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A 20-Year Journey Through an Orphan African Baobab (*Adansonia digitata* L.) Towards Improved Food and Nutrition Security in Africa

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The African baobab (*Adansonia digitata* L.) is a multipurpose orphan tree species of the semi-arid and sub-humid Sub-Saharan Africa where it plays an important role in rural livelihoods. Its wide distribution and dense nutrition properties make it an important species for food and nutrition security in Africa. However, despite the increasing interest in the species over the past two decades, the full potential of baobab remains underexploited. This review highlights strides made over the past 20 years (2001–2020) towards harnessing and unlocking the potential values of baobab in Benin, West Africa, to contribute to food and nutrition security. Challenges and threats are identified, and next steps suggested to guide research and development initiatives for orphan tree fruit species like baobab to address hunger and malnutrition in Africa.

Keywords: African baobab, *Adansonia digitata*, orphan species, food security, nutrition security, West Africa

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INTRODUCTION

Despite their status, orphan species, which are also popularly known as neglected and underutilised species (NUS) (Jamnadass et al., 2020), are treasure troves for livelihood improvement in the developing countries (Jamnadass et al., 2011; Tadele, 2019; Ulian et al., 2020). Indeed, owing to the strong cultural links between plants and nature (Díaz et al., 2018), orphan species like baobab have a special niche in the dietary habits of rural communities in Africa (Buchmann et al., 2010), where they offer a large untapped resource to support food security and agriculture (Ulian et al., 2020). As such, they could be important for food and nutrition security in these societies, in addition to representing the regional identity of human communities (Bedigian, 2018). The continued neglect of these species, which include 477 fruit tree species (Awodoyin et al., 2015), could be one of the reasons Africa is still characterised by poverty, hunger and malnutrition (Jamnadass et al., 2020; Ulian et al., 2020). Recently, the Lancet Commissions (Willett et al., 2019) reported that over 820 million people worldwide were food insecure and many more were malnourished, the majority of which were in Africa, thus calling for enhancing agro-biodiversity to improve food and agriculture.

The growing recognition in the use of orphan species to address local challenges (Borelli et al., 2020), coupled with the increasing urgent need for transformation towards healthy diets and sustainable agro-ecosystems (Willett et al., 2019; Vermeulen et al., 2020), points to increasing attention and utilisation of orphan species. This is could lead to the improvement of both the ecological and human well-being in Africa, where a substantial diversity of orphan species is found. Owing to their dense nutritional properties and low input requirements for their production (Tadele, 2019), broad gene pool and adaptability to niche marginal areas (Mabhaudhi et al., 2019), orphan species have a great stake in the strategies for transformational diets and agro-ecosystems in Africa through crop improvement, expansion into new agro-ecological zones and building resilience of marginal cropping systems (Mabhaudhi et al., 2019; Jamnadass et al., 2020; Ulian et al., 2020).

The African baobab (*Adansonia digitata* L.) (**Figure 1**) is a multipurpose orphan tree species, native to the dry savanna of the sub-Saharan Africa (SSA), where it plays an important role in the food security and livelihoods of rural communities (Kamatou et al., 2011), and is inextricably linked with cultural identity and local beliefs (Buchmann et al., 2010). Evidence points to West Africa as the origin of the African baobab, from which it became widely distributed to the rest of the savannas of Africa and Madagascar (Pock Tsy et al., 2009). All baobab parts (bark, flowers, fruits, leaves, roots, seeds) are useful and edible (Kaboré et al., 2011), even if the fruit pulp, leaves and seeds are the parts mostly used for food and nutrition security (Assogbadjo et al., 2008; Rashford, 2018). Over 300 baobab uses have been reported in West Africa alone spanning across 11 ethnic tribes (Buchmann et al., 2010). This demonstrates the diversity and cultural importance of baobab in the sustenance of livelihoods in Africa. Baobab is also valued at international markets such as Europe, where an estimated 300 baobab-derived products have been recorded (Gebauer et al., 2016). The breakthrough of baobab onto the international market follows the acceptance of baobab products as "novel products" at the European and American markets (Buchmann et al., 2010). This signifies the potential role baobab could play in addressing regional and global challenges such as food insecurity and malnutrition. Additionally, and as is common with a number of orphan plant species, baobab is well-adapted to local environmental conditions, and thrives in marginal areas and soils (Sidibe and Williams, 2002). These environmental characteristics make baobab an important species for agro-ecosystems in the SSA, where over 80% of the arable land has low soil fertility (Hengl et al., 2015).

FIGURE 1 | Part of a baobab trunk showing leaves and drooping immature fruits.

Recognition of baobab as an important resource dates back to the 1800s with reports of baobab leaves used as a vegetable (Wickens, 2007). More interest rose in the 1980s and 1990s with notable work on ecology, pollination and floral biology (Baum, 1995, 1996). Later, more comprehensive work on baobab was done by Sidibe and Williams (2002), who described a wide range of areas including biogeography, taxonomy, reproduction and domestication of baobab. Since then, several laudable efforts have been made on baobab addressing various aspects such as conservation genetics, ethnobotany, pharmacology, domestication, and baobab biology. However, these are littered in various publications. This makes it difficult for fledgling researchers, development practitioners, and policy makers to utilise the information generated to harness and unlock the potential benefits of baobab in addressing poverty, food and nutrition insecurity in Africa (Gebauer et al., 2016). According to Schumann et al. (2012), packaging of fundamental information at a small-scale level (national or regional), is critical for the development of utilisation and management strategies for orphan species like baobab.

Accordingly, this study is a review of the work carried out on baobab in the last 20 years (2001–2020) in Benin, West Africa. It aims to guide research and development agenda in harnessing and unlocking the potential benefits of baobab to address food and nutrition insecurity, ultimately contributing to the attainment of the 2030 Sustainable Development Goals (Goal 2) and Agenda 2063 aspirations in Africa (Aspiration 1). First, the study outlines the research strides made on baobab in Benin from 2001 to 2020 towards sustainable food and nutrition security. Second, it identifies challenges and constraints. Third, it proposes and discusses the next steps, by drawing lessons from the region and elsewhere. Finally, the study draws the conclusions. In all these steps, the study attempted to consider the food system dimensions (Timmer, 2014), namely, access, availability, utilisation, and sustainability of baobab resources.

METHODOLOGY

Benin is located between 6°25′ N to 12°30′N and 0°45′E to 4°00′E and has a total surface area of about 115,762 km^2. It has three contrasting climatic zones: (i) the Guinean in the south—humid zone with bimodal precipitation averaging 1,200 mm per year and an annual temperature range of 25–29°C; (ii) Sudano-Guinean in the centre—sub-humid zone with a tendency to unimodal precipitation averaging 900–1,110 mm per year and an

TABLE 1 | Summary of achievements on baobab based on research findings and their relationship with food security dimensions.

