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Conference on 'Food and nutrition security in Africa: new challenges and opportunities for sustainability'

Is there a place for nutrition-sensitive agriculture?

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The focus of the review paper is to discuss how biotechnological innovations are opening new frontiers to mitigate nutrition in key agricultural crops with potential for large-scale health impact to people in Africa. The general objective of the Africa Biofortified Sorghum (ABS) project is to develop and deploy sorghum with enhanced pro-vitamin A to farmers and end-users in Africa to alleviate vitamin A-related micronutrient deficiency diseases. To achieve this objective the project technology development team has developed several promising high pro-vitamin A sorghum events. ABS 203 events are so far the most advanced and well-characterised lead events with about 12 µg β-carotene/g tissue which would supply about 40–50 % of the daily recommended vitamin A at harvest. Through gene expression optimisation other events with higher amounts of pro-vitamin A, including ABS 214, ABS 235, ABS 239 with 25, 30–40, 40–50 µg β-carotene/g tissue, respectively, have been developed. ABS 239 would provide twice recommended pro-vitamin A at harvest, 50–90 % after 3 months storage and 13–45 % after 6 months storage for children. Preliminary results of introgression of ABS pro-vitamin A traits into local sorghum varieties in target countries Nigeria and Kenya show stable introgression of ABS vitamin A into local farmer-preferred sorghums varieties. ABS gene Intellectual Property Rights and Freedom to Operate have been donated for use royalty free for Africa. Prior to the focus on the current target countries, the project was implemented by fourteen institutions in Africa and the USA. For the next 5 years, the project will complete ABS product development, complete regulatory science data package and apply for product deregulation in target African countries.

Africa Biofortified Sorghum: Vitamin A: Malnutrition

Vitamin A deficiency is of public health significance in the developing world. Vitamin A deficiency is the world's commonest cause of childhood blindness, with about 228 million children affected sub-clinically and 500 000 children becoming partially or totally blind every year.[1]. More than half of the cases occur in developing countries and this is attributed to the consumption of vitamin A deficient diets[2]. Young children are the most vulnerable with globally 140 million children aged 5 years, of whom nearly 100 million live in South Asia or

Abbreviations: ABS, Africa Biofortified Sorghum; CFT, confined field trials; ICRISAT, International Crops Research Institute for the Semi-Arid-Tropics; OPV, open pollinated varieties.

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sub-Saharan Africa, have low serum retinol concentrations (<0·7 μmol/l)[3]. Countries of Eastern and Southern Africa have the highest prevalence (37 %) of preschool children with low serum retinol concentrations, followed by South Asia (35 %) and Western and Central Africa (33 %)[3]. In South Africa, one in three preschool children has a serum retinol concentration <0·7 μmol/l[4], and 55–68 % of children aged 1–9 years consume <50 % of the recommended dietary intake of vitamin A (700 μg retinol equivalents)[5]; children living in rural areas are the most affected[4,5]. Vitamin A deficiency is caused by a habitual diet that provides too little bioavailable vitamin A to meet physiologic needs[6]. Rapid growth and frequent infections, which cause ineffective utilisation of the vitamin, are also critical factors[7].

Strategies to control vitamin A deficiency include dietary diversification, food fortification and vitamin A supplementation[1,6,8]. Animal-sourced foods, although good sources of vitamin A, are too expensive for poor communities to afford[9]. This leaves foods of plantrigin as an important source of pro-vitamin A in the developing countries. Dietary diversification includes the production of carotene-rich crops, such as orange-fleshed sweet potato[6]. However, dietary diversification has limited impact in arid and semi-arid regions of Africa because of frequent droughts and lack of alternative foods. Of the 600 carotenoids found in nature, only three are important precursors of vitamin A in human subjects, namely, α-carotene, β-carotene and β-cryptoxanthin. β-Carotene is the major pro-vitamin A component of most carotenoid-containing foods[10]. The general objective of Africa Biofortified Sorghum (ABS) project is to develop and deploy sorghum enhanced with pro-vitamin A as the first priority product targeting people living in arid and semi-arid areas where sorghum is the main staple food.

Progress in technology development

To achieve the objective of alleviating malnutrition in Africa, the ABS project has envisaged developing and deploying three ABS products in the following decreasing order of priority: the first priority product is ABS with enhanced pro-vitamin A alone; the second will be ABS with enhanced pro-vitamin A and bioavailable zinc and iron; the third will be ABS with enhanced pro-vitamin A and bioavailable zinc and iron, and also improved protein quality and digestibility[11–13].

