combined soaking and roasting treatment (1.0 g/g and 1.1 g/g, respectively). Further, only pre-treatments significantly affected the WAC ($p = 0.000$).

Oil absorption capacity (OAC) of flours ranged from 0.56-0.68 g/g, which is lower than 1.3-2.0 ml/g DW reported by Diedericks and Jideani [298] and Adebowale, Adeniyi Afolabi [339]. In comparison to other legumes, the OAC was comparable to the 0.8 g/g reported for soaked cowpea flour [340], but lower than the 1.9 g/g for raw cowpea flour [256]. All pre-treatments increased the OAC in the red variety, but the opposite trend was observed in the black-eye variety. The positive effects of roasting on the OAC of legumes, which were confirmed by Yusuf, Ayedun [208], and Onimawo and Akpojovwo [341], are ascribed to emerging new binding sites that result from the dissociation and denaturation of protein during roasting. Oil absorption is important in oil-containing solid products, such as meat, sausages and donuts [331].

4. Conclusion

All pre-treatment methods improved dehulling and milling efficiency of BG varieties cementing applicability in flour production. The decisive factor in selecting the preferred method for a specific food application has to focus on the sensorial, functional and nutritional properties of the flour. Colour was affected by roasting, such that roasted flour had a darker colour. Nutritionally, bambara groundnut flour compares with other legumes such as cowpea and chickpea. Varietal differences in chemical properties were minor, except for protein content and ash content, which were much higher in the red variety, making it considerably more nutritious. Consequently, pre-treatment is expected to have more effect on the functional properties of the red variety.

Differences in thermal properties due to varietal differences and pre-treatment methods were observed. The flours from the red variety had higher gelatinization temperatures as compared to the black-eye variety, whilst roasting caused a higher onset gelatinization temperature. Starch granule alterations are credited in the increase in gelatinization temperatures. Black-eye flours had lower LGC values than the red variety flours, which can be attributed to the higher starch content in the former.

Concerning food applications, the low emulsification and low foaming properties reported, suggests that BG flour is not suitable for food products that require a high percentage of porosity. Therefore, the solution to this will be blending with wheat to improve the properties. The high WAC of dry-roasted flour and combined soaked and roasted flour indicates usefulness of flour especially in food formulations involving dough due to its ability to absorb water and swell for improved consistency in food.

In conclusion, based on functional properties, both varieties are recommended for flour processing. No single processing method is optimal, but is determined by the intended application. Based on functional properties, the soaked and combined soaked and roasted flours are recommended for further research in product development and consumer acceptance of locally consumed food products such as porridge, soups, bread, cakes and fritters as illustrated in Fig 6.7. Nutrient enhancement of staple foods such as maize by blending with flour is also suggested as a way of increasing diversity while at the same time alleviating malnutrition problems faced by marginalised communities.

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	Raw (R)	Soaked flour (S)	Soaking + roasting (S+R)	Dry roasting (DR)	Key	Flour choice
Dehulling	-	+	+	+	+=good, - = bad	S, DR and S+R
Milling	-	+	+	+	+=good, - = bad	S, DR and S+R
Colour	+	+	+/-	+/-	+ = good, +/- =neutral	R and S flour
LGC	+	+	+	+-	+=good, +/- =neutral	Porridge R, S and S+R flour
Peak	↑	↑	↑	↑	↑ = high and equal	Porridge
Trough	↑	↑	↑	↑	↑ = high and equal	R and S flour
Breakdown	↓ -	↓ -	↑ +	↑ +	=Increase/ decrease +=good, - = bad	
Final	↑ +	↑ +	↓ -	↓ -	=Increase/ decrease +=good, - = bad	
Setback	↑ +	↑ +	↓ -	↓ -	=Increase/ decrease +=good, - = bad	
EC	+	+	+	-	+=good, - = bad	Bread, Cakes, R, S and S+R
FC	+	+	+	-	+=good, - = bad	Bread, Cakes, R, S and S+R
WAC	-	-	+	+	+=good, - = bad	Sausage fillers DR and S+R
OAC	-	-	+	+	+=good, - = bad	Sausage fillers DR and S+R

Fig 6.7 Potential applications of bambara groundnut flour in food products

Chapter 7

General discussion

7.1 Introduction

The necessity for countries in sub-Saharan Africa (SSA) to be self-sustaining in the fight against food and nutrition insecurity is of crucial importance to maintain their autonomy. The right balance between the growing demand for food and the use of the limited production capacity is the first step to be taken to achieve food security. Global technological improvements previously focused on increasing food production by using fertilizers, pesticides and water at the expense of the environment [3, 342]. Presently, at global scale, food production systems still continue to deplete natural resources and pollute the world ecosystems at a rate that is unsustainable for future generations. To counteract this destruction whilst ensuring food security for the SSA region and the world at large, researchers nowadays suggest pathways such as the development of sustainable food supply chains (SFSCs). This encompasses sustainable agriculture (primary food production), sustainable food processing leading to dietary diversity, as well as reducing waste in all stages of the food supply chain [343, 344]. The potential impact of applying SFSCs to solve food insecurity are superlative for the SSA region, and these should therefore be implemented. This is because, according to Lazaridesa [344], SFSCs aim at efficient production, processing and distribution systems that protect quality and enhance consumer access to wholesome and healthy food at reasonable prices. Moreover, SFSCs support sustainable development of rural communities, which is a requirement for food sovereignty. Food sovereignty is defined as the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems [345]. Thus, sustainable food processing is an integral part of any SFSC and food sovereignty, which promote the use of local raw materials, ingredients and local food recipes, as well as improve product acceptance and healthy food profiles (quality, nutritional value). Additionally, sustainable food processing has the mandate to improve product yield, minimize environmental impact and minimize the use of water through process modifications and minimize the use of energy [344].

Protein-rich foods from plant sources are more sustainable than foods rich in animal protein because the crops use many fewer natural resources and are less taxing on the environment [346]. One of these protein-rich plant sources is bambara groundnut. In SSA, this leguminous crop is third in importance after groundnut and cowpea. For many rural communities in drought-prone areas in SSA, its contribution to food and nutrition security is vital. In the bambara groundnut supply chain as shown in Fig 7.1, farmers benefit, among others, from improved soil fertility and other bambara groundnut farming by-products. However, improved soil fertility is insufficient incentive to stimulate cultivation and utilization of the crop. Income generation from trade, nutritional benefits and drought resilience are also respectable motivations. However, the agricultural and nutritional potential of bambara groundnut is presently threatened by the lack of dietary diversity due to inadequate processing methods. The limited utilization of bambara groundnut warrants the redesigning of alternative processing methods that fit local conditions. Still, redesigning traditional foods also requires caution and introspection to avoid product failure.