Achievements	References	Relation to food and nutrition security
Baobab is distributed throughout Benin	Codjia et al. (2003), Assogbadjo et al. (2005a), Chadare et al. (2008), Djossa et al. (2015), and Dossa et al. (2015)	Accessibility
Baobab food resources are available almost all the year round in Benin	Assogbadjo et al. (2005a), Chadare et al. (2010), and De Caluwe and Van Damme (2011)	Availability
Elite baobab trees with locally preferred traits have been identified in Benin	Assogbadjo et al. (2008, 2009)	Selection for domestication, thus ensuring accessibility, availability and sustainability
Wide genetic and morphometric variations are found within baobab populations across climatic zones of Benin	Assogbadjo et al. (2005b, 2006)	Selection for domestication, thus ensuring accessibility, availability and sustainability
Baobabs in Benin have wide and dense food properties in pulp, leaves and seeds	Chadare et al. (2008, 2014) and Assogbadjo et al. (2012)	• Utilisation • Catalyst for industrial growth of baobab food products, thus improving access and availability
Baobab is revered by local communities and is a biocultural keystone species in the country	De Caluwé et al. (2009), Chadare et al. (2008, 2010)	• Utilisation • Catalyst for industrial growth of baobab food products, thus improving access and availability • Motivating factor for domestication, thus ensuring access, availability, and sustainability
Background information on the baobab value chain is available for Benin	De Caluwe and Van Damme (2011)	• Accessibility • Availability
Baobab is threatened by climate change but is amenable to domestication	Assogbadjo et al. (2011) and Sanchez et al. (2011)	Selection for domestication, thus ensuring accessibility, availability and sustainability
Baobab productivity is improved by fruit bats	Djossa et al. (2015)	Planning for its conservation in the landscape, thus ensuring accessibility, availability, and sustainability

annual temperature range of 25–29°C; and (iii) the Sudanian in the north—semi-arid zone with strictly unimodal precipitation averaging <1,000 mm per year and an annual temperature range of 24–34°C.

This study is not a fully-fledged systematic review but rather a traditional review that used some elements of the systematic approach (Haddaway et al., 2015). It used 16 peer reviewed articles on baobab published between 2001 and 2020 whose work has a footprint in Benin. Forty nine additional papers on baobab from elsewhere other than Benin and 37 articles on agroforestry/indigenous fruit trees/orphan species were used to augment the discussions and draw lessons. Three online search engines were used to select papers on baobab: Google scholar, Science Direct and African Journals Online (AJOL). A combination of terms “African baobab,” “baobab,” and “*Adansonia digitata*” with “food security,” “nutrition security,” and “Benin” or “Africa” were used. An advanced search option was used for the Google scholar. Records totalling 6,297 on baobab (Google scholar [5,824], Science Direct [353], AJOL [120]) were collected in the first week of January 2021. After scanning through the topics and removing duplicates, 315 publications were retained. Reading through the abstracts and keywords of these publications yielded a total of 65 articles on baobab (16-Benin; 49-elsewhere) which were retained for this review. These were publications that focused on food and nutrition, indigenous knowledge, value chain, domestication and conservation (genetics, population dynamics, and climate change effects on baobab). General articles on agroforestry, indigenous fruit trees and/or orphan species were randomly selected from the literature, whilst a couple others were suggested by anonymous reviewers of the draft manuscript.

STRIDES MADE TO UNLOCK AND HARNESS THE POTENTIAL VALUE OF BAOBAB FOR IMPROVED FOOD AND NUTRITION SECURITY

Table 1 summarises the strides that have been made in the last 20 years towards unlocking and harnessing the potential value of baobab to contribute to improved food and nutrition security in Benin in West Africa.

Baobab Is Distributed Throughout Benin

Several studies addressing various aspects of baobab and using different methods have demonstrated that baobab is widely distributed in the country, spanning all the three climatic zones. These include: ethnobotanical studies e.g., local edible vegetables (Codjia et al., 2003); indigenous knowledge and baobab food products (Chadare et al., 2008); ecological studies e.g., ecological diversity and productivity of baobab (Assogbadjo et al., 2005a); characterisation of natural populations of baobab (Dossa et al., 2015); and reproductive ecology (Djossa et al., 2015). For example, Assogbadjo et al. (2005a) showed that Benin has a baobab density of 1–5 trees per km^2, with the Guinean zone having a relatively higher density than the other two zones. Further, the authors observed that baobab density tends to decrease with increasing distance from farms and/or villages i.e., more baobabs are on farms or closer to the villages. The results may mean that, for millennia, baobab saplings close to the villages might have been protected and tendered by humans as opposed to baobab populations away from the villages that may have been subjected to damage by several factors including wild animals. Further, the wide distribution and closeness to villages imply baobab is available and can be easily accessed by the local communities in Benin for their utilisation.

The spatial dependence of baobabs on human settlements, albeit worrying recruitment rates, has also been reported in many parts of Africa including Mali (Duvall, 2007), Namibia (Lisao et al., 2018) and South Africa (Venter and Witkowski, 2010, 2011), buttressing the evidence of the long historical association between baobab and human cultures in Africa, considering that baobab is a very long-lived species (>1,000 years) (Patrut et al., 2015).

Baobab Food Resources Are Available Almost All the Year Round in Benin

Flowering, fruiting and leaf shedding are seasonal phenomena in baobab. In Benin, according to Assogbadjo et al. (2005a), flowering in baobab coincides with the peak of the rainy season (July–August) in the Sudanian Zone, and the peak of the two rainy seasons in the Guinean Zone. The peak of fruiting, however, corresponds with the onset of the dry season (October) with subsequent fruit maturity extending from December to March (dry season). On the other hand, leaves are generally retained throughout much of the year, except during episodes of leaf shedding at the peak of the dry season between October and April. During this time, variations are observed with a mixed of early, medium and late leaf shedding trees giving way to new tender shoots (Assogbadjo et al., 2005a). Generally, fruit availability in baobab is reported to be between April and October across Africa (Omotayo and Aremu, 2020).

Given that maturation of fruits and availability of leaves also coincide with the peak of the dry season, baobab thus becomes an important food species especially when field crops are in off-season. The overlapping of baobab resources with time of food shortage has also been reported in many countries (Sidibe and Williams, 2002; Jäckering et al., 2019). It would seem that subsequent storage of fruits and leaves (often harvested in bulk during the peak period), beefed up by the storage and distribution of a wide range of processed baobab products (Chadare et al., 2008, 2010; De Caluwe and Van Damme, 2011), make baobab food resources become available and accessible almost all the year round in Benin. The seasonal variations among climatic zones of Benin also work to the advantage for constant supply and distribution of baobab from one area to another virtually throughout the year, albeit low availability. This trend in the availability of baobab resources and the practise by communities to store baobab products, so as to spread over periods of food shortage is a common practice in Africa (Wanjeri et al., 2020).

Elite Baobab Trees With Locally Preferred Traits Have Been Identified in Benin

Local communities in Benin have demonstrated a great depth of knowledge that enables them identify baobab morphotypes with preferable traits. According to Assogbadjo et al. (2008), local communities use a matrix of 21 criteria to differentiate baobab morphotypes in Benin. The matrix criteria relate to leaf, fruit, bark and tree traits. The most distinguishing characteristics by farmers are: leaf taste, pulp taste, capsule size and shape, ease of bark harvest, and fertility of trees, even if leaf taste was found the dominant characteristic (Assogbadjo et al., 2008). According to Assogbadjo et al. (2008), farmers use this combination of traits as a guide when collecting baobab products. For instance, farmers could tell the taste of the pulp and leaves from the ease of bark harvest (ease of bark harvest = tasty pulp and leaves). Likewise, the taste of the pulp could be guaged from its texture (slimy pulp = tasty pulp), and from the orientation and arrangement of the fruit capsule (closely longitudinally marked fruit capsules = tasty pulp). Following this folk classification, eight morphotypes were identified in Benin, although a follow-up genetic fingerprinting analysis did not correlate with the traditional morphological identification (Assogbadjo et al., 2009). It is suggested that the traits used in folk classification could be influenced by environmental factors, hence the differences in the findings between the two studies (Assogbadjo et al., 2009).

Interestingly, somewhat similar desirable traits and selection criteria have been reported among the farmers of the Blue Nile State and North Kordofan State in Sudan (Gurashi et al., 2017), probably further indicating long historical use and sharing of indigenous knowledge associated with the widely distributed and important species among rural communities. The fact that there are morphotypes with desirable traits to local communities, presents a springboard for participatory selection and domestication of baobab, so as to increase access to, and availability of, baobab resources.