However, because the development and deployment of genetically modified food products are expensive and time consuming, the project will not embark on development of the three products simultaneously. Emulating and learning from the model used by Golden Rice Project, the ABS project is now focusing on development and deployment of ABS with enhanced pro-vitamin A alone, as the first product. In addition to product prioritisation, the countries of ABS product deployment have been prioritised and the first three priority countries are Nigeria, Burkina Faso and Kenya[11,12].

To develop the first product, the ABS technology development team led by DuPont Pioneer had developed several promising events. Africa Harvest, working with teams in Nigeria (the IAR and NABDA) and Kenya (KALRO) are carrying out the confined field trials (CFT). ABS 203 is so far the most advanced and well-characterised lead event for commercialisation. The event has about 12 μg β-carotene/g tissue which would supply about 40–50 % of the daily recommended vitamin A at harvest. In addition, the pro-vitamin A in ABS 203 is stabilised by the expression of vitamin E in the sorghum seeds. The event has been approved for CFT in Nigeria, while a CFT application is under consideration in Kenya. To ensure ABS project sustainability, DuPont Pioneer and Africa Harvest are continuously developing and evaluating other improved ABS events for technology backstopping.

Through application of gene sorting and optimisation of gene expression approaches, the DuPont Pioneer technology team has developed other improved ABS events that are under evaluation. These include ABS 214, 220, 235 and ABS 239. ABS 214 and 220 are under CFT evaluation in Johnston, Iowa in the USA. The purpose of this CFT is to evaluate the yield and other agronomic performances of ABS 214 and 220 that have β-carotene accumulation up to 25 μg/g. The CFT results demonstrated that higher β-carotene accumulation of up to 25 μg/g does not cause yield penalty. Through gene expression optimisation events ABS 235, ABS 239 have been developed with stronger red-orange colour than ABS 214 (25 μg β-carotene/g tissue) which indicates much higher β-carotene accumulation. Preliminary data from DuPont Pioneer indicate that ABS 239 event accumulate β-carotene in a range between 40 and 50 μg/g as shown by the chromatograms analysis, while ABS 235 has 30–40 μg β-carotene/g tissue.

The ABS pro-vitamin A, is similar to pro-vitamin A from all plant food sources such as carrots and spinach, as opposed to vitamin A from animals which is the retinol form of vitamin A.

Biochemical forms of vitamin A: retinol and pro-vitamin A

The ABS vitamin A is referred as pro-vitamin A. This is because vitamin A found in foods occurs in two major categories; retinol is the form of vitamin A found in food of animal origin and is readily used by the body. In plants, vitamin A occurs in the form of carotenes that include α-carotene, β-carotene, γ-carotene and the xanthophyll β-cryptoxanthin[14]. The most important of these is β-carotene because it is more readily converted into retinol that is used by the human body[15]. The rate of conversion varies from plant to plant and for ABS this is being determined but a conservative factor of 6 : 1 (i.e. six molecules of β-carotene give one molecule of retinol) is presently being used. The advantage of human subjects eating vitamin A in the form of pro-vitamin A rather than retinol is because when the body has adequate vitamin A, it automatically stops conversion of pro-vitamin A into retinol, avoiding the problem

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of vitamin A toxicity called hypervitaminosis A[14,16,17]. High doses of β-carotene (up to 180 mg/d) have been used to treat erythropoietic protoporphyria, a photosensitivity disorder, without toxic side effects[15]. That is why we do not get vitamin A toxicity when we eat high pro-vitamin A foods, such as carrots or spinach.

It is also noteworthy that the human body will only obtain nutritional benefits from ABS when it is eaten and converted into retinol. That is why the information on what quantities should be eaten and what is the conversion factor of β-carotene into retinol is so critical.

How much of the biofortified food should the consumer eat?

Although vitamin A is mostly known for improving human vision it has two other beneficial nutritional functions in the human body: first, it is important for growth and development and second, it is critical for the maintenance of the immune system. The vitamin A used for improved vision is retinol.

