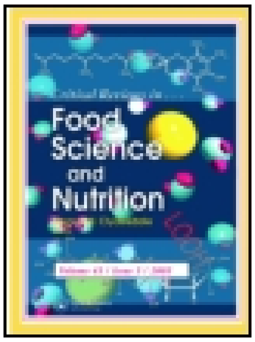

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REVIEW

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Exploring the potentials of underutilized grain amaranth (*Amaranthus* spp.) along the value chain for food and nutrition security: A review

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ABSTRACT
The burden of malnutrition in Africa calls for deeper exploration of underutilized species which are rich in nutrients and have the potential to reduce food and nutrition insecurity. The common staple crops are not able to meet daily requirements for both macro- and micro-nutrients. In order to lessen this burden; protein, calorie and micronutrient deficiencies must be properly addressed for optimal growth and development to be attained. African indigenous underutilized vegetables can play a significant role in the food security of vulnerable groups like under-five children and women in both urban and rural settings. The potential of grain amaranth in meeting the nutrition needs of humans has remained a subject of interest in scientific research. Amaranth is considered one of the most commonly produced and consumed indigenous vegetables on the African continent with high nutritional potentials but yet to be fully exploited. This review therefore aims at discussing the current knowledge of the inherent potentials of grain amaranths, its current application in the food industry and proposes a framework for actions and partnerships required to scale up and improve amaranth value chain

KEYWORDS
Grain amaranth; underutilized crop; malnutrition; value chain

Introduction

Africa represents a major block of the globe where malnutrition and poor living standard across the spectrum of the population is conspicuous and most intractable (UNICEF 2019; FAO 2018). Ninety per cent (90%) of children from Africa do not meet the minimum criteria for acceptable diet and 60% fall below the expected minimum meal frequency (Rickards 2019). Infant malnutrition in the African region is a serious treat and global health problem because of its consequential effects on childhood mortality, morbidity, impaired intellectual development and risk of diseases that can reduce the efficiency of adulthood working capacity (WHO 2013; Akombi et al. 2017). In low- and middle-income countries, child malnutrition contributes to about 45% of under-five year children mortality and this portends great danger to Africa growth and development. One third of child deaths in Africa are attributable largely to protein energy malnutrition and micronutrient deficiencies (Luchuo et al. 2013, Branca et al. 2020) which can be solved by exploring underutilized nutritious crop species of Africa origin.

Nations in Africa need to proactively think and plan to address these problems in order to have an adulthood future that is productive (Coulibaly et al. 2016). Consequently, there is a need for a policy framework and strategic roadmap that could reduce poverty and child malnutrition which is prevalent in most developing countries of Africa. This could be achieved by full exploitation and tapping into our underutilized food crop resources (Coulibaly et al. 2016). The projected growth in global population with attendant increase in food demands especially in the African region calls for focusing and devoting more attention to the underutilized crop species which have great potentials to influence and improve food security for African nations and promote sustainable rural growth and development.

The African continent is blessed with a rich diversity of food crops, most of which have received little or no attention in terms of research and development of policy frame works that can promote their effective commercial and industrial utilization. Grain amaranth (*Amaranthus* spp.) is one of such neglected and underutilized species. It is an indigenous leafy vegetable of Africa that has great inherent health promoting components good for human applications and uses (Kwenin, Wolli, and Dzomeku 2011; Zhu, 2020). The grain amaranth is a promising underutilized food crop because it can grow in a wide range of weather conditions. It is a drought tolerant crop with inherent strong market and industrial potentials which are yet to be fully tapped (Olaniyi 2007; Akin-Idowu et al. 2017). Amaranth has the

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Table 1. The qualitative morphological features of some species of Amaranthus.