Moreover, it is well-documented that the likelihood of success for conservation activities is high if they: (1) build on the local knowledge and cultural context (Waylen et al., 2010); (2) foster the daily livelihoods of local communities (Teuea and Nakamura, 2020); and (3) support for choice of the right species for given environmental conditions and established purposes (Kettle et al., 2020). Indeed, exclusion and non-active participation of local communities in decision-making processes are among the many factors that have contributed to the failure of laudable efforts in agroforestry programmes in many African countries (Leakey et al., 2012; Leakey, 2017, 2019), with most of the efforts failing to go beyond academic work (laboratory or field experiments). To reset the agro-ecosystems in Africa and achieve food and nutrition security, it is believed that "Cinderella" species, selected based on the local community criteria (Leakey, 2019), should be enhanced through participatory approaches (Leakey, 2017) and that science ought to embrace the needs and aspirations of smallholder famers (Nature, 2020).

Wide Genetic and Morphometric Variations Are Found Within Baobab Populations Across Climatic Zones of Benin

Studies have confirmed the presence of high genetic and morphological diversity within baobab populations in Benin. Assogbadjo et al. (2006) showed that baobabs in the country are highly polymorphic (78.34% polymorphism), with 82.37% of the total variation within populations and 17.63% among populations ($P < 0.001$). Genetic diversity is higher within than between populations, with the mean gene diversity within population (HS $= 0.309 \pm 0.000$) and average gene diversity between population (DST $= 0.045 \pm 0.072$). The authors further identified tree height, number of branches and capsule thickness as the three most distinguishing morphological traits. Related to productivity with respect to ecological zones, the Sudano-Guinean Zone is the most productive, producing the highest yield of pulp, seeds and kernels followed by the Sudanian Zone and lastly the Guinean Zone (Assogbadjo et al., 2006; Table 7, p. 827). Similar findings were made in an earlier study (Assogbadjo et al., 2005b; Table 2, p. 53).

Trait variations between baobab provenances have been reported elsewhere in Africa (Munthali et al., 2012, 2013; Wiehle et al., 2014), and these may be due to physical isolation and the resulting genetic structuring (Assogbadjo et al., 2006). Given that morphological diversity and genetic diversity are not completely correlated with each other (Assogbadjo et al., 2008), it was suggested that variations in baobab phenotypic traits are a consequence of environmental factors (Assogbadjo et al., 2011). Provenance variations due to environmental factors such as water stress have also been implicated in other wild fruit species such as *Sclerocarya birrea* (Jama et al., 2008).

The variability of both genetic and morphological parameters, especially capsule production in various climatic zones, imply availability of adequate precursor material for selection of elite trees of baobab to address the needs of the rural populations in Benin and Africa. The findings also provide a strong argument for *in situ* conservation of baobab populations to preserve the genetic integrity of the species for posterity.

Baobabs in Benin Have Wide and Dense Food Properties in Pulp, Leaves and Seeds

That baobab is nutritious is no longer questionable. Several studies have underscored this property in baobab (Sidibe and Williams, 2002; Chadare et al., 2009; Habte and Krawinkel, 2018). Probably, what is contentious is the variability of the nutritive properties (Habte and Krawinkel, 2018), which seems to be influenced by a number of factors including genetic and environmental factors, although more evidence is pointing towards edaphic physicochemical properties (Assogbadjo et al., 2012).

According to Assogbadjo et al. (2012), the dominant soils in Benin are rich in carbon, clay, fine silt and organic matter, and these correlate positively with the concentration of iron, potassium, vitamin C, carbohydrates, zinc, proteins and lipids in baobab. Further, the concentrations of proteins, lipids, carbohydrates and fibres in baobab parts do not vary among the three climatic zones in Benin. Furthermore, baobab seeds contain high levels of proteins and lipids but low levels of carbohydrates and fibres, with seeds containing 11 times and two times more proteins, respectively, than the pulp and leaves. In addition, seeds are ∼three times lower than pulp and leaves in carbohydrate concentration (Assogbadjo et al., 2012; Table 1, p. 96). The authors showed this by sampling baobab parts (pulp, leaves, seeds) from genetically different populations and soils in the three different climatic zones of Benin.

Regarding climatic zones, the authors reported that baobab pulp and leaves from the Guinean zone were relatively rich in iron, potassium, vitamin C, carbohydrates but had a low concentration of magnesium. It should be noted that pulp and leaves were taken from baobab trees that were established on soils rich in carbon, clay, fine silt, organic matter, with a high pH water and C/N ratio, but a low concentration in gross silt (Assogbadjo et al., 2012; Table 4; Figure 1, p. 98). On the other hand, pulp and leaves of the baobabs from the Sudanian and Sudano-Guinean zones were reported relatively rich in calcium and vitamin A, but had a low concentration of zinc, proteins and lipids. Samples for these came from baobab trees growing on soils with high levels of gross silt but poor in carbon, clay, fine silt, and having low pH water and C/N ratio (Assogbadjo et al., 2012; Table 4; Figure 1, p. 98).

In a follow-up study, Chadare et al. (2014) assessed mineral and carotenoids contents of different categories of baobab leaves and their *in vitro* solubility towards cooking. Calcium levels in raw leaves ranged from 1,371 (slimy, young) to 3,310 mg/100 g dm (bitter, old). The iron content of different types of raw young and old sweet baobab leaves was quite similar (9–10 mg/100 g dm). However, raw, bitter leaves contained a higher quantity of iron (16 mg/100 g dm). The zinc contents of different types of baobab leaves were lower than those of iron. Zinc in bitter leaves was lower than in sweet leaves, which contained 3–5 mg/100 g dm (Chadare et al., 2014; Table 2, p. 11). The main carotenoids detected in baobab leaves were lutein, trans-, and cis (1 and 2)—betacarotene (Chadare et al., 2014; Table 3, p. 14). Chadare et al. (2009) suggested that the variations in nutritional value and biochemical composition may be due to a number of factors. These are: the quality of the sample (mixture of samples, or samples obtained from markets or samples from individual trees), sample provenance, sample age, treatment and analytical methods, the storage conditions, the processing method, genetic variation, and the soil structure and its chemical composition.

The biochemical and nutritional trait variations in baobab based on plant tissue and place of origin have been reported from different countries across Africa by a number of authors (Parkouda et al., 2012; Muthai et al., 2017; Braca et al., 2018). For instance, in their pan-African study involving 17 baobab provenances from six countries (Kenya, Malawi, Mali, Tanzania, Zambia and Zimbabwe), Muthai et al. (2017) found marked variations in pulp moisture, protein, fibre, ash and elemental content among the studied provenances, although provenance variations at national level were also found. For example, regarding crude protein, the West African provenances had the lowest contents while the East African provenances had the highest (Muthai et al., 2017). This compelled the authors to suggest the influence of soil other than climate alone, since Mali (West Africa) is characterised by soils that are poor in nitrogen, nitrates, or nitrites which essentially make up proteins in plant tissues (Muthai et al., 2017).

These results confirmed the earlier suggestion by Assogbadjo et al. (2012) that the biochemical composition of baobab tissues in Benin may be a reflection of the microsite soil properties on which the species are found, which, according to Muthai et al. (2017), is dependent on a number of factors including resource mobilisation, translocation and redistribution within the tree species as influenced by local environmental factors. It can also be argued that this is an interactive process between genetics of the species and climatic conditions resulting into phenotypes with varying capabilities of mining available nutrients for their metabolic processes, which may further explain the observed within-population variations in the biochemical compositions. The influence of soil properties on the nutritional traits of plants has also been reported in other indigenous fruit trees such as tamarind (*Tamarindus indica* L.) in Mali where marked genetic variation was also observed (van den Bilcke et al., 2014).