However, one pertinent question is how much the consumer should eat to derive nutritional benefits from biofortified foods such as ABS. The amount that one eats to get benefits from pro-vitamin A will depend on five factors: stability of vitamin A when processed or stored; bio-availability of pro-vitamin in the body; conversion factor of β-carotene from ABS into retinol; presence of fat in the diet; age of the person consuming[18–22]. The bio-conversion of β-carotene into retinol in (μg β-carotene to μg retinol) has been determined for several biofortified foods to be 3·5 : 1, 6·5 : 1, 6·7 : 1 for golden rice (eaten with high fat content, low fat and no fat diet, respectively), 3·7 : 1 for biofortified cassava, 13·4 : 1 for high carotenoid maize, 15 : 1 for orange sweet potatoes, 21·1 : 1 for carrots and spinach (21 : 1)[19,22–25]. The retention of β-carotene after cooking has been determined to be 88–92 % and 70–80 % for medium-sized sweet potato roots of the same size and when roots of different sizes were boiled, respectively[26].

Reduced stability of pro-vitamin A with storage and process is a challenge to all biofortification programmes globally. A recent extensive review on the retention of conventionally bred pro-vitamin A biofortified cassava, maize and sweet potatoes after processing, cooking and storing biofortification has been reported[27]. Sun drying was more detrimental to pro-vitamin A levels (27–56 % retention) in cassava than shade (59 %) or oven (55–91 %) drying. The pro-vitamin A retention levels of sweet potatoes ranged from 66 to 96 % and did not significantly differ among the various drying methods. Overall, boiling and steaming had higher pro-vitamin retention (80–98 %) compared with baking (30–70 %) and frying (18–54 %). Gari, the most popular cassava dish consumed in West Africa had a pro-vitamin A retention of 10–30 %. The pro-vitamin A retention of staple crops during storage reached levels as low as 20 % after 1–4 months storage and was highly dependent on genotype[27].

Several studies have quantified amount of biofortified foods to eat and the retinol activity equivalents. Zimbabwean men eating 300 g cooked high carotenoid maize received 40–50 % of the adult vitamin A US RDA[28]. For golden rice with 20–30 μg β-carotene/g tissue, 100 g rice would provide 500–800 μg retinol representing 80–90 % of the estimated average requirements for men and 55–70 % of the estimated daily average requirement (RDA) for women. A total of 50 g golden rice served to children aged 4–8 years would provide >90 % of vitamin A estimated average requirements (275 μg) or >60 % RDA[18].

There are ongoing studies at various ABS collaborating institutions involving competent nutritionists to determine the importance of these factors in determining the nutritional benefits of ABS. Preliminary results using conservative figures show that ABS 203 with 12 μg β-carotene/g tissue will meet 40–50 % of RDA for children, while other events such as ABS 235 and 239 will give higher benefits. Pro-vitamin A in ABS 203 has been stabilised through the expression of 15 μg/g vitamin A and has a half-life of 10 weeks. ABS 239 with 50 μg β-carotene/g tissue would provide 2 × RDA pro-vitamin A for children after harvest, 50–90 % after 3 months storage and 13–45 % after 6 months storage. Both ABS 203 and ABS 239 have their pro-vitamin A stabilised by expression of vitamin E (tocopherol).

Biosafety of Africa Biofortified Sorghum genes and gene products

The ABS project will develop a full regulatory biosafety package that will be submitted to the National Biosafety Authorities in Kenya, Nigeria and Burkina Faso for deregulation and commercialisation. The regulatory package will cover the standard core and event specific regulatory data packages. However, preliminary biosafety data show that the genes and their gene product used in developing ABS have no likelihood of eliciting toxicological and allergenic reaction when consumed.

ABS events are based on the use of similar genes used in development of golden rice, including *crt1, pmi* and *psy1*, except for vitamin E gene *hv-hggt*. The *psy1* gene that encodes phytoene synthase and *crt1* that encodes carotene desaturase I have been introduced in the ABS to catalyse the biosynthesis of pro-vitamin A. The ABS events did not use herbicide resistance genes but instead used *pmi* gene which encodes phosphomannose isomerase as the selectable marker gene and the latter has been deregulated. Bioinformatics analysis and digestibility studies for these proteins, phosphomannose isomerase, carotene desaturase I and phytoene synthase protein that have been done for golden rice development showed that the expressed proteins were neither toxic nor allergenic.