Plant species	Color of stem	Color of leaves	Color of the root	Color of inflorescence	Shape of leave	Presence of spines	Arrangement of leave on stem	Seed color	Source
A. hybridus	Green	Green	Brown	Green	Ovate	Absent	Alternate	N.D	Alege and Daudu (2014)
	Purple/Green	N.D	N.D	Green	N.D	N.D	N.D	Cream	Akin-Idowu et al. (2016)
A.caudatus	Purple & Green	Purple & Green	Purple	Purple	Ovate	Absent	Alternate	N.D	Alege and Daudu
	Pink base & green mid-stem to tip	N.D	N.D	Green	N.D	N.D	N.D	Cream/ black/Pink	Akin-Idowu et al. (2016)
	N.D	N.D	N.D	N.D	ovate to rhomboid	N.D	N.D	reddish to dark brown	Grubben (2004)
A. viridis	Green	Green	Brown	Green	Obovate	Absent	Alternate	N.D	Alege and Daudu (2014)
A.spinosus	Green	Green	Brown	Green	Obovate	Present	Alternate	N.D	Alege and Daudu (2014)
A. dubius	Purple	Green	Purple	Green	Obovate	Absent	Alternate	N.D	Alege and Daudu (2014)
A. cruentus	N.D	N.D	N.D	Green/ Pink/	N.D	N.D	N.D	Cream	Akin-Idowu et al. (2016)
	N.D	Green/purple	N.D	N.D	N.D	N.D	N.D	yellowish white to pale brown	Grubben (2004)
A.hybrid	Pink	N.D	N.D	Green, wine	N.D	N.D	N.D	Cream, Black, cream and black	Akin-Idowu et al. (2016)
A. hypochondriacus	Green/Pink	N.D	N.D	Green/Wine	N.D	N.D	N.D	Cream/Gold	Akin-Idowu et al. (2016)
	N.D	N.D	N.D	N.D	ovate to rhomboid	N.D	N.D	creamy white to gold	Grubben (2004)

ND: Not determined.

ability to grow and adapt in extremely harsh weather conditions (Olufolaji, Odeleye, and Ojo 2010). It can be successfully cultivated for leaf or grain in many regions and seasons where other crops cannot thrive (Mlakar et al. 2009; Ebert, Wu, and Wang 2011; Grundya et al. 2020).

The development of sustainable value chains for grain amaranth from cultivation on the field to production of different value-added products, and understanding of its numerous health benefits could enable a significant intervention to uplift millions of rural and poor urban households in developing countries where malnutrition is glaring with its attendant health consequences. Thus, amaranth appears to be an economically viable underutilized crop with great potential.

Species

Suma et al. (2002) reported that there are about 70 species and 400 varieties of amaranthus which are distributed throughout the world with only a few being domesticated in different countries. The species of Amaranthus are often difficult to characterize because of their similarities and existence of intermediate forms. Table 1 shows the morphological features of some amaranth species as described in literature.

The common species such as *Amaranthus cruentus; Amaranthus caudatus* and *Amaranthus hypochondriacus* are usually domesticated for grain production (Trucco and Tranel 2011) and are commonly referred to as "pseudo-cereals" while species such as *Amaranthus tricolor Amaranthus blitum*, *Amaranthus dubius*, *Amaranthus spinosus*, and *Amaranthus viridis* are the type mostly cultivated as leafy vegetables (Ebert, Wu, and Wang 2011). Das (2012) classified *A. spinosus*, *A. viridis*, *A. retroflexus*, *A. graecizans*, *A. dubius*, and *A. hybridus* as weedy types.

Several species of amaranth have been domesticated for use in different parts of the world. *Amaranthus cruentus, A. hybridus*, *A. blitum* and *A. dubius* are the most widely grown in West Africa while *A. tricor* is mostly grown in East Africa, China and India. *A. caudatus* is used as a cereal crop in South America and *A. dubius* as a vegetable in the Caribbean and China. *A. hybridus* is also grown in the southwestern United States. Countries like Indonesia, Malaysia, Mexico, Thailand, Philippines, Nepal, grow *A. hybridus* either for vegetable or grain (Orona-Tamayo and Paredes-López 2017; National Research Council 2006).

Common amaranth species grown for grain and their uses

Amaranthus cruentus

This is one of the species grown primarily for grains, although, its leaf may be consumed when they are still tender. The protein of *A. cruentus* species has a high content of sulfur containing amino acids which include methionine and cysteine (Escudero et al. 2004; Schmidt 1977; Martinez-Nunez et al. 2019), making it a good combination with cereals which can be used for the formulation of complementary foods and snacks. When eaten as a leaf vegetable, it is prepared by cooking and consumed as a vegetable dish or as an ingredient in sauce. The leaves and tender stems are cooked or fried in oil and mixed with meat, fish, groundnut and palm oil. In many localities, the amaranth soup cooked with all the ingredients is eaten with the prepared meal from cereals and tubers. As a way of adding value to prolong its shelf life, the leaf can be dried and milled into powder form to be used in sauces preparation during the dry season when the vegetable may not be abundantly available (Grubben and Denton 2004). In South Africa, it is grown commercially for canning and sold in supermarkets. In Nigeria, it is valued for its ornamental properties rather than for its grains. It is common as weeds, especially around urban centers (Ogwu 2020). Therapeutically, the roots are boiled with honey as a laxative for infants, its water extract is used to treat pains in the limbs, used as a tape worm expellant and in wound dressing. It is further used industrially as lubricants in the computer industry, cosmetics and health foods (Paredes-Lopez and Hernández-López 1992).