Recognising the influence of environmental factors such as edaphic characteristics on nutritive value can aid in selecting not only super plus trees for breeding (van den Bilcke et al., 2014), but also sites for cultivation and domestication. This is a critical step towards enhanced research and development for the expansion (increasing accessibility and availability) and utilisation of orphan species like baobab. For instance, to increase utilisation of iron and vitamin C in Benin, Assogbadjo et al. (2012) recommended the use of baobab populations from the Guinean zone, whereas those from the Sudanian Zone or Sudano-Guinean Zone should be targeted for calcium and Vitamin A utilisation.

The combined richness of iron and Vitamin C in the morphotypes from the Guinean zone presents an interesting opportunity for the utilisation of baobab, as it provides a double punch to the fight against malnutrition. Consumption of Vitamin C enhances iron bioavailability, and in this regard, baobab Vitamin C could improve non-heme iron absorption in the most vulnerable populations (Evang et al., 2020).

Baobab Is Revered by Local Communities and Is a Biocultural Keystone Species in the Country

A biocultural keystone species is a species which has disproportionally critical roles in local cultures (Shackleton et al., 2018). Culture identifies a group of people, and this is often reflected in the utilisation of food products (Bedigian, 2018; De Caluwe and Van Damme, 2011). Baobab plays a crucial role in the food culture of Benin, as it is used in the daily diets, influenced by age, gender and ethnic tribes (Codjia et al., 2003; De Caluwé et al., 2009).

In Benin, Chadare et al. (2008) identified 35 baobab food products processed from leaves, pulp, seeds and kernels (**Figures 2A–D**). The products have varying cultural importance and they include dough, gruel, drinks, sauces, snacks and flavouring agents. Local communities also ferment some

FIGURE 2 | (A–D) Traditionally processed baobab products: pulp powder **(A)** leaf powder **(B)** *Tayohounta* from kernels **(C)** and *Mutchayan* from pulp **(D)**.

products e.g., *Dikouanyouri* from seeds ($pH = 6.5$), *Tayohounta* from kernels ($pH = 7$), and *Mutchayan* from pulp ($pH = 4.2$). The authors reported that fermentation in *Dikouanyouri* is induced by *Bacillus* spp. (8.5 Log cfu/g), so too is *Tayohounta* (9.5 Log cfu/g), but *Mutchayan* is induced by lactic acid bacteria (8.1 Log cfu/g) and yeasts (7.2 Log cfu/g). While *Dikouanyouri* and *Tayohounta* are used as snacks and flavouring agents in sauces or drinks, *Mutchayan* is used as a beverage and main dish (Chadare et al., 2008, 2010).

The wide range of baobab products, as well as the associated knowledge and practises, provide an opportunity for research and development including technologies aimed at increasing access, availability and utilisation of baobab products in Benin and Africa. Further, premised on these findings, enhanced agro-technologies can be used to add value to the local products and minimise post-harvest handling losses, thus increasing access and availability of baobab food products. Besides, it is a considered view that the cultural context and existing local values of a particular species are effective springboards for collaboration between local communities and scientists (Waylen et al., 2010; Kettle et al., 2020). This is particularly important for the success and sustainability of research and development projects targeting the species upon which the communities rely for their livelihoods (Waylen et al., 2010; Allendorf et al., 2018).

Background Information on the Baobab Value Chain Is Available for Benin

Relating to non-timber forest products, Jensen (2009) considers a value chain analysis as a process of tracing the information flow from harvesting to consumers, aiding in clarifying the dynamics in the product value chain especially in light of commercialisation. The author further states that the principal aim of a value chain analysis in this regard is to elicit patterns of value addition and identify actors and domains of value-appropriation while showing responses to increased harvesting and scarcity of the resource. Indeed, value chain analyses help identify opportunities and constraints for the industry upon which recommendations could be drawn for various actors including decision makers to optimise the market and its enabling environment (Jäckering et al., 2019).

Accordingly, De Caluwe and Van Damme (2011) investigated the value chain of baobab by conducting interviews with stakeholders along the value chain in Benin and Mali. As is common with other countries such as Kenya (Jäckering et al., 2019), baobab products in Benin are harvested by smallholder farmers, mostly women, using traditional harvesting techniques which require low-cost tools and manual labour. Further, baobab products are made from low-cost and simple technologies, and are mostly sold at farm gates by women, contributing to an estimated 11% of the total income of the poorest household (De Caluwe and Van Damme, 2011). This implies that the baobab market is at a smallholder scale level in Benin. Further, it suggests that in addition to household consumption, baobab products help smallholder farmers earn considerable income which can help them diversify food products, thus enhancing access to food. The use of income generated from sales of baobab products to diversify food for households is common in Africa (Venter and Witkowski, 2013b; Wanjeri et al., 2020). In Nigeria alone, Onyekwelu et al. (2015) estimated that households could earn between US$ 300 and US$ 1,300 (representing 20–60% of annual household income varying along the value chain) from the sale of indigenous fruit tree products.

The high participation of women in the baobab value chain has also been recently reported in Kenya (Jäckering et al., 2019), where 72% of the respondents in the value chain analysis were women. The fact that women make the majority of the stakeholders in the baobab value chain and other indeginous fruit trees (Sanou et al., 2019a), offers an opportunity for enhancing women economic emancipation and reducing social inequalities in Benin and Africa, thereby contributing to the UN Sustainable Development Goal 5 (gender inequality) and Goal 10 (reduced inequalities), respectively.

Recent studies from Kenya (Jäckering et al., 2019) and Malawi (Darr et al., 2020) have shown that an improved baobab value chain could raise baobab products from the status of neglected and underutilised to being invaluable and premium–priced products in Africa and beyond. Through value addition, product diversification, good packaging and storage, wastage could substantially be reduced, thereby improving the accessibility, availability, utilisation and sustainability. Likewise, the baobab value chain in Benin also appears to be improving in the recent years, especially in processing and packaging, as evidenced by an influx of value-added products such as juices in the formal and informal markets.

Baobab Is Threatened by Climate Change but Is Amenable to Domestication

The need to domesticate baobab spans several years, and Gebauer et al. (2016) summarised a number of studies that are in agreement with this cause. The need arises from the increasing threats on baobab resources including wild animals and land use change such as forest clearing for agriculture (Wickens, 2007), commercialisation (Buchmann et al., 2010), as well as climate change (Sanchez et al., 2011; Birhane et al., 2020). These are expected to negatively affect accessibility, availability and sustainability of baobab resources.

According to Cuni Sanchez et al. (2011), only 5 to 48% of the current suitable habitat for baobab in West Africa would be suitable under future climatic conditions (c.f. 27 to 69% for East Africa), with Benin showing a marked contraction towards the south (Cuni Sanchez et al., 2011; Figure 2, p. 238). Further, no single current protected area in Benin is anticipated to host baobab in the future distributions (Cuni Sanchez et al., 2011; Table 3, p. 241). The wide range (5–48 %) and the marked variations between West and East African baobab populations may be an indication of how variable baobab populations will respond to climate change in West Africa and across Africa. Recent findings from East Africa of contractions in the baobab populations (41–100%) (Birhane et al., 2020), further support the evidence for baobab vulnerability to climate change. It is thus pertinent that conservation planning and utilisation strategies take these findings into consideration for the sustainability of baobab genetic resources.

Given that local communities in Benin regard baobab in high esteem, such that incipient management seems to be protecting baobab on farms (Assogbadjo et al., 2005a), provides an opportunity for domestication. This requires propagation materials, and different techniques exist (Sidibe and Williams, 2002; Verheij, 2006), which can be verified under local conditions. Accordingly, trials investigating the adaptable response of baobab populations to some of these techniques have been done in Benin. These include seed germination and vegetative propagation (e.g., grafting, stem cuttings, layering) (Assogbadjo et al., 2011).