Approaches for wide adoption and impact of Africa Biofortified Sorghum

Factors determining adoptions of new agricultural technologies especially in the developing countries are widely studied and documented. These include: economic

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benefits, availability of technology transfer supporting packages, such as seeds and fertiliser, availability of market pull, credit to facilitate farmers to purchase inputs, supporting government policies and regulatory framework[29–32]. Although the importance and magnitude of the influence of these factors will be country and target-area specific, we expect the same factors to influence the adoption of ABS.

The ABS project has proactively embarked on positive modulation measures of some selected factors to spur wide adoption of high nutritious pro-vitamin A sorghum in target countries. Key to these include deploying sorghum in already commercialised and widely adopted open pollinated sorghum varieties, developing sorghum seeds system for the deployment of quality seeds to farmers in partnership with other stakeholders and examining the future potential of deploying high pro-vitamin sorghum through sorghum hybrids that will ensure high yields and, better maintenance of seed and trait quality.

Introgression of high pro-vitamin A in widely adopted open pollinated sorghum varieties

High pro-vitamin A sorghum will be deployed in local adopted National Agricultural Research Stations /International Crops Research Institute for the Semi-Arid-Tropics (ICRISAT) sorghum varieties with wide adoption through introgression[12]. Two primary regions selected for deployment include: (i) East-Africa/ Anglo-phone and (ii) West-Africa/Franco-phone and West-Africa/Anglo-phone[13,33]. There are also plans to extend deployment to Southern and Northern Africa. Nigeria (through the ICRISAT/National Agricultural Research Stations system) has selected sorghum varieties that have wide regional adaptation and acceptance. These include SAMSORG 40, SAMSORG 14 and SAMSORG 17[34]. These varieties were developed through joint efforts of ICRISAT and National Agricultural Research Stations. SAMSORG 14, 17 and 40 were selected for the West-Africa Anglo-phone[13]. SAMSORG 40 (ICSV 400) is a short season variety (matures in 95–100 d) adapted to Sudan Savannah ecology (Fig. 1). SAMSORG 17 (KSV3 (SK5912)-is a long season variety (matures in 165–175 d) adapted to Southern Guinea Savannah ecology. Both SAMSORG 40 and 17 yield 2·5–3·5 tonnes (t)/ha. SAMSORG 14 (KSV8) is a medium season variety (matures in 130–140 d) adapted to Northern Guinea Savannah ecology. It yields 2·5–3·0 t/ha[34]. The Guinea Savannah and Sudan Savannah are the vast stretch of African savannah land that spreads across ten countries in West Africa and has the potential to turn several African nations into global players in bulk commodity production, according to a study just published by FAO and the World Bank (Fig. 1).

For Eastern and Southern Africa ABS traits will be introgressed into Tegemeo (2KX 17/B/I), Macia (SDS 3220), KARI Mtama I and Gadam sorghum varieties. The improved sorghum variety Macia (SDS 3220) was released on 14 December 1999 by the Tanzania National Variety Release Committee. Macia is a high-yielding, early maturing, white-grained variety jointly developed by ICRISAT and national scientists in Southern Africa. It has so far been released in five South African Development Community countries of Mozambique, Botswana (under the name Phofu), Zimbabwe, Namibia and Tanzania. It is suitable for areas with a growing season of 3–4 months and yield up to 4 t/ha[36–38].

KARI Mtama I sorghum variety is mainly grown in Kenya and matures in 3–3·5 months with white grain