Amaranthus hypochondriacus

Amaranthus hypochonriacus is specie commonly grown for its grain in some part of the world which includes South America and Asia. Because of its excellent nutritional composition, the grain can be pooped, roasted and milled like maize which is being used to make bread in many households in India (Mlakar et al. 2009). In Africa, it is grown as an ornamental. The quality of its starch granule makes it a useful material in industries, as lubricants in the computer industry and cosmetics (Grubben and Denton 2004; Schippers 2002). The grain comprises oil which contains squalene which has been found to have good application in food, cosmetic and pharmaceutical industries (He et al. 2002; He and Corke 2003). It was also reported that this squalene has important beneficial effects on cancers (Rao and Newmark 1998) and reduces the cholesterol level in the blood (Smith 2000). The grain of *A. hypochonriacus* has been suggested as alternate natural sources of squalene mainly found in marine shark (He et al. 2002).

Amaranthus caudatus

This specie of amaranths just like the previous two is grown mainly for its grain. It is food crop cultivated in some part of Argentina, Peru, and Bolivia. Studies done so far indicated that *Amaranthus caudatus* has an excellent nutritional profile with high level of protein, minerals and fat as compared to the commonly utilized cereals. (Mekonnen et al. 2018). Its grain can be dried, milled and used for human nutrition in the form of whole-meal amaranth flour, crackers, brown bread without gluten, biscuits, cookies, (Mekonnen et al. 2018). The crop contains a great deal of genetic diversity in South America. Although only a small sampling has been introduced to other continents, much genetic diversity has been observed in the germplasm collections from Northern India (Akin-Idowu et al. 2013).

Common amaranth species grown for leaves and their uses

Amaranth species are cultivated and consumed as a leaf vegetable in many parts of the world. No clear separation between vegetable and grain species exists, because the leaves of young grain varieties can be used as potherbs sauce. There are four species of *Amaranthus* documented being popularly cultivated as vegetables: which include *Amaranthus cruentus*, *Amaranthus dubius Amaranthus blitum* and *Amaranthus tricolor*. However, *Amaranthus cruentus* can be cultivated both as vegetable and a grain depending on the target market of the producer.

Amaranth leaves can be used both in cooking and for salads, it has a delicious, slightly sweet flavor (Herbst 2001). In East Africa, amaranth leaf is sometimes recommended by some doctors for people having low red blood cell count (Alemayehu, Bendevis, and Jacobsen 2015). In West Africa, such as in Nigeria, it is a common vegetable, and goes with all Nigerian carbohydrate dishes such as pounded yam, *amala* and *fufu* (Enama 1994; Akin-Idowu et al. 2013).

Nutrition and health benefits of amaranth

Amaranthus species are ancient crops with excellent nutritional and therapeutic value but their full potentials are yet to be optimally exploited. Many underutilized leafy vegetables of African origin have been employed by local communities in different part of African nations for diverse therapeutic purposes (Kwenin, Wolli, and Dzomeku 2011). The ability of these vegetables to promote health benefits is largely attributable to nutritional and bioactive compounds available in them (Cornejo et al. 2019).

Amaranthus are highly nutritious; both the grain and leaves are utilized for human as well as for animal feed (Mustafa, Seguin, and Gelinas 2011). The crop has high levels of protein and minerals as compared to the commonly utilized cereal grains such as millet, sorghum, rice, wheat and corn (Mustafa, Seguin, and Gelinas 2011). Moreover, it has a balanced content of essential amino acids and unsaturated fatty acids. Its protein is rich in lysine, a limiting amino acid that is absent in many other grains. (Amare et al. 2015). The protein is also relatively rich in the sulfur-containing amino acids, which are normally limited in the pulse crops. The protein of grain amaranth has been claimed to be very near to the levels recommended by FAO/WHO because of balance in amino acid profile (O'Brien and Price 2008; Murya and Pratibha 2018). Amaranth was declared as one of the future promising crops to feed the global population (Mekonnen et al. 2018). Among the green leafy vegetable and cereals, amaranthus species are regarded as store house for vital vitamins such as vitamin C, $B_{6,}$ folate and carotene (Musa et al. 2011). Table 2 shows the nutrient profile of grain amaranth and other cereal grains.