In the framework of promoting sustainable food processing to contribute to alleviating food and nutrition insecurity, this thesis explored the applicability and sustainability of bambara groundnut processing methods to circumvent the HTC phenomenon for resource-limited communities, a case of a SSA country, namely Zimbabwe. The hypothesis of the present project was that alternative sustainable processing methods can bring products that could constitute a suitable vehicle for the enrichment of the diet with protein, energy and minerals that are deficient in the current diet of the majority of poor rural communities.

The specific aim of the thesis were:

i. To understand how the development of the hard-to-cook phenomenon in legumes impacts on the utilization of bambara groundnut, focusing on technological solutions implemented during processing;

ii. To gather information and gain insights on the present bambara groundnut farming, processing techniques and consumption patterns in semi-arid regions of Zimbabwe;
iii. To investigate the role of legume polyphenols and their response to alkaline cooking during legume softening;
iv. To evaluate grit production as a processing strategy for a better utilization of bambara groundnut nutrients;
v. To assess the impact of variety and processing methods on the nutritional and functional properties of bambara groundnut flours and identify suitable uses.

This discussion chapter addresses the relevance of the study findings (see Table 7.1) in view of the current state of food security in Zimbabwe and the extent to which the objectives were achieved. The contribution of the current research to the SSA challenge of sustainable food and nutritional security are also addressed. Finally, recommendations are given that are specifically addressing the needs of resource-limited communities.

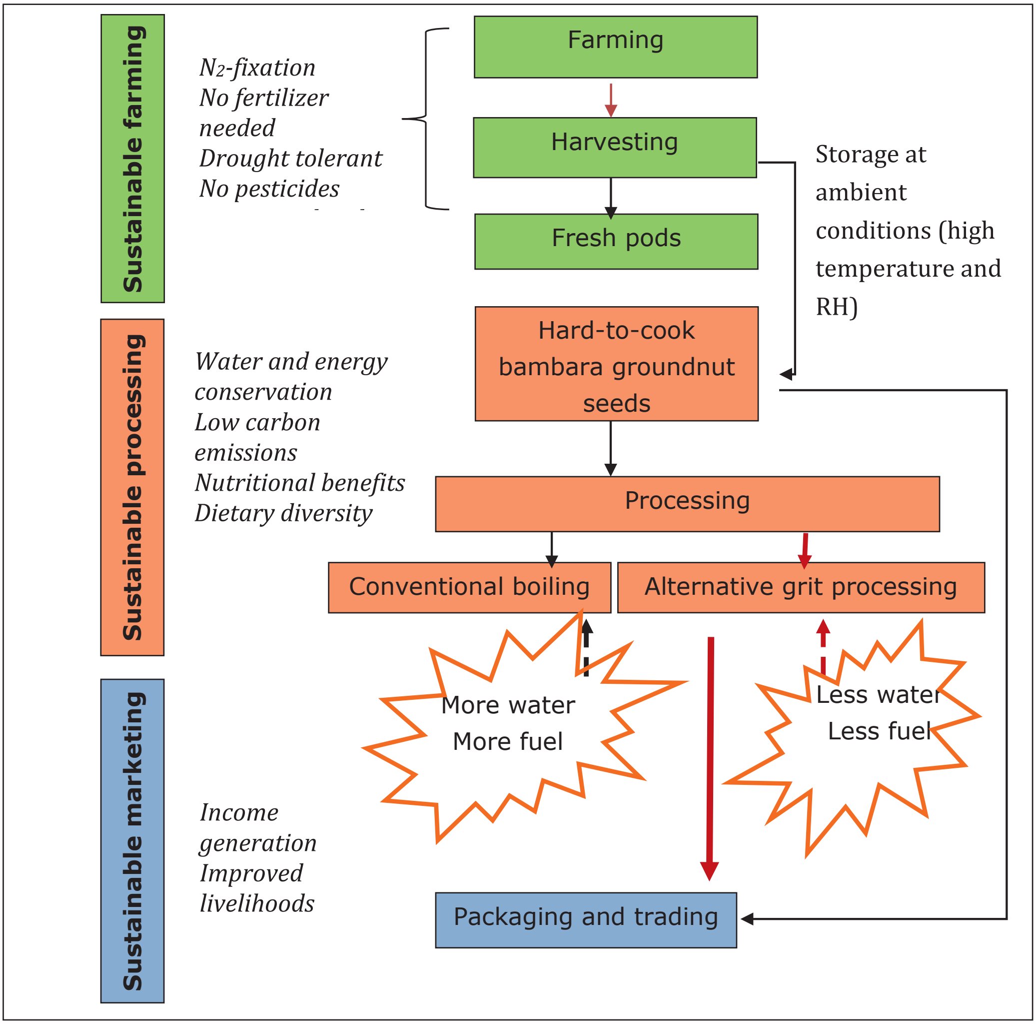

Fig 7.1 Bambara groundnut supply chain. Red arrows indicate sustainable route

Table 7.1 Summary of the main findings of this thesis.

Objective	*Main results*
Background investigation	
Chapter 2	
• To gather indigenous information on the present bambara groundnut processing techniques in selected rural communities. • To evaluate the processing techniques and choose the most sustainable methods.	• Boiling is the most common processing method, but other alternative products were found, which include the making of grits and flour. • Making of grits seems a promising alternative to boiling to circumvent HTC. Bambara groundnut flour has potential as an important intermediary product.
Chapter 3	
• To understand the development of the hard-to-cook (HTC) phenomenon in legumes. • To highlight the implications of HTC in the utilization of bambara groundnut and other legumes. • To review existing technologies in managing HTC and rank them based on sustainability and applicability.	• Storage conditions, and seed structural and compositional changes were implicated in HTC development. • Previous studies use different cooking aids to study the mechanism of softening. Contribution of pectates and protein in response to salt action during bean softening. • Implication of polyphenols in the softening mechanism.
Chapter 4	
• To study and evaluate the use of alkaline salts as a way of address the HTC phenomenon in the processing of bambara groundnut. • To understand the mechanism of softening with reference to polyphenols as indicators.	• Alkaline salts reduce cooking time sparingly. • Polyphenols (namely catechin and epicatechin) are indicators of softening.

