Samson A. Oyeyinka
Beatrice I. O. Ade-Omowaye *Editors*

Food and Potential Industrial Applications of Bambara Groundnut

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Foreword

It is widely recognised that global reliance on a few major starch-enriched grain crops represents a major risk for global food and nutritional security. Increasing the biodiversity of crop production is a sound mitigation strategy that is also likely to increase regional resilience in the face of confounding issues such as land and water resource limitations, climate change, population growth and urbanisation.

This volume brings together information representing the current state of the art for the under-utilised legume crop Bambara groundnut (BGN; *Vigna subterranea*). Set against the backdrop of poverty, malnutrition and current adverse effects of climate change in sub-Saharan Africa, BGN has many attributes of an exemplar under-utilised crop [1]. Unfortunately, as with many minor crops, it has received relatively limited concerted support from governmental or international agencies. However, the costs of generating pre-breeding information can be significantly reduced through concerted and systematic efforts that focus on sharing data related to common traceable genetic resources. This is helped by the rapid reduction in costs of genomic sequencing, but places a premium on high quality phenotyping.

The 13 chapters of this book cover many essential topics to guide future research and development underpinning integrated food supply chains, from which all stakeholders may benefit. The volume combines excellent practical advice for artificial pollination and cultivation practices, postharvest handling and processing, with in-depth consideration of issues such as how variation in physical and nutritional properties affects downstream processing, cooking and end use. Some factors, such as the "hard to cook" trait, are generic to many legumes, and benefit from detailed understanding of interactions with seed microstructure and other parameters. This is systematically covered in greater detail, alongside documenting variation in grain composition, anti-nutritional factors and other phytochemical traits that contribute to human nutrition. Such information is not only useful for resolving the genetic basis of underlying component traits, but can guide development of processing technologies for novel products and so open up potential new markets. This book places such knowledge in the context of improved agronomic practices required for small-scale and commercial farmers in developing countries in managing high-yielding cultivars with disease and pest resistance.

In order to address food and nutritional security through crop improvement, for BGN and many under-utilised crops there is huge potential to benefit from genomic and information technologies that are driving innovation in major crops. However, capitalising on accumulated genetic resources and traditional knowledge needs to be placed in context of international conventions and treaties, including the 2010 Nagoya Protocol. Efforts within communities of practice such as the DivSeek International Network [2] strive to ensure that researchers and other stakeholders are aware of their obligations for access and benefit sharing associated with plant genetic resources, issues that require careful and inclusive dialogue to establish best practices for exchange of germplasm, and to recognise associated origins and traditional knowledge. The provision of training in enabling technologies and practices for a wide range of under-utilised crops is just one potential mechanism for benefit sharing, as is facilitating open access to extensive datasets for established crops, from which all may benefit and make valuable comparisons.

The theme of variation in key traits and comparative reference to other legumes permeates the research presented in this volume. The history of secondary crop domestication process shows us that marked increases in genetic gain are achieved following establishment of formal selection and inter-breeding programmes. For BGN, recognising the value of region-specific crop ideotypes, which incorporate factors affecting both production and end use, can contribute to sustainable crop diversification. However, a collective breeding strategy based on use of advanced technologies such as genome-wide association analysis needs to go hand in hand with rigorous and explicit tracking of genetic resource materials and consistent phenotyping.

In summary, this volume will be of value to any with a particular interest in Bambara groundnut, as well as those seeking a general understanding of R&D required to support under-utilised crops throughout the production and food supply chain. Based on the collective information brought together here are the seeds of knowledge that will hopefully flourish and support development of under-utilised crops that can contribute to resilient food production.

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Preface

Bambara groundnut is a traditional crop indigenous to Africa. The name of the crop was derived from the name of a tribe in Mali called “Bambara”. Bambara groundnut has remained a traditional crop for years with applications limited to domestic uses. However, there have been concerted research efforts to improve the utilisation of the crop beyond traditional usage. The tremendous efforts by research scientists and the increased research outputs strongly signalled that Bambara groundnut is fast becoming an industrial crop; hence, the need to put a book of this nature together. This book entitled *Food and Potential Industrial Applications of Bambara groundnut* would perhaps be the first edition that could bring out more editions in the future.