The chemical evaluation of different species showed that nutritional and chemical compositions vary slightly (Kadoshnikov et al. 2005).The protein content of the leaves can vary between 17.2 and 32.6% on dry weight basis for various species (Murya and Pratibha 2018). Andini, Yoshida,

Table 2. Nutritional composition of grain amaranth and other cereals.

Nutrients (%)	Amaranth	Millet	Sorghum	Rice	Wheat	Corn
Moisture	11.29	8.67	12.4	N.D	N.D	10.21
Protein	13.56	11.02	10.62	6.67	10.91	9.42
Lipid	7.2	4.2	3.46	2.22	1.82	4.74
Ash	2.88	3.25	N.D	N.D	N.D	N.D
Carbohydrate	65.25	72.85	72.09	75.56	80	74.26
Fiber	6.7	8.5	6.7	2.2	2.2	N.D
Energy (kcal/100g)	371	375	329	356	364	365
Mineral (mg/100 g)	Amaranth	Millet	Sorghum	Rice	Wheat	Corn
Iron	7.61	3.01	3.30	1.11	3.27	2.17
Zinc	287	1.68	1.67	N.D	2.73	2.21
Magnesium	248	114	165	N.D	109	127
Manganese	3.3	1.6	N.D	N.D	N.D	N.D
Potassium	508	198	363	202	400	287
Calcium	159	8.0	13	4	36	7

N.D: not determined.
Source: Gebhardt et al. 2008.

and Ohsawa (2013) compared the protein content in the leaves of amaranth grown for grains, vegetables and weed; the highest protein content was found in the leaves of weedy amaranth. This supports the claim that wild edible plants may be superior in terms of their nutrients (Guil, Rodriguez-Garcia, and Torija 1997), thus the need for further exploration of their utilization and incorporation into diets for food and nutrition security.

In addition to its nutritive value, amaranth grain contains bioactive compounds with health promoting effects (Karamac et al. 2019). The potentials of amaranth species seem enormous and promising which make its exploration health purposes and industrial applications most imperative. Studies have shown that regular consumption of amaranths has the potential (Karamać et al., 2019) to reduce cholesterol level, benefit people suffering from hypertension and cardiovascular disease (Olaniyi 2007; Kolawole and Sarah 2009). Other published studies on health benefit using animal model experiment has demonstrated that extract of *Amaranthus caudatus* has a cholesterol reducing effect (Chavez-Jauregui, Silva, and Arĕas 2000), improves liver functions (Kim et al. 2006; Kim, Kim, and Shin 2006) and prevents cancers (Bario and Anon 2010). The ability of amaranth to exhibit health benefit is due to bioactive compounds present in it. Bioactive compounds in amaranth grain include phenolic acids such as protocatechuic, hydroxybenzoic, caffeic, and ferulic acid, rutine, nicotiflorin and isoquercetin. There is evidence that routine slows down the aging process, quercetin prevents oxidation, and nictoflorin helps in the protection of memory functions (Alvarez et al. 2010).

The campaign for consumption of grains and vegetables for maintenance of good heart vegetables has become ever more popular globally (Lillioja et al. 2013). In Zimbabwe, Tagwira et al. (2006) reported that consumption of amaranth species was found to impact health benefits among local communities. The communities claimed that eating grain amaranth made them healthier and they also noticed significant improvements in their children's health such as improvement in appetite, fast healing of mouth sores and reduction in overweight. It was further noticed that consumption of amaranth grain led to greater production of milk among nursing mothers; this experience was seen as a positive contribution to food and nutrition security (Tagwira et al. 2006). In parts of Benin, vegetable amaranthus were recommended for young children, lactating mothers and patients with constipation, fever, hemorrhage, anemia or kidney complaints (Akubugwo et al. 2007). In Senegal, the roots are boiled with honey as a laxative for infants. In Ghana, the water of macerated plants is used as a wash to treat pains in the limbs. In Ethiopia, *A. cruentus* is used as a tape worm expellant. In Sudan, the ash from the stems is used as a wound dressing. In Gabon, heated leaves were used on tumors (Grubben 2004). *Amaranthus tricolor* and *A. caudatus* are used externally to treat inflammations, and internally as a diuretic (Agong 2006; Kim et al. 2006; Kim, Kim, and Shin 2006; Martirosyan et al. 2007).