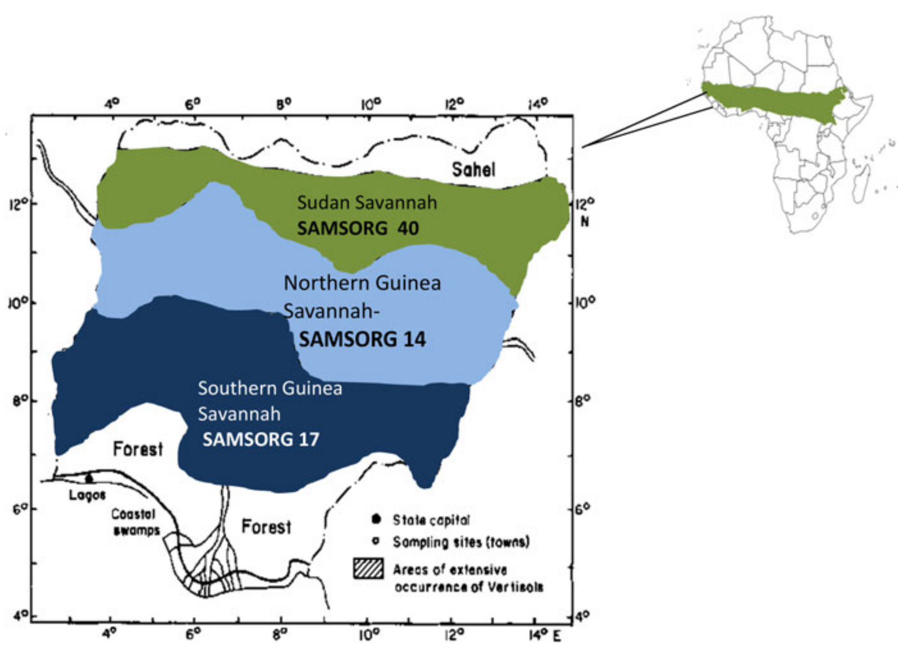

Fig. 1. (Colour online) The Guinea Savannah and Sudan Savannah regions of Nigeria and their extension into other African countries showing selection of appropriate sorghum (SAMSORG) variety[35].

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colour and has wide adaptation. It grows in moist mid-latitudes of Kenya (Busia, Siaya and Homa Bay), semi-arid low lands (Kitui, Makuweni, Mwingi and Ntharaka) and humid Coast (Kwale, Kilifi and Taita Taveta)[39]. Tegemeo sorghum variety was released in Tanzania in 1986 and on-station yield of 4·2 t/ha has been reported in Tanzania with a yield advantage of 114 % over the local unimproved cultivars and is also grown in Kenya.

Development of sorghum seed systems

Prerequisite to availability of quality seeds for small-scale farmers is the development of a functional formal seed system especially when dealing with biotech crops. In general, a functional seed system comprises organisations, individuals and institutions involved in different seed system functions that include the development, multiplication, processing, storage, distribution and marketing of seeds. Rules and regulations such as variety release procedures, intellectual property rights, certification programmes, seed standards and contract laws influence the structure, coordination and performance of the seed system[40].

A quick appraisal of sorghum seed systems in ABS target countries shows that Kenya has an established formal seed system dealing with hybrid maize consisting of several companies that are now diversifying into sorghum seed[41,42]. The Kenya Plant Health Inspectorate Services implements the regulatory role consisting of seed certification and registration. Among ABS target countries, Kenya has established seed companies marketing sorghum including Kenya Seed company and Western Seed Company[42].

Nigeria has a rudimentary formal seed system with fewer seed companies involved in marketing quality seeds. Seed certification in Nigeria is done by the Plant Quarantine Service of the Federal Department of Agriculture. In Kenya, ABS in partnership with other stakeholders needs to help streamline the seed system to manage the deployment of biotech seeds. In Nigeria considerable efforts will be required to get quality ABS seeds to the farmers.

Deployment of high pro-vitamin A sorghum hybrids

Sorghum hybrid will be ideal for deployment for ABS pro-vitamin A traits. Hybrids ensure high economic benefits of the technology and better quality maintenance of ABS traits compared with open pollinated variety (OPV). However, sorghum hybrids development and deployment in Africa is in its infancy. The grain productivity increased by 47 % in China and 50 % in India, which corresponds well with adaptation of hybrids in these countries[42]. In the USA, Australia and China, over 95 % of the sorghum area is planted with hybrid sorghum. In India, over 85 % of the rainy season sorghum is planted with hybrids. The hybrid vigour was discovered in 1927 and the germplasm used to develop hybrid sorghum in other countries originated from Africa, which is the centre of origin of sorghum. It is a paradox that in Africa the development and commercialisation of hybrid sorghum is at infancy.

Experience of the West African Sorghum Hybrids Adaptation Trials by ICRISAT, in the mid-1980s in seventeen West Africa countries[43] is that the low yields inherent in OPV can be raised by shift to hybrid sorghum. Virtually everywhere the sorghum hybrids and inbred varieties were compared, hybrids showed a yield advantage, commonly of 20–60 % over the inbred varieties[44].

As growing conditions become more stressed, the yields of hybrid and OPV landraces decline, but the yield differences between hybrids and OPV become proportionately larger in favour of the hybrids[44]. Out of the seventeen sorghum-growing countries in West and Central Africa, only Mali, Nigeria and Niger have formally released sorghum hybrids. In Mali, for example, four sorghum hybrids, including 'Fadda' Sigui-kumbe, Sewa and Bensema were released in 2008. Large-scale testing of this and other hybrid is ongoing in Niger and Nigeria[45,46].