We are pleased to see the production of this book go through to completion. This book covers a general introduction, production and agronomic practices, post-harvest handling of the grain, physical properties and limitations to its utilisation. Other aspects covered are description of the major components, i.e., starch and protein as separate chapters, while the phytochemical composition, use of the grain in complementary feeding and traditional uses of the grain were discussed in other chapters. A section was dedicated to microbiology and safety of Bambara groundnut, while another, which perhaps is a major focus of the book, highlights the potential industrial applications of the crop. The last chapter summarises the entire book and gives a future outlook.

This book could be used to teach food processing and preservation of Bambara groundnut and other pulses like cowpea, pea and pigeon pea with similar composition and structure to undergraduates and postgraduates. Additionally, it is hoped that this book, with its robust information on Bambara groundnut, will serve as a useful reference for scientists and professionals involved in research and processing areas related to agriculture and nutrition of pulses. Bambara grain is not only used in Africa but also in some parts of Europe and Asia. Hence, the book can be used in other regions of the world to teach traditional foods that are consumed in Africa. It could also avail readers the opportunity to plant the grain in their regions with the hope of better yield and utilisation in value-added products.

The Editors would like to specially thank all the contributors for sharing their experience in their fields of expertise. Their time, commitment and hard work made it possible to have a very robust book on Bambara groundnut for the very first time. We hope you enjoy reading the book and benefit immensely from the fruits of their labour. Lastly, on behalf of the editors, authors and reviewers, we express our profound gratitude to God for the opportunity to produce a professional book of this nature that is of topical interest. We thank the editorial and production teams at Springer for their time, effort, advice and expertise.

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About the Editors

Beatrice I. O. Ade-Omowaye is a Professor of Food Science at Department of Food Science, Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Nigeria. She has made significant contributions in the area of minimal processing of foods with special attention on pulsed electric fields (PEF) as a mild gentle non-thermal technique that retains both the nutritional and sensory quality of food better than conventional thermal techniques. Other areas of her research foci include reduction of postharvest losses, value addition to and quality enhancement of under-exploited food species and agricultural wastes, exploration of alternative protein sources from underexploited hard to cook legumes, and edible insects, with overall goals of addressing food and nutrition insecurity in developing countries. She has trained and mentored hundreds of students at both undergraduate and postgraduate levels, many of whom now hold positions of responsibility contributing notably to developments in academia, industry and government agencies at home and abroad. She has also served as visiting Scientist in the United Kingdom and Germany. Prof. Ade-Omowaye has published many scientific articles in reputable journals and contributed to several book chapters. She has made notable contributions to her field of study and her research findings have been well cited by several authors across the globe. She is a Professional member of the Nigerian Institute of Food Science and Technology (NIFST).

Samson A. Oyeyinka is a Research Fellow at Department of Biotechnology and Food Technology, University of Johannesburg, South Africa, and a Visiting Professor to the Department of Food Technology, Bicol University, Philippines. He is a budding academic with research interest in value addition to underutilised and neglected crops. In the last few years, his research thrust has focused mainly on characterisation and modification of starch using environmentally friendly methods for improved functionality and application. Specific areas include understanding the relationships between structural and functional properties of starch, enzymatic hydrolysis of starch, development of resistant starch and other dietary fibres for food applications and development of value-added products from pulses and cereal grains. He has 96 publications including 4 book chapters with 1154 Google Scholar citations and an h-index of 19 and 14 for Google Scholar and Scopus, respectively. Dr. Oyeyinka has trained in different countries including Benin Republic, China, India, Israel, Nigeria and South Africa. He is an Editorial Board Member of Legume Science and a Professional Member of the Institute of Food Technologist (IFT), South African Association of Food Science and Technologist (SAAFoST) and Nigerian Institute of Food Science and Technology (NIFST). He is happily married with children.

Chapter 1
Bambara Groundnut Perspective

Samson A. Oyeyinka and Beatrice I. O. Ade-Omowaye

1.1 Background Information

Bambara groundnut (*Vigna subterranea* (L.) Verdc.) is a legume that originated from West Africa but has become widely distributed throughout the semi-arid zone of sub-Saharan Africa (SSA) (Hillocks et al. 2012) and some regions in Southeast Asia like Indonesia and Thailand (Mayes et al. 2019). Bambara groundnut derived its name from a tribe in Mali called "Bambara" (Murevanhema and Jideani 2015; Yao et al. 2015). It is the third most important legume in the semi-arid Africa after groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) (Bamshaiye et al. 2011). The Bambara plant is an erect- bushy or prostrate annual herb that could reach between 10 and 15 cm in height. The plant is highly branched with hairy stems having short internodes and a well-developed taproot with profuse geotropic lateral roots bearing nitrogen-fixing nodules (Lim 2012). The pods are ellipsoid-globular and can have varying lengths between 1.5 and 2.5 cm with one seed per pod (Plate 1.1a). The grains of Bambara groundnut come in different shapes, sizes and colours (Plate 1.1b–e) (Oyeyinka 2017) and may have up to seven varieties differentiated by their colour ranging from black, red to cream/black (Oyeyinka and Oyeyinka 2018).