Processing aptitude, nutrient quality and usefulness of products

Chapter 5	
• To evaluate grit production as a processing strategy for an optimal utilization of bambara groundnut nutrients. • To evaluate the effect of processing on the digestibility of protein, starch and bioaccessibility of minerals	• Processing aptitude of grits is better than boiling, no varietal significance, thus can be applied across varieties. • Mineral and starch digestibility were either comparable or higher than boiled seeds. Protein digestibility of grits was slightly lower than of boiled seeds. • Use of grits is offers new promising food options.
Chapter 6	
• To assess the impact of variety and processing methods on the nutritional and functional properties of bambara groundnut flour and suggest appropriate flour uses.	• Three types of flour with different functionalities. Products are suggested. • Methodology considerations are relevant.

7.2. Learning from indigenous knowledge on processing and utilisation of bambara groundnut

A recipe for failure in developing sustainable diets is redesigning traditional diets in rural communities, to e.g. circumvent the HTC phenomenon, without consultation and proper analysis of the socioeconomic setup and cultural habits. As already mentioned by Johnston, Fanzo [21], sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically affordable, nutritionally adequate, safe and healthy while optimizing natural and human resources. Indigenous Knowledge Systems (IKS) in food processing practices form a cornerstone of a community's collective wisdom passed through generations. Rural communities, especially women when to comes to food preparation, have ideas, strategies and tactics that work in their day-to-day processing of traditional foods in their socio-cultural framework. However, these strategies might just need perfection and propelling forward for adoption.

Based on this rationale, we report in **chapter 2** on a baseline survey conducted to understand Zimbabwe's bambara groundnut supply chain from farm to fork and to gain insight in how bambara groundnut fits among other indigenous legume crops and small grains. This meant documenting and comprehending farming aspects, storage practices, processing techniques as well as constraints, consumption patterns and preferred food attributes. The survey was carried out in semi-arid regions in natural agro-ecological regions III, IV and V, the driest parts of Zimbabwe, where most bambara groundnut is grown [50]. The locations were selected based on their importance in subsistence agriculture and on socio-cultural diversity. The research was not pursued in other SSA countries to limit research costs, thus Zimbabwe was designated as a model country representing southern SSA assuming that our findings apply to all the southern SSA countries. Essentially, the stakeholders of bambara groundnut were farmers, processors, consumers and traders. We found that the majority of farmers produce different crops on their farmland and they allocate land based on preferences and end use. Very often, these stakeholders played more than one role thus someone would be a farmer, a processor and a consumer, whilst also having a minor role as a trader. The impact of this observed multi-role system on the bambara groundnut supply chain needs further investigation. The surveys also showed that having a legume as part of the assorted crops is a common practice as a way of household resilience to drought and also because of the benefits of crop rotation as reported by Ncube, Twomlow [347]. Since the visited districts valued bambara groundnut, groundnut and cowpea differently, does this possibly mean that the current ranking of bambara groundnut as third in importance is perhaps outdated? This question calls for further research in detailing the ranking of indigenous legume crops and their importance in sustainable food security.

We also learnt that bambara groundnut processing in rural Zimbabwe was at household level and occasionally as a collective practice during functions or community activities. Constraints in conventional boiling methods did exist, as evidenced by a lack of diversity in the dishes. Some of the already known problems of legume processing such as long cooking time were reiterated, as well as problems to do with flatulence. Firewood shortages and water accessibility were reasons linked to underutilization as rural communities need to travel long distances to obtain these scarce resources. Processing methods including soaking, boiling, roasting, milling and several combinations of these methods to produce diverse products. Out of this product range, alternative, less utilized methods of processing with potential, included production of grits and flour, which is achieved after soaking, roasting or combined, soaking and roasting.

Consumption frequency was also reported for the different communities in semi-arid regions. Between 50-80% of respondents in all districts consumed bambara groundnut once to twice a week during the summer from July to December. This is an important time in Zimbabwe as it overlaps with the lean season during which food is generally scarce and communities are involved in land preparation and farming activities.

As a subsequent step, learning the causes of legume hardening and methods to circumvent HTC from other stakeholders, e.g. in other localities or countries, was suggested as well as evaluating the effects of processing on nutritional quality and consumer acceptance of products.

7.3. Towards understanding the development of the hard-to-cook (HTC) phenomenon in legumes and its impact on food security

In **chapter 2** we unveiled the agronomic and nutritional importance of bambara groundnut among other legumes. Analysis of agronomic data showed that most land in SSA countries is suitable for cultivation of drought tolerant crops such as bambara groundnut. Optimal use of this land would increase food production, thus covering the food deficit gap brought about by successive droughts and lack of farming inputs like fertilizers. Moreover, a comprehensive library for protein, carbohydrate and mineral contents revealed that the nutritional composition of bambara groundnut favourably compares to that of other legumes. Even though little information on vitamin contents was reported, it was concluded that the crop should be given the same value as other legumes like cowpea. Regardless of varietal-based nutritional differences previously quoted for i.e. protein, carbohydrates and fat content [37, 107], bambara groundnut is considered a complete food capable of supplying the necessary nutrients to meet the RDI of children and adults and offering communities resilience to the ravages of food insecurity. Irrefutably, malnutrition and micronutrient deficiencies are a major challenge in southern SSA [10], thus the region requires all the resources it can obtain.

Most reports confirmed that bambara groundnut is still underutilised. From the processing methods brought forward, the hard-to-cook phenomenon, which also manifests as hard-to-mill phenomenon, were said to be responsible for the difficulties faced by processors and consumers [70]. Our review also indicated that bambara groundnut seeds have different physical properties which can impact on scaling up or transferring of processing techniques. Moreover, the differences in physical properties, if not considered, can also mean processing failure. We recognized that before proposing techniques to manage the HTC phenomenon, the contributing factors to the HTC development needed to be understood. From data compiled from previous studies on other legumes and pulses, we understood that HTC develops due to climatic conditions experienced in SSA, i.e. hot and humid conditions [47]. Structural and compositional changes occurring in the seed coat and cotyledons were implicated in the development of the HTC phenomenon. The major structural changes observed under the scanning electron microscope were deteriorations in cytoplasmic contents of the cooked cotyledon. Compositional changes in starch structure, non-starch polysaccharides and composition, changes in composition of phenolic compounds resulting also in lignification, changes in protein structure and composition were also implicated [202].