Baobab seeds could be sown without scarification, as non-scarified seeds had registered the best germination rate (57%) by day 25 from the date of sowing, particularly from the Guinean zone (Assogbadjo et al., 2011). The authors recommended seed germination on sand substrate first before transferring the seedlings to the substrate with organic matter for further growth. The authors further recommended use of autochthonous seeds within specific climatic zones, as one measure towards maintaining genetic diversity.

Trials on vegetative propagation (Anjarwalla et al., 2017; Jenya et al., 2018), a review study on the same (Agbohessou et al., 2020) and use of seeds to produce edible root tubers (Jansen et al., 2020), all provide evidence of baobab amenability to domestication. These findings may be useful in the multiplication and domestication programmes of baobab to increase access to, and availability of baobab resources, thereby promoting sustainability of the baobab wild populations.

Besides, unlike seed propagation, vegetative propagation has advantages of reducing the fruiting delay in baobab from more than 10 years in the natural stands to <five years (Anjarwalla et al., 2017), and maintains valuable traits of the mother tree (Awodoyin et al., 2015). It is believed that improvements in earlier fruiting will create incentives to cultivate indigenous fruit

trees such as baobab (Omotayo and Aremu, 2020), since this will provide early rewards and therefore reduce investment costs on the part of the farmer (Mwase et al., 2015).

Baobab Productivity Is Improved by Fruit Bats

Baobab is a sexually reproducing species. Therefore, the importance of pollination ecology cannot be overemphasised: no pollination, no fruits! Thus, understanding what pollinates baobab is critical for the conservation of the genetic diversity of this species, particularly in view of the impacts of land-use change on the spatial distribution of species (Salako et al., 2019). The question regarding the pollination in baobab has eluded researchers for long, with both cross-pollination (fruit bats, wind, moths and hymenopterous insects) and self-pollination implicated (Sidibe and Williams, 2002; Wickens, 2007).

The contribution of fruit bats to pollination success in baobab was investigated in Benin by comparing pollination success in caged and non-caged flowers using freshly opened flowers (Djossa et al., 2015). Caging was by small nets that excluded bats, and fruit bat flower visitation was monitored for 2–8 weeks. The study was conducted in three sites: Comé-Houéyogbé district (Guinean Zone), Dassa district (Sudano-Guinean Zone) and Matéri district (Sudanian Zone). According to the authors, Dassa had the lowest visitation rate, suggesting low fruit bat abundance in the area, and non-caged flowers had higher pollination success than caged flowers (Djossa et al., 2015; Figure 5, p. 286). Since fruit-set and production were observed in both treatments, the authors did not rule out self-pollination and the involvement of other agents (sphingid moth species). Moreover, caged flowers showed a tendency to higher fruit abortion, compelling the researchers to suggest self-incompatibility owing to limited pollination success as a result of caging (Djossa et al., 2015).

Surprisingly, pollination success rates were the same among the populations, in spite of the observed significant differences in visitation rates (Djossa et al., 2015). This further compelled the authors to suggest probable differences in pollination efficiency by the fruit bats, with those of Dassa (lowest visitation rate) considered the most efficient. The involvement of fruit bats as pollinating agents and high fruit abortion rates in baobab has been reported elsewhere on the continent (Munthali et al., 2012; Taylor et al., 2020).

Although Djossa et al. (2015) did not solve the mystery surrounding pollination in baobab, but their findings suggest that fruit bats ought to be given space in the landscape for the conservation and sustainable utilisation of baobab genetic resources.

CHALLENGES AND CONSTRAINTS

In spite of the registered successes, there are a number of factors that are constraining the exploitation of the full potential of baobab to contribute to improved food and nutrition security in Benin. The challenges and constraints are drawn from Benin and also from lessons in other countries across Africa. It should also be noted that the identified factors tend to overlap and influence each other.

Low Consumption

Despite the generation of information on the nutritive values of baobab products (fruit pulp, leaves, seeds, and processed products), there appears to be low consumption levels of the products among other sectors of the society. Prevalence of low consumption of fruits and vegetables below the recommended daily intakes is a persistent phenomenon in developing countries (Okop et al., 2019).

For baobab, this could be due to many factors including: (i) low quality of baobab products (De Caluwe and Van Damme, 2011), which may put off other consumers and result into reduced market potential, both local and international (as discussed in the subsequent section); (ii) cultural beliefs, which may affect consumer preferences and therefore undermine utilisation and markets, as is the case in Kenya, where baobab food products like candies "mabuyu sweets" are considered the poor man's food (Kiprotich et al., 2019); (iii) lack of familiarity with baobab products and/or limited knowledge of preparation as reported in Nigeria (Omotesho et al., 2013) and Kenya (Kiprotich et al., 2019); (iv) negative attitudes towards wild foods and/or low interest in wild fruits (Darr et al., 2020), which may also result from low or limited consumer awareness and understanding of the various benefits of fruit consumption (Borelli et al., 2020); and (v) affordability, which may be influenced by fluctuating prices for baobab products and limited disposable income of consumers, especially in the urban areas, with larger households routinely consuming less baobab products (Kiprotich et al., 2019).

Indeed, according to Jamnadass et al. (2011), the current marketing systems of indigenous fruits are weak, poorly structured and coordinated, and characterised by high fruit prices for urban consumers, thereby limiting availability and accessibility of baobab products to consumers. Low fruit consumption among limited-resource urban consumers has also been reported by different authors (Bvenura and Sivakumar, 2017; Okop et al., 2019).

While affordability may affect consumption among stakeholders other than producers, it is also possible that producers themselves may consume less of baobab products due to high levels of poverty in the rural areas. Farmers may be forced to sell whatever little they harvest of baobab to earn an income, in view of the fact that trading of indigenous fruits or their derivatives is a lucrative enterprise in Africa (Onyekwelu et al., 2015; Omotayo and Aremu, 2020).

Put together, this shows that low consumption, which may arise from various socio-economic traps including cultural beliefs, limited knowledge on the benefits of fruit consumption and poverty, could partly explain why belts that are rich in baobab and other wild fruits are also synonymous with perpetual food and nutrition insecurity (Maruza et al., 2017; Momanyi et al., 2019). It has been shown in Malawi, though, that consumers' negative perceptions of baobab can be overcome by, among other things, proper design of the enterprise development that meets different segments of the consumers, capitalising on the changing preferences for natural, healthy and authentic food products by the urban middle class (Darr et al., 2020). Further, it has been suggested that awareness raising on the potential health and nutritive benefits of baobab could address many other constraints related to consumption, thereby enhancing the market demand for baobab which seems to be fast growing (Buchmann et al., 2010; Jäckering et al., 2019).

Aspects of limited knowledge on the preparation may lower utilisation of baobab products in several ways such as limiting the available dietary micronutrients and bioactive compounds, as well as wastage through poor preparation methods (Tembo et al., 2017). In this regard, Tembo et al. (2017) tested the effect of thermal treatment and storage of selected quality attributes of baobab juice. The study has shown that vitamin C can be retained by thermal pasteurisation (72°C, 15 s) with an extended shelf-life under refrigeration (6°C). If incorporated and up-scaled in baobab product development, these findings would go along away in increasing the consumption by way of increasing accessibility and availability of baobab products, especially to the urban populace and for export markets.