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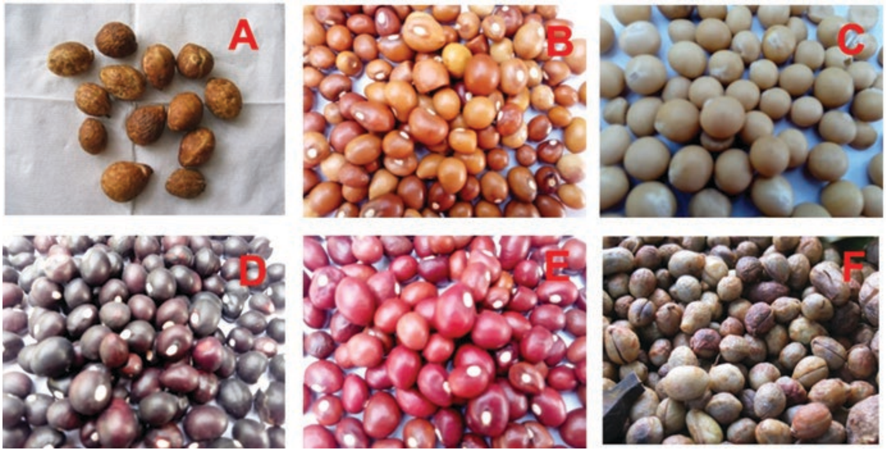

Plate 1.1 Bambara groundnut within and outside the pods (Oyeyinka 2017). (**a**) Bambara groundnut pod; (**b**) Brown Bambara groundnut; (**c**) Cream Bambara groundnut; (**d**) Black Bambara groundnut; (**e**) Maroon Bambara groundnut; (**f**) Cooked Bambara groundnut pods

According to Hillocks et al. (2012), the cultivation of Bambara groundnut predates that of groundnut. However, unlike groundnut and soybean which are industrial crops with much awareness about their nutritional importance, the awareness about the industrial potentials of Bambara groundnut is yet to be fully known. Furthermore, until now, Bambara groundnut has received limited support from governmental or international agencies (Mayes et al. 2019) and has largely been ignored by the research community (Oyeyinka et al. 2017a; Oyeyinka et al. 2015; Mubaiwa et al. 2018). The early uses of the grains were in the preparation of local dishes such as steamed pudding (*moi moi* or *okpa*) in some parts of Nigeria (Ukegbu and Uwaegbute 2014) and for bread making in Zambia (Brough et al. 1993). Swanevelder (1998) also noted that the seeds may be eaten as a snack after boiling or roasting. Matured Bambara groundnuts are boiled in their shells and are offered for sale, already cooked (Plate 1.1f), on roadsides and in markets in various parts of Africa (Lim 2012). No doubt, the limited utilisation of Bambara groundnut may be attributed to several factors as highlighted above, but has also been associated with other factors like the beany flavour, high levels of antinutrients and the hard-to-cook defect that prolongs cooking time (Ijarotimi and Esho 2009; Oyeyinka et al. 2017b).

For a very long time, traditional uses of the grains seem to have dominated the bulk of the application as a food. Research efforts to further promote the grain and enhance its utilisation beyond traditional usage has yielded some fruitful efforts. For instance, Bambara groundnuts have been used in the production of low-fat yoghurt (Falade et al. 2015), value-added snacks (Oyeyinka et al. 2018), vegetable milk (Poulter and Caygill 1980; Obizoba and Egbuna 1992; Brough et al. 1993; Murevanhema and Jideani 2015), *dawa-dawa* type condiment (Adebiyi et al. 2019; Amadi et al. 1999a) and tempeh (Amadi et al. 1999b). The grains have also been used in making a puree for infant feeding in rural communities in Southern Africa (Oyeyinka et al. 2017a).