Moving on with the quest to find HTC management solutions, the first port of call to managing HTC was low temperature and humidity storage (low temperature storage) [47]. However, this was obviously unattainable for those rural SSA communities who undeniably require the benefits of legumes. Therefore, the methods of processing HTC seeds were compiled from the perspective of other SSA countries who value the legume. Methods included chemical treatments (use of alkaline cooking aids), biological treatments (germination and fermentation), and physical treatments (milling, roasting and canning). The use of cooking aids commonly practised in West Africa had some positive results in reducing cooking time [195]. Several studies used cooking aids to study the mechanism of legume softening and various theories were put forward. Beneficial effects of using salts in cooking were postulated to be both ion exchange and chelation mechanisms occurring between monovalent cations (i.e., Na^+ and K^+) in solution and divalent cations (Ca^{2+} and Mg^{2+}) in pectates of the middle lamella [202]. However, even after the reported studies, the understanding of the mechanism of softening was still regarded as incomplete [70].

The incomplete scientific knowledge about the mechanism of legume softening due to the action of alkaline salt received further attention in **chapter 4**. Following the suggestion of del-Valle, Cottrell [202], that cross-linked phenolic compounds also may contribute to the salt softening effect, the hypothesis was that as alkaline salts reduce the cooking time of legumes, phenolic compounds that contribute to hardening also play a role in the softening process. As such, the interaction of alkaline salts and characterization of changes in bambara groundnut phenolic compounds was used to provide a link to the possible mechanism of softening. The outcome was that indeed flavonoids (e.g. catechin and epicatechin) and other phenolic acids (e.g. protocatechuic acid and gallic acid) can be regarded as indicators of softening.

Even though the use of salts reduced cooking time, the reduction was found to be minimal. Moreover, according to previous studies, the use of salts reduces protein quality. This trade-off is highly undesirable as bambara groundnut is consumed for its protein content. Additionally, sustainability and applicability of the use of cooking aids in southern SSA is doubtful as it is not a common practise and would infringe on the norms of sustainable diets as indicated in chapter 3. Other methods to manage the HTC phenomenon were evaluated by considering their applicability for rural communities and sustainability to optimize use. The conclusion was that bambara groundnut seeds are highly valued for their nutritional content, that indeed HTC development is inevitable in arid and semi-arid regions, and that protein quality cannot be a trade-off in bambara groundnut processing. Moving forward, it was decided to learn about methods that circumvent HTC from the stakeholders in the localities, evaluate the effects of processing on nutrients and consumer acceptance of products.

7.4. Processing strategies for an optimal utilization of bambara groundnut

7.4.1. Bambara groundnut grits

Having established that 3 h boiling of bambara groundnut is unsustainable as it requires large amounts of firewood, which causes deforestation and obstructs the essence of legume farming in reducing green-house gases emissions [344], sustainable alternatives are urgently required. Moreover, with malnutrition and food insecurity prevailing in the SSA region, legume cultivation, processing and consumption were reckoned indispensable when moving towards healthy and sustainable diets. Thus, indicators of aptitude (sustainability) were suggested and evaluated to ascertain the applicability of suggested alternative methods of bambara groundnut processing. The defined processing aptitude indicators included firewood use, water use, processing time and cost of dehulling.

The next step was to choose the appropriate bambara groundnut varieties for processing. This was accomplished in consultation with the Crop Breeding Institute, Harare Research Station, Zimbabwe. This is a government organisation responsible for collecting both local and exotic germplasm for use in the development of varieties adapted to the Zimbabwean climate with characteristics such as high yield potential, drought tolerance, disease resistance and attractive seed colours. Two bambara groundnut varieties, i.e. the red-seeded *Mana* and brown-seeded *Kazuma,* released in January 2003, were selected. Both are high yielding, averaging around 2.4 and 2.6 t/ha in high potential areas, respectively, and 1.2 and 1.3 t/ha in low potential areas, respectively. Both varieties were reported to have higher yield than other landraces in both high and low potential areas, thus were recommended for all bambara groundnut planting areas. The recommended planting dates for both varieties was mid to end of November, maturing after 136 days.

Producing bambara groundnut foods from grits proved to be an efficient way -in terms of labour, time and water use- of circumventing the HTC phenomenon as compared to traditional boiling of seeds. Production of dry roasted grits was most efficient since the process omitted the soaking and drying stages that are incorporated in combined soaking and roasting processes. Altogether, as in the case with alkaline salt cooking whereby protein quality was compromised, further evaluation of nutritional quality was necessary using protein, starch and mineral bioaccessibility and polyphenol reduction as indicators. Both traditional boiling and grit production improved IVSD, IVPD and mineral bioaccessibility. Additionally, grit production was superior in improving mineral bioaccessibility, i.e. Zn, K, P and Mg, while at the same time reducing the amount of polyphenols.

However, before drawing conclusions on the IVPD and IVSD found in the study, both the *in vitro* digestion method and analytical methods used needed to be considered. Various digestion models have been developed, which differ from each other regarding pH, mineral type, ionic strengths, digestion time and enzymes used, making comparison of data challenging. The study of Yagoub and Abdalla [143] describes a digestion method developed by Saunders, Connor [348] using a pepsin pancreatin system of digestion. To solve these issues, a standardised *in vitro* digestion protocol was developed [239]. This harmonised static model uses simple key parameters and conditions avoiding high variability. It is important to note that this model does not take into account complex interactions between food and body, making accurate predictions limiting. For more accurate predictions, research in *in vivo* digestion conditions is also possible, but those are time and energy consuming [239]. For the actual digestion, freeze-dried samples were used instead of fresh samples to have more precise and reproducible data. Thus, the aim was to obtain a thin paste-like consistency. Nevertheless, it is also reported that freeze-drying changes the food matrix, which can also affect the digestibility found in the study [349].