An additional aspect of perception, which is often opaque in the literature, is the perceived health risk associated with the consumption of baobab seed oil caused by cyclopropenoid fatty acids (CPFAs) (Msalilwa et al., 2020). This perception has the potential to lower the market demand, especially for the urban and export market (both regional and international) where such issues may become more glaring. Interestingly, using gas-liquid chromatography (GLC) in Tanzania, Msalilwa et al. (2020) found that the major breakdown of CPFAs occurs at 200°C. The authors have thus recommended the refining of baobab crude oil at higher temperatures (200–250°C) to reduce CPFAs. These findings too, if well-incorporated into the baobab enterprise development, would improve the market base for baobab, thereby increasing utilisation.

Low Quality of Products

Currently, the baobab industry is still largely rudimentary, characterised by low product quality (De Caluwe and Van Damme, 2011; Jäckering et al., 2019). Low product quality affects consumer demand with consequent poor economic returns to the producers. Considering that consumers have different preferences, improving the product quality can be a catalyst for better market development for orphan species like baobab. For instance, in Kenya, Meinhold and Darr (2020) have shown that establishment of community-based enterprises through multi-stakeholder engagement could promote the production of high-quality baobab products such as baobab powder and oil, thereby contributing to enhanced baobab management, increased acceptability by consumers and subsequent increased consumption and improved economic returns to the farmers.

Likewise, the development of vibrant local market chains of baobab in Benin would improve baobab product quality and subsequently provide a fertile ground for regional and international markets (De Caluwe and Van Damme, 2011). Low product quality, which is associated with low acceptability and therefore poor market, is considered a threat to orphan species and has been implicated in the displacement of orphan species by introduced species (Awodoyin et al., 2015).

Inadequate Investment in Formal Research and Development for Baobab Species Improvement

The existing investment in research and development for improvement of orphan species in general, and baobab species in particular, is generally low and almost nil in Benin. As such, most research is done at the mercy of teams of individuals who have dedicated their time to the plight of orphan species. This could be a consequence of local policy failure, or inadequate provision in strategies for orphan species as important species that could help mitigate the challenges of hunger and malnutrition. Currently, the existing food and nutrition regulatory frameworks in Benin such as the Strategic Plan for Development of Food and Nutrition (PSDAN) and Strategic Plan for Agricultural Sector Development (PSDSA) (2016–2021) do not put emphasis on orphan species in the fight against these challenges. As such, the national direction on research for orphan species is hazy and investment for research and development in such species is almost non-existent.

Consequently, harvesting of baobab is still from the wild, the whole value chain is still rudimentary, and the baobab species improvement remains a long, far-fetched dream. Inadequate investment in formal research and development for the improvement of orphan species including baobab is widely considered a challenge for many developing countries (Awodoyin et al., 2015; Marunda et al., 2019; Omotayo and Aremu, 2020). It is not surprising, therefore, that Africa has not yet started benefiting fully from baobab and other indigenous fruit trees. This is because rigorous research and development is key to addressing the numerous knowledge gaps such as those in production and/or harvesting, processing and marketing that constrain the unlocking of potential benefits from indigenous fruit trees (Awodoyin et al., 2015; Omotayo and Aremu, 2020).

Given that trading in indigenous fruits seems a lucrative adventure (Omotayo and Aremu, 2020), one would expect the private sector to invest in the baobab value chain. However, this is not the case for many countries in Africa (Marunda et al., 2019). This could be explained by the inadequacies in the national regulatory frameworks such as nutritional security, livelihood and poverty alleviation strategies that fail to embrace orphan species like baobab. The private sector is profit-oriented and requires an enabling business environment (e.g., stable markets), which is largely dictated by policy provisions. The impact of disabling policies and regulatory frameworks in failing to encourage production and consumption of orphan species through various aspects including limiting investment in research and development has been reported elsewhere (Borelli et al., 2020).

Limited Propagules for Domesticating Baobab

Insufficient and ineffective seed supply systems are some of the key constraints to smallholder agroforestry programmes based on native species like baobab (Kettle et al., 2020). In Africa, inadequate quality tree seedlings available to smallholder farmers is one of the barriers to adopting fruit cultivation

(Takoutsing et al., 2012; Mwase et al., 2015). This constraint is further compounded by an ineffective seed supply and technical backstopping system (Kettle et al., 2020), thereby limiting production and consumption of indigenous fruit products like baobab.

In Benin, for instance, although trials on seedling establishment and selected vegetative propagation techniques for baobab have been done (Assogbadjo et al., 2011), and preferred morphotypes have been identified in a participatory manner with the farmers (Assogbadjo et al., 2008), baobab is yet to be cultivated. This is due to a number of factors. Chief among them are limited investment into orphan species improvement and inadequate policy provision (as earlier discussed), as well as limited availability of quality planting material. However, in the event that planting materials are made available, the lack of a national research agenda on orphan species or indeed non-inclusion of orphan species in the national food security and nutrition strategies would affect the distribution of planting materials and associated extension messages, since such efforts would require major changes in the existing extension services (Sidibe and Williams, 2002). This suggests the need for concerted effort from all stakeholders and political will to multiply and make available planting materials of baobab for cultivation and/or domestication.

In this regard, the use of Agroforestry Rural Resource Centres (RRCs) (Takoutsing et al., 2012) could become useful for baobab. For instance, through RRCs, farmers in the Western Highlands of Cameroon are trained to multiply tree planting materials and also distribute planting materials (Takoutsing et al., 2012; Essougong et al., 2018). The centres also serve as platforms for knowledge exchange, thereby bridging the extension service gap (Takoutsing et al., 2012). According to Takoutsing et al. (2012), the approach has effectively improved the timely dissemination, accessibility, affordability and availability of quality planting materials. Through the RRCs, farmers also network with various stakeholders in commodity value chains such as financial lending institutions (Wouapi et al., 2019), which is important for farmer capital investment into fruit tree production.

The use of RRCs in Benin for baobab could help strengthen the seed system for baobab, through multiplication and distribution, given the current limited public extension service facilities. However, before rolling out the RRCs, it would be wise to conduct a feasibility study and/or pilot study to determine the practicability and acceptability of such innovations in the context of Benin. Such a study would be important in view of the fact that perceptions, preferences and attitudes, which may be influenced by socio-cultural factors, are among the strong determinants for farmer adoption of agroforestry technologies (Sanou et al., 2019b).

Low Production Levels

Since baobab, as for other indigenous fruit trees, is not domesticated, products are harvested from naturally growing and often low yielding trees. This undermines not only the quantity, but also the quality and stability of baobab products to meet the urban consumer demand and export market. It is recognised, though, that production may not increase if demand is low. However, evidence abound that the demand for baobab products is growing (Buchmann et al., 2010; Jäckering et al., 2019), but what is critical is the diversity and quality of products to meet consumer preferences, and market stability to stimulate more demand.

Moreover, collection from the wild is not sustainable considering that wild baobabs in Africa are characterised by low yields (averaging 80 kg fruits, 14 kg pulp, 23 kg seeds and 130 kg leaves annually per tree) (Habte and Krawinkel, 2018), with some trees consistently being very poor fruit producers (Venter and Witkowski, 2019), thus putting into question the baobab market stability.

Several factors have been suggested for the low productivity in baobabs, these include: old age for most trees (Sanchez, 2011); low pollination rates in baobab (Venter et al., 2017) mainly due to rarity of pollinators (Venter et al., 2017; Taylor et al., 2020), owing to sparse distribution of baobab as a result of land-use changes (Assogbadjo et al., 2005a; Venter and Witkowski, 2010); and high rates of fruit abortion (Djossa et al., 2015) due to maternal regulation (Verheij, 2006). Besides, high rates of predation (>85% loss) of young fruits by wild animals have also been reported (Venter and Witkowski, 2011), thus further compounding the low availability of harvestable fruits. All these put together, support the need for cultivation and domestication of baobab to increase production levels so as to meet the increasing urban and export market demand.