Many of the progress made in the utilisation of the grains seem to have increased the awareness about the potential of Bambara groundnut as a food crop (Mayes et al. 2019). The increased awareness may be attributed to several factors. Firstly, the Bambara plant is highly resistant to drought and can produce a reasonable crop even on poor soils (Oyeyinka et al. 2015). In addition to this, the crops ability to fix nitrogen is also one of the reasons the crop is still of high relevance (William et al. 2016; Mayes et al. 2019). This first and very crucial reason is of immense benefit to the agronomist since such crops can help improve the soil quality and enhance the growth of other crops planted through mixed cropping. A second reason, which perhaps is very important from the Food Science and Technology point of view and of utmost industrial relevance is the relatively high nutritional value of Bambara groundnut. The grains are a cheap source of protein (15–27%) and carbohydrate (57–67%) (Adebowale et al. 2002; Sirivongpaisal 2008; Ade-Omowaye et al. 2015; Oyeyinka et al. 2015) and unlike many other legumes, it contains an appreciable amount of methionine (1.8–2.84%) (Aremu et al. 2006; Ijarotimi and Esho 2009; Kudre et al. 2013; Ade-Omowaye et al. 2015). Hence, the grain can be effectively used to improve the food and nutrition security status of rural households (Mubaiwa et al. 2018).

More recently, the protein hydrolysate and peptide fractions from the grains were reported to have strong activity against high blood pressure and oxidative stress (Arise et al. 2016; Arise et al. 2017). In addition to these, are the starch components which may be explored in food systems for texture modification, thickening, and as fat replacers after modification (Oyeyinka and Oyeyinka 2018). Starch is an important functional ingredient with several applications including the food, textile and pharmaceutical industries. Currently, the grains primarily used as dietary and industrial starch sources include maize, wheat, potato, cassava and rice, but pulses such as cowpea (*Vigna unguiculata*) and Bambara groundnut can also provide appreciable quantities of starch for industrial uses. The starch from pulses is exceptionally rich in resistant starch with beneficial physiological effects such as improvement in the absorption of minerals, prevention of colon cancer and could be used as prebiotics (Hoover et al. 2010).

Beside its starch component, Bambara groundnuts have also been found to be good sources of soluble and insoluble dietary fibres with possible use as thickening agents, stabilisers, healthy ingredients as well as cryoprotectants in frozen dairy products (Maphosa and Jideani 2016). High fibre diets are being sought after due to the physiological beneficial effects such as a reduced risk of diabetes, coronary heart disease, obesity, some cancers and haemorrhoids (Daou and Zhang 2011; Maphosa and Jideani 2016).

The enormous potentials inherent in the grains as evident in various literature may have encouraged the increase in production of Bambara groundnut among rural farmers. For instance, in 2002, the Food and Agricultural Organisation estimated the worldwide Bambara groundnut production to be 58,900 m (William et al. 2016). Other literature reported higher production (330,000 m), of which 45–50% is produced in West Africa (Alhassan and Egbe 2013). With the growing production of Bambara groundnut and the need to provide sustainable storage systems for the grain as well as efficient processing technologies to produce value-added products from the grain, a book of this nature entitled 'Food and Potential Industrial Applications of Bambara groundnut' is timely. The research efforts on the grain have opened up the potentials in Bambara groundnut and have further positioned the crop for various industrial utilisation. To further boost the awareness of Bambara groundnut and to enhance its status as an industrial crop, a compendium of research outputs done for several decades including recent ones have been harnessed by researchers from different disciplines. Therefore, this book was written to document the various researches done so far on Bambara groundnut in a holistic approach and to further popularise Bambara groundnut and promote its use beyond the current level of usage.

1.2 The Structure of This Book

This book has 13 chapters covering the agricultural production practices with regards to the breeding efforts to improve agronomic traits; pre-and post-harvest handling and storage of the grains; description of the grain structure and composition; the starch and protein components; phytochemicals and traditional uses of the grain; limitations to its utilisation; application in complementary feeding; the microbiology and safety; and potential industrial applications of the grain. The book concludes with a chapter that summarises the entire book while highlighting the industrial potentials of Bambara groundnut and indicating future research trends towards its increased production and utilisation. It is hoped that this book will form a good reference book for teaching processing of plant foods, especially legumes at various levels in higher institution of learning. Furthermore, it could also be valuable for researchers and other stakeholders including the industry involved in cultivation, processing, storage and the utilisation of pulses similar to Bambara groundnut in composition and structure.