In view of this, it is difficult to compare the protein digestibility for bambara groundnut with previous studies. When comparing the data with other papers, many factors should be taken into account namely sample variety, the *in vitro* protein digestibility method and the protein measurement method. Different methods of protein analysis contribute to dissimilarities as digestible protein was, for example, previously analysed using the micro Kjeldahl procedure [143]. Nielsen, Petersen [244] evaluated different methods for measuring protein hydrolysis and concluded that the O-phthaldialdehyde (OPA) method is more accurate, easier and faster to carry out, and has a broader application range. The OPA method quantifies free α- and ε-amino groups in amino acids, peptides and proteins as well as their hydrolytic and proteolytic products. OPA is a fluorogenic agent with the ability to react with the organic molecule that contains the primary amino ($-NH_2$) group in the presence of dithiothreitol in an alkaline medium. This results in a fluorescent product detectable at 340 nm. OPA is thus used to determine the degree of hydrolysis (DH) after protein hydrolysis, defining the percentage of cleaved peptide bonds. Various methods that were regarded as less important include the pH-stat method that makes use of a base, proportional to the amount of DH as well as the trichloroacetic acid (TCA) method that measures the amount of total nitrogen. Another described method is the TNBS method, based on the reaction of trinitro-benzene-sulfonic acid (TNBS) reagent with primary amino groups [244].

Starch hydrolysis and sugar analysis methods also contribute to differences. Currently, starch is hydrolysed by KOH and glucose is analysed by the glucose oxidase/ peroxidase (GOPOD) method, whereas Yagoub and Abdalla [143] applied the dinitrosalicylic (DNS) method for analysis expressing IVSD as mg maltose/g sample. During the course of the research, HPLC analysis was also employed to measure glucose and calculation of starch digestibility.

All the same, superior processing aptitude and nutritional quality are not enough if the products are not meeting the wishes and needs of its intended consumers. Considering the need to circumvent the HTC phenomenon and the fact that dry-roasted cowpea grits are a common product in Zimbabwe and, bambara groundnut grit production based on roasting appeared to be a viable option in meeting the RDI of nutrients. The dry roasting produced a characteristic colour and flavour caused by Maillard reactions.

7.4.2. Bambara groundnut flour as a functional ingredient to favour the use of an unexploited sustainable protein source

Rural communities use bambara groundnut flour as an intermediate product in making a variety of secondary products. The need for product diversity and optimal use of flour necessitated investigation into effects of different processing methods on the nutritional and functional properties of flour. Bambara groundnut flour is regarded as nutritious and comparable to other legume flours such as from cowpea and chickpea. Varietal differences of the studied landraces in chemical properties were minor, except for protein content and ash content, which were much higher in the red-seeded variety, making it considerably more nutritious than the black-eye seeded variety. The fact that both varieties had the same dehulling efficiency, means that processing techniques are likely to be applicable to other landraces. Concerning food applications, all bambara groundnut flours would do adequately due to their low Least Gelation Concentration (LGC), with roasted bambara groundnut being the least performer. Overall, flour from soaked and combined soaked and roasted bambara groundnut is recommended for incorporation in food products.

Maize (*Zea mays*) is the staple food of Zimbabwe and is used in the production of several traditional foods for the whole household and for weaning children [6, 350]. Unfortunately, maize is low in protein, essential minerals (such as calcium, potassium, iron and zinc) and essential amino acids (lysine and tryptophan) [17, 40-42]. Fortification of maize with inexpensive sources of plant proteins has been used as strategy to help alleviate the problems of malnutrition in developing countries [17]. In view of this, non-governmental organisations operating in Zimbabwe carry out supplementary feeding schemes using maize and soya bean blend (CSB), which is used to make porridge, bread and fermented beverages, e.g. *mahewu* [351, 352]. However, soya bean is expensive to grow (more herbicides required, combine harvesters and also irrigation), but bambara groundnut is not and is already widely grown in rural Zimbabwe [27]. *Mahewu* is a traditional maize-based fermented non-dairy probiotic drink consumed mainly by low income rural communities of Zimbabwe [9, 353-355]. It is an adult type of food, although it is also commonly used to wean children [356]. Traditionally, *mahewu* is prepared from maize porridge, which is mixed with water and inoculated with either sorghum, millet malt or wheat flour for fermentation [351, 353]. Therefore, investigations on the possibility of bambara groundnut-based *mahewu* versus soya bean based are recommended.

7.5. Contribution of this thesis to the concepts of healthy and sustainable diets

Our research programme was designed to investigate how technological improvements and promotion of local crops can contribute to healthy and sustainable diets. According to Sabaté and Soret [346], the pointers of healthy and sustainable diets include those that are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy. As shown in this thesis, inclusion of the model crop bambara groundnut in cropping systems enhances productivity as well as increases diversity, accordingly reducing the reliance on a cereal monoculture and answering the food availability facet of attaining food security. Moreover bambara groundnut farming improves soil fertility by nitrogen fixation[347].

Equally, sustainable diets should be respectful of gender and cultural habits. Bambara groundnut is a women's crop, which is locally available and accessible by communities. Accordingly, women were found to be stakeholders and overseers of bambara groundnut farming, processing and trade. This thesis allowed inclusivity and an active role in research and development of rural communities on matters that affect them [7]. As food sovereignty is an important aspect that should be satisfied in sustainable diets, did the interdisciplinary approach allow the stakeholders, from farm to fork, to contribute to issues that are relevant to them? The research allowed the provision of a two-way communication with the stakeholders and these interactions enabled sensitisation about what is required to proceed. The research was tailor made to address the needs of the stakeholders as shown by the efforts made in evaluating the production process, processing and consumption of the local crop from their point of view for the betterment of nutrition. With malnutrition and mineral deficiencies experienced in southern SSA, bambara groundnut products were found to be healthy and sustainable as they contribute to dietary diversity and the RDI values for protein, starch and minerals. Since climate change affects productivity and availability of foods in marginal areas of semi-arid regions, reliance on indigenous crops like bambara groundnut cushions rural communities from food and nutrition insecurity.

Conversely, as sustainable diets are supposed to be protective and respectful of biodiversity and ecosystems, the downside of traditional processing of bambara groundnut is the long cooking time whose consequences are an increased demand for firewood and deforestation leading to reduced supply of firewood [49] as well as a reduced use of bambara groundnut in diets. The question was whether the consumption of energy was a necessary trade-off or whether a solution could be found to maintain the value of bambara groundnut as a sustainable legume. The attempt to find promising processing methods was successful, in that the provision of grits and flour as intermediate products would bring good results and dietary diversity. Processing of grits is a culturally acceptable technique, which is commonly applied to cowpea, but not commonly applied to bambara groundnut due to the HTM property. Bambara groundnut flour is a promising intermediate product as many products can be formulated from it. Given the nutritional and functional potential, maize flours fortified with bambara groundnut possess desirable functional and nutritional properties to improve dietary diversification, food and nutrition security and livelihoods [40, 152, 357, 358].