These successful model of sorghum hybrid technology transferred to smallholder farmers show that the technology is appropriate for increasing food security and nutrition among smallholder farmers in Africa. However, the coverage of these hybrids in West and East Africa remains insignificant. For Nigeria, hybrids were developed for the malting industry; in Kenya preliminary research shows that sorghum hybrids can yield up to 50 % more than OPV. Despite the demonstrated yield superiority of hybrid sorghum, sorghum-farming systems in Africa are still dominated by the low-yielding varieties. It cannot therefore be overemphasised that future deployment of ABS nutrients in sorghum hybrids will greatly enhance the economic benefits of the technology. Although biofortification has great potential to alleviate malnutrition in Africa, there are other complementary alternative methods for curbing malnutrition.

Alternatives to biofortification for alleviating micronutrient deficiency

The key strategies for alleviating the global problem of malnutrition include food fortification, dietary diversification, dietary supplementation, nutrition education and public health measures to control intestinal parasites and other infectious diseases[47]. These approaches are complementary and their application and benefits to the target population vary depending on prevailing socio-economic status, eating habits and infrastructure among others.

Food fortification

Fortification has been a major strategy aimed at improving the nutritional quality of the food supply in industrialised countries for many decades but has only recently been applied in many developing countries[47]. It is arguably the most cost-effective and practically feasible strategy in the short term. A review of some of the literature

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on cost-effectiveness and cost–benefit of food fortification strategies as they apply to developing countries has been reported[48].

The favourable cost-effectiveness (as measured by the cost per death averted or cost per disability-adjusted life-year saved[49]) has helped to give fortification high priority as a preventive health-care intervention. Fortification with iron, iodine and potentially zinc provides significant economic benefits and the low unit cost of food fortification ensures large benefit : cost ratios, with effects via cognition being very important for iron and iodine[48]. High benefit: cost ratios (comparing the economic benefits and costs of fortification) have likewise put fortification in the forefront in public policy regarding social sector investments[48]. The relatively low unit costs of food fortification along with the proven benefits to the quality of life of the poor in developing countries contribute to large benefit : cost ratios and justify the investment[48]. *Ex ante* economic analysis shows that ABS has a benefit : cost ratio that is at least 10 and cost per disability adjusted life-years saved of < US$100, twenty times more cost-effective than WHO and World Bank average[50].

However, similar to biofortification outlined in the preceding sections, the success of a fortification programme depends on several prevailing factors. These include: the presence of suitable food vehicle that is widely consumed, a centralised food-processing infrastructure[47,48], availability of nutritional surveillance procedures, technical expertise to ensure uniform addition of the nutrients to the food at low costs; availability of suitable fortificants in forms that are stable to storage and cooking; suitable government oversight and quality control procedures to monitor addition to the food vehicle; an education programme to inform people of the benefits of consuming fortified foods; continued nutrition-monitoring programmes to assess the impact of fortification and to guard against excessive intakes of nutrition[47]. Although many if not all of the earlier conditions are in place in most industrialised nations, many less-developed countries lack the resources to meet them, creating difficult challenges for implementing a successful fortification programme[47].

However, despite these challenges, it re-emphasises that, based on economic analysis, fortification is a very high priority investment, but will not reach all individuals and is the most attractive as an investment where there is a convenient food vehicle, where processing is more centralised, and where either the deficiency is widespread or the adverse effects are very costly even though only a small group is affected[48]. It is further reported that fortification of the selected nutrients has been shown to have a significant impact on reducing child mortality, improving cognitive development and raising economic status[48]. However, there are populations hard to reach with commercial fortification particularly those living in remote geographical areas and or not utilising purchased foods[48].

Conclusions

The Africa Biofortified Sorghum project complements other approaches for alleviating malnutrition such as food fortification, dietary diversification and dietary supplementation. The project has made tremendous progress towards the development of ABS product. To date several ABS events with optimised amounts of β-carotene have been developed. The key tasks left include introgression of ABS traits into local sorghum varieties, development of full biosafety and regulatory data package, nutritional studies and development of seed systems for commercialisation of final ABS product. To fully realise these key objectives the project urgently needs further multi-donor financial support.

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Conflicts of Interest

None.

Authorship

All authors were jointly responsible for all aspects of research and of preparation of this paper.

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