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Chapter 2
Production Practices of Bambara Groundnut

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2.1 Introduction

Bambara groundnut (*Vigna subterranea* (L.) Verdc), a leguminous crop belonging to the family Fabaceae; subfamily *Papilionoideae*, is widely cultivated in sub-Saharan Africa (SSA) because of its economic potential. *Subterranea* is the only cultivated species, while wild forms belong to the progenitor, var. *spontanea*. This crop is thought to have originated in Africa, specifically in the West African sub-region (Begemann 1988). Some scholars believe that Timbuktu in central Mali is the putative center of origin, hence its name Bambara (Goli et al. 1991). However, Linnemann et al. (1995) reported that cultivated Bambara groundnut is believed to have evolved from var. *spontanea,* which has widespread occurrence in West Africa, particularly in Nigeria and Cameroon. Although the Bambara is native to the SSA, it has shown wide adaptation across Southeast Asia, Australia, and in Central and

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South America, suggesting the potential existence of secondary centres of genetic diversity.

Based on the nomenclature, the common name given to the crop is Bambara groundnut and the preferred scientific name of *Vigna subterranea* with the other scientific name of *Voandzeia subterranea* (L.) Thousars, are synonymous. It belongs to the plant kingdom of the family of *Fabaceae* and sub-family of *Faboidea* (Bamshaiye et al. 2011). In different geographical locations and ethnic groups in the world, different names are given to the crop; for example, in Nigeria, the given name by the Igbos in the Southeast is *Okpa*, while the Hausas in the north call it *Gurujia*. In South Africa, it is called *Njugo* bean, *Nzama* in Malawi, and *Ntoyo* (CiBemba or Katoyo) in Zambia (Okonkwo and Opara 2010). Other names in Africa are Congo groundnut, Congo goober, Madagascar groundnut, earth pea, baffin pea, *voandzou*, *indhlubu*, and underground bean (Stephens 2012).

2.2 Botanical Description and Taxonomic Tree for Bambara Groundnut

Bambara groundnut is a herbaceous, intermediate, annual plant, with creeping stems at ground level (Bamshaiye et al. 2011). It is a small legume plant that grows to a height of 0.25–0.37 m with compound leaves of three leaflets (Bamshaiye et al. 2011; Shegro et al. 2013). The plant generally looks like bunched leaves arising from branched stems, which form a crown on the soil surface. After self-fertilization, pale yellow flowers are borne on the freely growing branching stems; these stems then grow downwards into the soil, taking the developing seed within the pods, which makes breeding and development of new cultivars for the traits of interest difficult. The seeds will form pods encasing seeds just below the soil.

The taxonomic tree for Bambara groundnut

Domain: Eukaryota
Kingdom: Plantae
Phylum: Spermatophyta
Subphylum: Angiospermae
Class: Dicotyledonae
Order: Fabales
Family: Fabaceae
Subfamily: Papilionoideae
Genus: *Vigna*
Species: *subterranea*

2.3 Breeding Methods and Focus Traits

One of the main reasons for the decrease in Bambara groundnut production and productivity is the absence of improved agronomic management practices and high yielding cultivars with disease and pest resistance for small-scale and commercial farmers in developing counties, including those in SSA. Bambara groundnut has never benefitted from any breeding programs targeting the development of improved cultivars, mainly because of its complex reproductive system, which is recalcitrant to artificial hybridization. To date, there are no registered or improved cultivars of Bambara groundnut and farmers still use landraces, which have been developed through several generations of mass selection. Although some of these landraces have essential adaptive traits, they are generally low yielding (Massawe et al. 2003a).

The complex anatomy of the Bambara groundnut reproductive system has been a significant impediment to the improvement of the crop. The crop has tiny florets that are difficult to hand pollinate and emasculate. Nevertheless, the Bambara is amenable to artificial hybridization (Massawe et al. 2003a; Suwanprasert et al. 2006). Several factors are fundamental in enhancing cross-pollination in Bambara and these include a suitable nursery environment which is the first step, short-day lengths (<12 h), and an average temperature of 26 °C which is required for optimum flowering and pod formation and a relative humidity of 90%. These conditions are achievable in Conviron growth chambers (Massawe et al. 2003b). When emasculating and pollinating, great diligence is necessary as the Bambara stamens and pistils are very fragile (Plate 2.1). The female plants should be stress-free soon after pollination. Massawe et al. (2003a) and Suwanprasert et al. (2006) developed several breeding populations in Malaysia, some of which have the potential for release as improved cultivars in Africa. Plant breeders can generate additional genetic variation through mutation breeding. The ability to make crosses, coupled with the elucidation of the annotated Bambara genome, means that careful trait selection can now commence, leading to the development of elite Bambara groundnut cultivars (Mayes et al. 2019) for the traits of interest.