7.6. Implications for future research and recommendations

Previous researchers focused on the benefits of legumes like the improvement of cropping systems, ecosystems and nutrition (particularly as a source of protein), but less emphasis was put on the sustainability of the legume supply chain from farm to fork. Much is reported on legumes as cheap protein sources but the unanswered question is the overall sustainability aspect in the context of resource-limited communities. Improved collaboration along the legume supply chain and its standardization with different possibilities will allow better implementation of innovations. Thus, instead of focusing on managing the HTC phenomenon in legumes, sustainable, realistic solutions should be crafted in line with the resource-limited communities as they must be the beneficiaries of the food resource. In view of this, carbon footprints and embedded water concepts of bambara groundnut supply chains should be further explored, given different scenarios that exist in the global village to assess sustainability of the chain. This can be extrapolated to give pointers for other legumes as well. For example, as legume storage is a challenge as it leads to HTC, what are the potential trade-offs in processing of bambara groundnut. This perception proposes that for legumes to be regarded as healthy and sustainable, the solution to the management of the HTC phenomenon should not be a single action but requires interdisciplinary efforts that consider all the facets and how they are interlinked.

Further, in line with calculating trade-offs, the dilemma of bambara groundnut as a healthy and sustainable legume is also at risk because the factors that contribute to the undesirable hardening (HTC) also can be defined in contributing to the nutritional quality of food products. Specifically, bioactive compounds such as polyphenols are widely implicated in the fight against non-communicable diseases such as cancer because of their anti-oxidant and anti-inflammatory activities [231]. Moreover, dietary fibre, which has beneficial health benefits [359, 360], has been associated with flatus factors causing discomfort to some consumers. Therefore, the HTC phenomenon and the trade-offs in terms of nutritive value of the diet should be studied holistically. Moreover, the impression that bambara groundnut is highly valued as a cheap protein source does not help its value at the market place, especially when other important nutritional components are not reported.

In this thesis, the *in vitro* digestibility of protein was studied for conventionally cooked and alternative bambara groundnut products. However, the amino acid profile of products before and after *in vitro* digestion were not studied. To fully comprehend protein digestibility, it is also important to characterise and quantify the amino acids of products before and after digestion. As previously reported, the sulphur-containing amino acids such as methionine and cysteine are the limiting amino acids in bambara groundnut (like in other legumes) [25, 38]. It is of interest to see the changes in essential and nonessential amino acids and whether they meet FAO requirements. Previously, it was reported that bambara groundnut had a high protein score (i.e., the amino acid score of the most limiting amino acid), namely of 80% as compared to 74% for soya bean, 65% for groundnut and 64% for cowpea [43]. The storing quality of grits should also be fully assessed, paying special attention to oxidative rancidity. Further, as dry roasted grits were preferred to soaked and combined soaked and roasted grits, the flavour compounds produced in dry roasted grits need to be determined as background knowledge for continued product development.

Most functional properties of bambara groundnut flour as affected by processing have been determined, but still some functional properties, such as nitrogen solubility and gel strength need further research. Furthermore, the effect of variety and processing on physical properties can be determined at a macromolecular scale to obtain in-depth understanding of the changes occurring in starch and protein in relation to functional properties. Determining the functional properties of protein and starch isolates from bambara groundnut flour, combined with standardization for protein, starch or moisture content, is advocated to define the effect of the components on the functional properties to better understand the mechanism of these functional properties. Bambara groundnut flour has shown to have adequate functional properties for the use in products so far, but the goal should be to replace soya bean flour in legume-starch blends [361]. Given the nutritional and functional potential, maize flours fortified with bambara groundnut possess desirable functional and nutritional properties to improve dietary diversification, food and nutrition security and livelihoods [18, 40, 152, 357]. To determine the functional properties and concentration of such a blend further research is still needed. Product development using the different bambara groundnut flours should be further undertaken and the ideal formulations set according to the needs and sensory preferences of its consumers.

All in all, this thesis has demonstrated that bambara groundnut plays a beneficial role in supplying important nutrients for resource limited communities and this role can be strengthened by continued research into the sustainable way of managing HTC for optimum utilization.

Chapter 8

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Summary

Background and aim

Sub-Saharan Africa is rich in neglected and underutilized indigenous foods that have received minimum research attention. Previous technological advancements focused on modern methods of food processing to improve sensorial attributes, utilisation and shelf life, whilst traditional methods of production, processing, preservation and storage have been overlooked. Nonetheless, the growing impacts of climate change in the region, including food insecurity, rampant malnutrition and the growing population demand urgent adjustments.

To be self-reliant and resilient against food and nutrition insecurity, researchers suggest adoption of indigenous underutilized legume crops such as bambara groundnut, which fit cultural habits of communities in Sub-Saharan Africa. Bambara groundnut, which features in rural sub-Saharan Africa subsistence farming, has great agronomic and nutritional potential to alleviate malnutrition and improve food security of poor communities. Despite all the reported potential, bambara groundnut remains underutilized. A drawback in use is the development of the post-harvest hard-to-cook (HTC) phenomenon in tropical and sub-tropical regions, characterized by a long cooking time and making domestic processing challenging. Since the crop is an important resource in the alleviation of food insecurity and hunger in sub-Saharan Africa, the objective of the study was to find ways of managing the hard-to-cook phenomenon in the context of resource limited communities. Managing the hard-to-cook phenomenon in the context of sustainability required an interdisciplinary approach that dealt with multiple dimensions of sustainability, while taking into account the specific characteristics of the crop and factors that contribute to underutilisation. This was achieved by (i) gathering and assessing indigenous knowledge on the utilization of legumes (bambara groundnut, cowpea, and groundnut) in Zimbabwe; (ii) investigating the mechanism of development of HTC in legumes and assessing the softening mechanism; (iii) assessing the impact of different processing techniques on the cooking time and quality of bambara groundnut to determine processing options that fit local conditions. The thesis emphasis was to facilitate a wider use of HTC bambara groundnuts in the poorest sections of Zimbabwe and sub-Saharan Africa.