However, as pointed out earlier, baobab domestication is still at infancy in Africa. In Benin, for instance, in a study to investigate the local communities' motivations for plant domestication (Vodouhè and Dansi, 2012), reported that domestication of baobab was at stage two—naturally growing wild species maintained in the fields during land preparation. Therefore, cultivation could improve the production levels and somehow stabilise the market. It may also improve quality standards right from the production phase of the baobab value chain, thereby stimulating demand for baobab products.

To increase production through cultivation would require planting materials, which are currently inadequate (as discussed herein above). Moreover, poor farm management practises is one of the constraints to smallholder farmers' involvement in fruit cultivation in the SSA (Jamnadass et al., 2011). Again, RRCs could help in this case. Through RRCs, baobab farmers could gain technical skills in baobab cultivation, postharvest handling and marketing, so as to improve the availability and stability of baobab products even for export market.

The institutional organisation of farmers could also strengthen the farmers' bargaining power, which is currently weak owing to the weak marketing systems which disproportionate farmers with low farm- gate prices (Jamnadass et al., 2011). Consequently, farmers are unable to invest in fruit production because they cannot afford the high input investment costs which may unlikely be recouped (Jamnadass et al., 2011). However, as suggested herein above, a feasibility study through participatory approaches ought to be done to determine the practicability and acceptability of RRCs in this regard.

NEXT STEPS

Increase Awareness on the Health Benefits and Nutritive Values of Baobab

Attitudes have a long history in the use of wild food, and knowledge can play a crucial role in attitudinal change (Bvenura and Sivakumar, 2017). In this regard, increasing evidence of the nutritive value of orphan species like baobab can eventually lead not only to access (Borelli et al., 2020), but also proper utilisation, thereby helping address food and nutrition insecurity.

Malnutrition is a global public health concern, with global undernutrition as manifested in childhood stunting, wasting and underweight estimated at over one million deaths per year, and Africa having comparably the highest rates (Ssentongo et al., 2021). In Benin, anaemia is estimated at 72 % in children under the age of 6–59 months, and nearly 58% in women of reproduction age; 5% of the children under 5 years suffer from wasting; stunting is at 7.4%, whereas 12.4% of the population is diabetic (Hounkpatin et al., 2020). Therefore, raising the profile of nutritious dense plant species like baobab may enhance utilisation, consequently contributing to the fight against micronutrient deficiencies in Benin and Africa. This could be done by way of increasing awareness to all stakeholders in the baobab value chain including consumers and decision makers using evidence-based information. Recently, Kiprotich et al. (2019) found awareness levels had positive influence on the utilisation of baobab in Kenya. The need for increased public awareness to enhance the utilisation of orphan species for improved food and nutrition security in Africa has been echoed by many other scholars (Sogbohossou et al., 2018; Borelli et al., 2020).

Further, appropriate packaging of nutritive benefits from baobab targeting decision-makers may facilitate inclusion of baobab and other orphan species in relevant national policies and/or strategies as species of importance for ameliorating food and nutrition insecurity. Moreover, putting orphan species on the national agenda is a strategy many countries like Brazil, Kenya, Sri Lanka and Turkey are keenly pursing (Hunter et al., 2019) and lessons can be learnt from such countries.

Furthermore, increasing awareness to relevant decision makers including government and private sectors may also foster improved investment by way of financial investment, technological development and market creation. This would subsequently lead to improved research and development in the area of orphan species such as baobab, ultimately leading to increased accessibility, availability, utilisation and sustainability of agrobiodiversity for improved food and nutrition security.

Create Markets for Orphan Species

Deliberate policies ought to be made by the public and private sector to create markets for orphan species, which are already playing critical roles in rural livelihoods and food and nutrition security. Apart from access and availability, markets can help smallholder farmers earn income and motivate them to domesticate orphan species like baobab as is the case with "mainstream" crops (Borelli et al., 2020). One option for policy consideration in the market creation could be to use baobab as a novel species to help reduce iron deficiency in Benin and Africa, a challenge which is currently a public health concern in the view of the alarming prevalence rates (Hounkpatin et al., 2020). Consideration may be given to use some baobab food products in school feeding programmes, and as mandatory nutrient supplements for pregnant and lactating women.

Mandatory use of local agrobiodiversity in national feeding programmes like School feeding Programme has shown promising outcomes in Brazil (Wittman and Blesh, 2017; Resque et al., 2019), where government has decreed the use and public procurement of local agrobiodiversity in the national feeding programmes. Benin can borrow a leaf from these developments. Besides, this approach has triple effects: addressing malnutrition, improving income and livelihoods of smallholder farmers, and conservation of local agro-biodiversity for posterity.

Currently, Benin has the National Integrated School Feeding Programme and the Coordinated Early Childhood Nutrition and Development Project as the main interventions through which the government is striving to address malnutrition (Hounkpatin et al., 2020). According to Hounkpatin et al. (2020), these initiatives are showing positive outcomes this far. Therefore, incorporating baobab products as mandatory supplements in these programmes could go a long way in the fight against malnutrition, as the race against time to achieving Zero Hunger (Goal 2) of the 2030 Sustainable Development Goals is also becoming intense.

However, deciding the appropriate recipes and product formulations for both acceptability and positive outcomes will be some of the key aspects for consideration in such feeding programmes. It is apparent, though, that most African meals are cereal-based, and therefore baobab fruit pulp could enhance provitamin A carotenoid bioavailability in cereal formulations (Debelo et al., 2020).

Enhance Technological Development

Enhanced technologies could help improve the baobab value chain, considering that currently it is mostly rudimentary and at the smallholder level across Africa (De Caluwe and Van Damme, 2011; Jäckering et al., 2019), thus negatively impacting access, availability, utilisation and sustainability. The technologies and innovations may be critical to unlock and harness the potential benefits of baobab as these may be important in reducing most of the constraints currently faced along the value chain from production, harvesting, processing, storage, to research and development.

The technologies and innovations may include: (i) genes and crop development technologies, such as those that can facilitate integration of baobab into the production systems, and reduce farm labour requirements (Dawson et al., 2019); (ii) efficient and effective processing technologies, such as those that can help retain nutrients, enhance nutrient-bioaccessibility, and value addition technologies—those that lead to the development of high-quality food products in line with consumer demand; (iii) storage technologies, such as those that can increase the shelf life; and (iv) organisational and marketing innovations, such as traceability of raw materials along value chains. However, for adoptability, farmer input into the designs of the various technologies and innovations should be sought and gender dimensions ought to be considered (wherever applicable).

Scale-Out Multiplication of Planting Materials for Cultivation Programmes

Several studies have indicated the need to cultivate and domesticate baobab (Gebauer et al., 2016). The ultimate aim is to increase access and availability, as well as to promote sustainability of baobab resources which are currently threatened in the wild. However, the agroforestry adoption rate is currently low across Africa (Mwase et al., 2015; Sanou et al., 2019b). Various factors for this trend have been reported including gender and household farm-size (Mwase et al., 2015; Sanou et al., 2019b), local community needs and preferences influenced by local traditional practises and cultural context (Waylen et al., 2010; Poole et al., 2016), as well as inadequate planting material (Mwase et al., 2015). Therefore, to ensure adoptability and sustainability of baobab, multiplication and domestication programmes should consider these dynamics, and should build on the existing local decision-making tools (Kettle et al., 2020).