As an underutilised crop, there is a lack of information relating to biotic and abiotic constraints affecting the productivity of Bambara. Hence, breeding priorities for Bambara improvement should be set, following extensive participatory rural appraisals to elucidate farmer trait preferences to stimulate uptake of the improved cultivars. At present, Bambara yields in peasant farm environments rarely surpass 1.00 t ha^{-1}, especially in tropical and subtropical regions, including southern Africa (Mayes et al. 2011). Selection for increased pod number per plant, pod weight, and seeds per pod can be a strategy for yield improvement.

The strict photoperiod requirement of Bambara also limits its productivity in countries further away from the equator. Long day lengths (>12 h) have a negative effect on pod-setting in some accessions, leading to crop failure. For smallholder farmers in various parts of Africa, where the timing of the rains often determines the cropping season, meeting photoperiod requirements of the local growing season can improve crop productivity, yield stability, and adaptation. Some accessions from

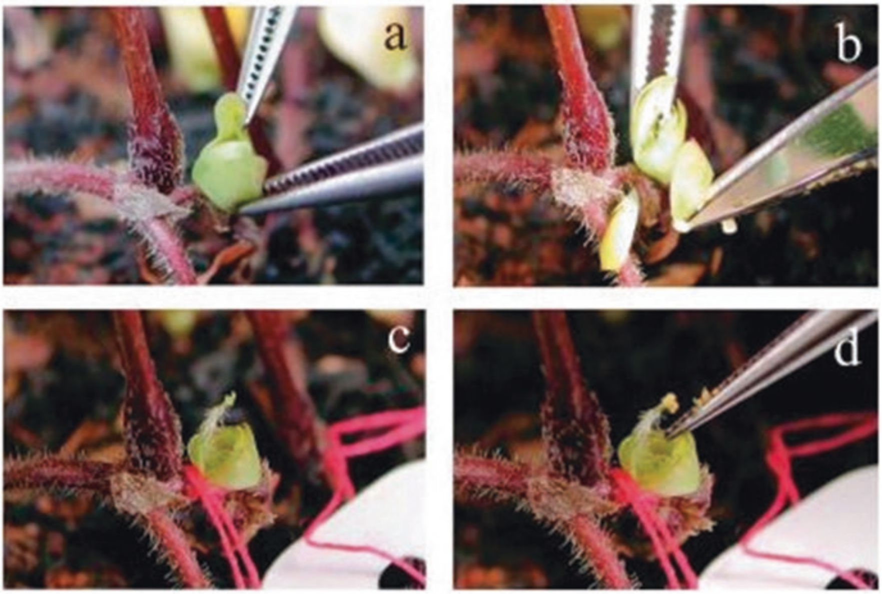

Plate 2.1 Methods of emasculation and pollination of Bambara (**a**) rending half of the keel petal to the top, (**b**) cutting-off the upper half of the petal, (**c**) tagging the emasculated flower at the peduncle level, (**d**) adhesion of pollen to the stigma of the female parent. (Source: Suwanprasert et al. 2006)

Mali, West Africa differ in photoperiod response to flowering time and pod-setting (Linnemann et al. 1995). For example, "TigaNicuru (TN)" is day-neutral in response to flowering time and photoperiod-sensitive for pod-setting. At the same time, the selection "Ankpa-4" is highly photoperiod-sensitive in terms of days to flowering and pod-set. This suggests genetic control of the trait. Hence, these accessions can be used to develop populations for association mapping to identify loci for photoperiod genes to initiate marker-assisted selection.

Bambara groundnut also has the "hard to cook" phenomenon (HTC) (Mubaiwa et al. 2017). Prolonged boiling time, often more than 4 h, is required to make the seed edible, and therefore high-energy is expended during cooking compared to other legumes such as cowpea, lentils, and common bean. Given the global energy crisis, there is a need to focus research on reducing cooking time and the overall functional utility of Bambara. This is because hardening of seeds causes a decrease in nutritional quality and extended boiling leads to reduced nutritional quality and digestibility. The hardening of legume seeds causes a decrease in nutritional quality, and extended boiling leads to reduced protein digestibility and further, processors also avoid grain with the HTC as the trait affects hydration during canning. The HTC phenomenon is not unique to Bambara but has been resolved in other legumes and cereals, including the common bean (Guzmán-Maldonado et al. 2003) and pearl-millets (Bouis and Welch 2010).