Findings

The critical review presented in Chapter 3 aimed at investigating published data on nutritional information and physical properties of bambara groundnut relative to the development of the HTC phenomenon. The resultant framework of knowledge was used as a basis to identify, analyze, and categorize HTC management and the improvement of current bambara groundnut processing procedures for improved food security. Published data on the hard-to-cook (HTC) phenomenon implicated microstructural and compositional changes as factors leading to its development. Further, methods of managing HTC in legumes were categorised as chemical, physical, and biological treatments. Useful and sustainable techniques to process HTC legumes in developing countries included cooking with alkaline salts, milling, roasting, fermenting, and malting. To be successful, it was recommended to learn from other developing countries in sub-Saharan Africa and build on locally developed practises and indigenous knowledge systems to supply culturally acceptable nutritious foods from bambara groundnut.

In chapter 2, a survey approach was used to gather and assess indigenous knowledge on the utilization of legumes in Zimbabwe. This approach was used to learn from the stakeholders about the problems that concern them. It was realised that Indigenous Knowledge Systems (IKS) in food processing practices form a bedrock of a community's composite and collective wisdom, which is passed through generations. A baseline study was conducted in seven districts in semi-arid regions of rural Zimbabwe to gather indigenous knowledge on production and utilization of bambara groundnut and to assess its current role in providing sustainable food security for rural populations. Results revealed that boiling, soaking, roasting and milling were the bambara groundnut processing techniques applied in surveyed districts. Respondents reported long cooking time, milling challenges and firewood and water shortages as constraints to processing and consumption of bambara groundnut. It was concluded that current processing techniques should be improved to promote sustainable bambara groundnut processing while optimising nutrient bio-accessibility and consumer acceptance of the products. Moreover, it was understood that community resilience to food insecurity can be realised by the promotion of the exchange of bambara groundnut processing knowledge among the production areas, which can be initiated by different stakeholders in the food supply chains.

Chapter 4 aimed at investigating the contribution of phenolic compounds to alkaline salt softening effects. This was achieved by exploring the solubilisation pattern of phenolic compounds of bambara groundnut cooked in alkaline salts in relation to reduction in cooking time. Further, the assessment of changes occurring in the extractability of phenolic compounds of bambara groundnut cooked in alkaline salts in relation to legume softening was used to explain the salt softening effects. In this research, red bambara groundnuts were cooked in MilliQ water, *gowa* (i.e. a local rock salt) and $NaHCO_3$. The effect of the alkaline salts on polyphenol profile, antioxidant activity and total phenol content was investigated at time intervals. Catechin and epicatechin were shown to have the highest concentration in bambara groundnuts as well as in cooking water. Protocatechuic acid, catechin and epicatechin were chosen as indicators of softening in relation to use of sodium bicarbonate in cooking time reduction.

In Chapter 5, the study compared the traditional boiling of bambara groundnut with alternative (namely grit) methods of processing that circumvent HTC and hard-to-mill (HTM) phenomena to determine if the latter efficiently yield nutritious foods. Assessment criteria included processing efficiency, consumer acceptance as well as mineral bioaccessibility, *in vitro* protein (IVPD) and starch digestibility (IVSD) of red and brown varieties. Data showed grit production as an efficient sustainable way of circumventing the HTC phenomenon as shown by a shorter cooking time and less water and energy consumption. Different methods of grit processing had a similar dehulling efficiency with no significant varietal influence. Both traditional boiling and grit production improved IVSD, IVPD and mineral bioaccessibility. Additionally, grit production was superior in improving mineral bioaccessibility, i.e. Zn, K, P and Mg. Overall, processing of grits was recommended as an alternative way of circumventing HTC while simultaneously contributing to the protein, starch and mineral recommended daily intake (RDI) for young children and adults.

The study presented in Chapter 6 investigated the effect of processing on chemical composition and functional properties of bambara groundnut flour. The aim was to obtain knowledge to support decision-making concerning the choice of variety for processing and suitability of flour for different food applications. All pre-treatment methods decreased flour emulsification capacity and stability. Dry-roasting caused a greater decline than other methods, whereas soaking had little effect on emulsion stability. Further, soaking increased foaming capacity, whilst a decline was observed in roasted flour. All pre-treatment methods increased oil absorption capacity of both flour varieties. Bambara groundnut flour is regarded as nutritious and comparable to other legume flours such as from cowpea and chickpea. Varietal differences in chemical properties were minor, except for protein content and ash content, which were much higher in the red variety, making it considerably more nutritious. Consequently, pre-treatment is expected to have more effect on the functional properties of the red variety. In conclusion, based on functional properties, both seed varieties are recommended for flour processing. Moreover, the soaked and combined soaked and roasted flours are recommended for further research in product development and consumer acceptance of locally consumed food products such as porridge, soups, bread, cakes and fritters. Nutrient enhancement of staple foods such as maize by blending with bambara groundnut flour is suggested as a way of increasing diversity while at the same time alleviating malnutrition problems faced by marginalised communities.

Conclusions

The research presented in this thesis contributes to technological improvements and promotion of local crops for healthy and sustainable diets. The study allowed the provision of a two-way communication with the stakeholders enabling sensitisation about the needs of communities. As food sovereignty is an important aspect that should be satisfied in sustainable diets, the interdisciplinary approach of the thesis allowed the stakeholder to contribute to issues that are relevant to them. Accordingly, the research was tailor-made to address the needs of the stakeholders as shown by the efforts made in evaluating the production process, processing and consumption of the local crop from their perspective for the betterment of nutrition. With rampant malnutrition and mineral deficiencies experienced in southern SSA, bambara groundnut products were found to be healthy and sustainable as they contribute to dietary diversity and the RDI values for protein, starch and minerals. Since climate change affects productivity and availability of foods in marginal areas of semi-arid regions, reliance on indigenous crops like bambara groundnut cushions rural communities from food and nutrition insecurity. Overall, insights provided by this thesis can be used in designing effective interventions for sustainably managing processing problems for legume crops for resource-limited communities, thereby contributing to improved food and nutrition security.