Incipient management of baobab is already high among communities in Benin. Similarly, farmers in other countries such as Niger have shown high preference for agroforestry systems based on baobab species (Agúndez et al., 2020), thus providing potential for adoptability of baobab cultivation programmes that would eventually require planting materials. As stated earlier, RRCs as used in Cameroon could become useful platforms for multiplication and vehicles for distribution of baobab planting materials in Benin to scale-out cultivation of the species. They could also be used for awareness raising on various ecosystem services that could be accrued from incorporating baobab as an agroforestry tree, thereby increasing the adoption rate, eventually contributing to increased availability and accessibility of baobab.

Address Research Gaps in the Reproductive Ecology, Sustainable Harvesting, and Effect of Drought Stress on Quality of Baobab

From the foregoing, it is apparent that there are a couple of research gaps in baobab to enhance its sustainable utilisation for improved food and nutrition security. For instance, although fruit bats are coming out strongly as pollinating agents of the baobab (Sidibe and Williams, 2002; Djossa et al., 2015; Taylor et al., 2020), but the role of arthropods such as hawk moths remains a mystery (Sidibe and Williams, 2002; Taylor et al., 2020), and the general knowledge of the baobab reproductive biology including mating systems is evidently lacking (Venter and Witkowski, 2019). A clear understanding of the dynamics of pollination/reproduction ecology in baobab is critical for the design and planning of conservation programmes for the sustainability of baobab resources. Some of the research questions in this regard may include: (1) Do baobabs have mixed mating systems which are site specific? (2) What is the degree of fertility in baobab populations; (3) What percentage of ovules in baobab fruit can be attributed to lack of fertilisation, abortion and pre-dispersal seed predation?

Research on sustainable harvesting (leaves and fruits in this context) is also an important area for the sustainable utilisation of baobab. For instance, leaf harvesting, according to Dhillion and Gustad (2004) causes mutilation in baobab, consequently resulting in fruit reduction; whereas, fruit harvesting impacts dispersal and establishment (Shackleton et al., 2018). Similarly, while baobab is generally considered drought tolerant (Sidibe and Williams, 2002), but there are variations between populations (Cuni Sanchez et al., 2010), and poor seedling establishment due to infrequent rainfall has been reported in South Africa (Venter and Witkowski, 2013a), suggesting baobab vulnerability to the looming reduced precipitation (Dai, 2013). Understanding the impact of drought stress on the quality of pulp and leaves will therefore aid in planning for breeding programmes for enhanced access, availability and sustainability. In this regard, answers are needed to these questions: (1) What are the seasonal variations in the yield of baobab leaves and pulp across ecological climatic zones? (2) What quantities can be considered sustainable harvest, and how could these be achieved? (3) How does drought stress affect the biochemical and nutritional composition of baobab pulp and leaves?

To reduce competition for land in the agro-ecosystems, given the small household land holding size in Benin (<2 ha) (Adjimoti, 2018), investigations on how exactly baobab fits into these agro-ecosystems would be important. For instance, it would be important to know: (1) Which crops compete with baobab, and which ones are either outcompeted or facilitated by its presence? (2) What are the appropriate planting densities that would allow both the establishment of viable baobab populations and ecosystem services enhancement on farm? Further, given that baobab has variant tree shapes (Gebauer et al., 2016) and local communities use a matrix of criteria to identify baobab morphotypes with preferred qualities (Assogbadjo et al., 2008), it would also be worth investigating the correlation between these morphotypes (e.g., tree shape) with the preferred qualities of baobab leaves and fruit (Rashford, 2018).

Baobab Breeding

Cultivation using seedlings (to increase variability) and vegetative or clonal material (to maintain the preferred traits) may serve as a short-and medium-term strategy to enhance access to, and availability of baobab resources. Whereas, breeding for improvement should be considered as a long-term strategy. Since fruits, leaves and seeds are used for food and nutrition, a national research agenda ought to be made: whether the breeding programme should focus on leaves or fruits, or both. In this regard, Ræbild et al. (2011) recommended the testing, selection of super plus material and multiplication of young baobab plants for leaf production breeding programmes, and the testing and evaluation of mature trees for fruit character breeding. Considering that baobab pulp has more export potential and leaves are more important for the daily household needs in West Africa (Jensen et al., 2011), and given the existing variations in the cultural importance of leaves and fruit products in Benin and West Africa (De Caluwé et al., 2009; Buchmann et al., 2010; De Caluwe and Van Damme, 2011), it would be wise if both approaches were pursued to meet the diverse needs and market demands.

In either case, breeding focusing on reducing the maturity period, tree size (dwarfism) and yield increase is recommended. The huge size of baobab is a limiting factor not only for management (Awodoyin et al., 2015), but also access to baobab resources (fruits, seeds and leaves), as harvesting is usually difficult from very tall trees, and often leads to poor quality harvest (Verheij, 2006).

It is evident that in Africa, unlike in other continents, smallholder farmers lack better practises for fruit tree management on farm (Jamnadass et al., 2011) and indigenous fruit tree improvement programmes are either inadequate for some species or non-existent for others. Perhaps this is because for a long time, research efforts on orphan plant species have mostly been related to species ecology and biology, genetics, ethnobotany, and chemical/nutrient composition. It is only until the late 1980s that researchers began to seriously consider elements of domestication and plant breeding (Jamnadass et al., 2011), and more recently commercialisation (i.e., markets, products, value chains) (e.g., De Caluwe and Van Damme, 2011; Jäckering et al., 2019). This might explain why Africa is where it is now with regard to indigenous fruit tree cultivation and/or domestication and enterprise development.

Encouragingly, laudable efforts are being made by the African Orphan Crops Consortium, which is currently empowering African plant breeders in the use of advanced genetic approaches to tailor-breed orphan species including baobab to the needs of the local producers, processors and consumers in Africa and beyond (Jamnadass et al., 2020). These efforts dovetail nicely with the aspirations for baobab breeding in as far as this study is concerned.

CONCLUSIONS

As for many other orphan species, research on baobab has for many years focused on its biology, genetics, ecology, ethnobotany, propagation, and chemical and/or nutrition composition. Commercialization, domestication and plant breeding of the species have, until recently lagged behind, largely due to inadequate capacity in these subject areas among African scientists. This has undermined baobab product development, subsequently limiting accessibility to, and availability, utilisation and sustainability of baobab resources. Encouragingly, capacity has increasingly grown over the past decade, thanks to the support from cooperating partners such as the World Agroforestry Centre (ICRAF) and many others.

To date, substantial information has been generated and practical solutions along these subject areas have been developed that could inform decision making regarding unlocking and harnessing the potential benefits of baobab for improved food and nutrition security in Benin and Africa. The use of evidence-based information to unlock the potential values of orphan species is considered paramount, as this can help change attitudes regarding orphan species across all divides of stakeholders (Borelli et al., 2020).

Various factors constrain the full potential of baobab to contribute to improved food and nutrition security. These include low consumption, low production levels, and inadequate investment in research and development for baobab species domestication and improvement. These are essentially limiting accessibility to, and availability, utilisation and sustainability of baobab resources. There is need, therefore, to increase awareness on the nutritive values of baobab, enhance domestication and technological development considering gender dimensions, define the national research agenda on the role of orphan species in nutrition, and increase investment in research and development. Practical solutions from Cameroon and Brazil that could promote the cultivation and consumption of baobab, are worth emulating going forward.

To enhance and unlock the potential benefits of orphan species like baobab to contribute to improved food and nutrition security requires active participation of all stakeholders along the product value chain including farmers, researchers and policy makers. Indeed, with stronger synergies among interested stakeholders and better connection between science and policy (Hunter et al., 2019), orphan species such as baobab could transform the food systems and livelihoods in Africa.

AUTHOR CONTRIBUTIONS

AA and LM conceived the idea. AA designed the methodology and manuscript outline and gathered the publications. LM drafted the manuscript. FC and BS critically reviewed the manuscript. All authors read and approved the submitted version.

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