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About the author

CURICULUM VITAE

Juliet Mubaiwa was born on the 6th of July 1984 in Harare, Zimbabwe. She obtained a BSc Honours degree in Food Science and Technology at the Chinhoyi University of Technology, Zimbabwe. Before enrolling for a master's programme, Juliet was working as an Assistant Research Scientist in the Food and Biomedical Technology Institute (FBTI) at Scientific and Industrial Research and Development Centre (SIRDC). One of the main projects she was involved entails the exploitation of indigenous legume crops and other food crops for food security and nutrition. The vision was to come up with nutritious products that are locally available, accessible, and affordable and of highest quality. The exposure obtained cemented her desire to continue focusing on products that are beneficial in nutrition. From 2009-2011, Juliet earned an MSc in Food Technology from Gent University (Belgium). Upon completion of her MSc degree, she then returned to Zimbabwe and joined Chinhoyi University of Technology from which she became a lecturer at the Department of Food Science and Technology. However, because she still had a dream to know more about legume processing, the interest continued to grow intensely, hence prompted her to enrol for PhD in the Food Quality and Design at Wageningen University in collaboration with the Chinhoyi University of Technology as from 2013.

Publications

Full papers

1. **Mubaiwa J**, Fogliano V, Chidewe C, Linnemann AR. (2018). Bambara groundnut (*Vigna subterranea* (L.) Verdc.) flour: A functional ingredient to favour the use of an unexploited sustainable protein source. *PLOS ONE*, 13(10)

2. **Mubaiwa, J**., Fogliano, V., Chidewe, C., Bakker, E. J., & Linnemann, A. R. (2018). Utilization of bambara groundnut (*Vigna subterranea* (L.) Verdc.) for sustainable food and nutrition security in semi-arid regions of Zimbabwe. *PLOS ONE*, 13(10)

3. **Mubaiwa,** J., V. Fogliano, C. Chidewe, and A. R. Linnemann. (2017). Hard-to-cook phenomenon in bambara groundnut (*Vigna subterranea* (L.) Verdc.) processing: Options to improve its role in providing food security. *Food Reviews International* 33 (2), 167-194

4. Musundire R, Zvidzai CJ, Chidewe C, Ngadze RT, Macheka L, Manditsera FA, **Mubaiwa J**, Masheka A, (2016). Nutritional and bioactive compounds composition of *Eulepida mashona*, an edible beetle in Zimbabwe, *Journal of Insects as Food and Feed* 2 (3), 179-87

5. Musundire R, F Mazodze F, Macheka L, **Mubaiwa** J, Manditsera F. (2015). *Eucalyptus grandis* and *Tagetes minuta* leaf powders effectively protect stored maize against Sitophilus zeamais without affecting grain organoleptic properties. *African Journal of Agricultural Research* 10 (2), 49-57

6. Zvidzai CJ, Chidewe C, **Mubaiwa J**, Tinofa S, Manjeese W, et al. (2014). Pilot Plant Optimization for Alcohol Production in Fermentation of an Opaque Beer by Varying Sieve Size. *Ferment Technol* 2:111. doi: 10.4172/2167-7972.1000111

7. Macheka. L, Ngadze. R, Manditsera. F, **Mubaiwa. J,** and L. K. Nyanga. (2013). Barriers, benefits and motivation factors for implementation of food safety management system in the food sector in Zimbabwe. *Food Control* 34 (2),126-131

8. Macheka. L, Ngadze. R, Manditsera. F, **Mubaiwa**. J, Musundire, R (2013). Identifying causes of mechanical defects in banana fruit supply chain and establishment of critical control points to prevent incidence of the defects, *International Journal of Postharvest Technology and Innovation,* 3 (2),109-120

Submitted papers

1. **Mubaiwa, J.**, V. Fogliano, and A. R. Linnemann. Processing strategies for an optimal utilization of bambara groundnut (*Vigna subterranea* (L.) Verdc.)

2. **Mubaiwa J**, Fogliano V, Chidewe C, Linnemann A. R. Hard-to-cook phenomenon in bambara groundnut (*Vigna subterranea* (L.) Verdc.): the role of phenolic compounds in alkaline cooking

Conference Abstract

1. **Mubaiwa, J** (2014). Hard-To-Cook Phenomena in Legumes: Improving Domestic Processing of Bambara Groundnut (*Vigna subterranea* L. Verdc.) To Enhance Food Security in Southern Africa. Technology.

Overview of completed training activities

Discipline specific courses and activities		
Genetics and Physiology of Food related microorganisms	VLAG, Wageningen	2013
Sensory Perception and Food Preference	VLAG, Wageningen	2013
3rd International Conference on Food Digestion. (INFOGEST) COST Action FA 1005	INFOGEST, Wageningen	2014
Advanced Food Analysis	VLAG, Wageningen	2014
Reaction Kinetics in Food Science	VLAG, Wageningen	2016
Food Safety and Security Conference	University of Johannesburg, South Africa	2016
Applied Statistics	VLAG, Wageningen	2016
Multivariate analysis in Food Sciences	VLAG, Wageningen	2016
Healthy and sustainable diets: synergies and trade-offs	VLAG, Wageningen	2017

General courses and activities		
VLAG PhD week	VLAG, Wageningen	2013
How to write a world class paper	WGS, Wageningen	2013
Philosophy and Ethics in Food Science and Technology	WGS, Wageningen	2014
Information Literacy for PhD Including Endnote Introduction	WUR Library, Wageningen	2014
Techniques of writing and presenting a scientific paper	WGS, Wageningen	2014
Project and time management	WGS, Wageningen	2015
PhD Workshop Carousel	WGS, Wageningen	2015

Optional courses and activities		
Preparation of research proposal	FQD, Wageningen	2013-2014
PhD Colloquia.	FQD, Wageningen	2013-2014
Edulink workshop on Enhancing Nutrition and Food Security through improved capacity of Agricultural Higher Education Institutions in East and Southern Africa	Chinhoyi University of Technology, Zimbabwe	2014
1st PhD symposium	WPC, Wageningen	2013
Processed Products Food Fair	ZAVSAP, Zimbabwe	2014
Role of SME's in food security in Africa, inclusive business by African entrepreneurs	KLV , Wageningen	2014

New Innovations in Food Safety Separations	Phenomenex, Wageningen	2017
Zimbabwe trip of supervisors	Zimbabwe	2016
IFS Training course on research proposal writing with focus on upgrading value chains of neglected and underutilized species of plants	IFS, Mutare, Zimbabwe	2014

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