Amaranthus grain has been found to provide alternative food ingredient in the development of food products other than wheat and other cereals for celiac patients. A gluten-free diet is the only therapeutic treatment currently available for patients with celiac disease; an autoimmune disorder of the small intestine associated with a permanent intolerance to gluten proteins (Martínez-Villaluenga et al., 2020). Amaranth proteins consist mainly of albumins and globulins, where prolamins, the toxic proteins for celiac patients, are very scarce.

Antinutrient composition of amaranth grain

Some of the reported antinutrients in amaranth are phytate, saponins, tannins, oxalates, protease inhibitors and nitrates. The effects of oxalates and phytates on nutrient inhibition are of more concern in amaranth grain. Amaranth grains contain little amounts of saponin; Dobos (1992) found very low concentration of saponin (an average of 0.09%) in various amaranth species. Likewise, only small amounts of protease inhibitors (trypsin and chymotrypsin) are found in amaranths compared to other common cereals while nitrates are concentrated in the leaves and mot the grains.

These antinutritional elements serve protective effects in plants, for instance, phytic acid serves as a form of storage for phosphorus in the plants. But in humans, they inhibit nutrient absorption. Phytate is not digestible by humans and is therefore not a dietary source of inositol or phosphate. Rather, it forms complexes with proteins thereby limiting its availability. In addition, inhibition of starch digestion has been reported for phytate and oxalate. Saponins form complexes with mineral elements such as zinc and iron; oxalate binds calcium and thus reduces its absorption (Cuadrado et al. 2019).

Different processing methods have been used to lower antinutrient contents of amaranth. Tannins are present in high concentrations in the grain hull, removal of the hull eliminates most of the tannins but this does not remove the phytic acid. Phytic acid is distributed uniformly in the grain, thus it cannot be reduced by abrasive removal of the external grain layers or by water extraction. Babatunde and Gbadamosi (2017) explored the effects of five processing methods (defatting, blanching, germination, fermentation and autoclaving) on the protein digestibility and antinutrient composition of grains *Amaranthus viridis*. It was reported that germination at 30 °C for 72 hours has the most significant effect on protein digestibility; with 82% increase compared to fermentation which improved protein digestibility by 76%. Heat treatment such as autoclaving and blanching were more effective in reducing tannin and oxalate content.

Njoki (2015) examined the effects of dry heating processes (roasting at 160 °C for 10 minutes and popping at 190 °C for 15 seconds) and wet heating techniques (boiling whole grains at water: seeds of 4:1) and boiling amaranth flour at water:flour of 6:1) on important parameters of grains of *Amaranthus albus*. Boiling of flour and whole grain increased the protein digestibility by 24% and 15% respectively while roasting decreased the protein digestibility. Effect of boiling in reducing tannin, phytate and oxalate content was higher than roasting and popping. Kanensi et al. (2011) optimized the steeping and germination time for amaranth grain; steeping amaranth grain for 5 hours and germinating for 24 hours were recorded as the optimum processing times based on dry matter loss and reduction in antinutrient levels. Certainly, the presence of antinutrients in amaranth grains may pose a challenge in its utilization for food security; nevertheless, proper processing methods can minimize their antinutrient content.

Production of amaranth and the need for a seed management system

Amaranthus belongs to the *Amaranthaceae* family. It is an herbaceous annual or short-lived perennial plant (Petruzzello 2016). It is a high yielding vegetable crop and a crop of great toast among rural and urban population in many communities (Chelang'a, Obare, and Kimenju 2013), Amaranth is a very versatile crop and has been called a multipurpose crop it resists drought, heat, pests and adapts more readily to new and harsh environments than conventional cereal crops. Its tolerance to a wide range of weather conditions and short production cycle present amaranth as possible "golden" vegetable of high economic importance (Hoidal et al. 2020). As a home garden vegetable, it can be grown all year round. Although, amaranth can cope with adverse conditions and adapt to a variety of soil types, it will do best on fertile, well-drained and loose soils with high organic matter content (Stetter, Vidal-Villarejo, and Schmid 2020).

The highest producers of grain amaranth are Mexico, Russia, China, India, Nepal, Argentina, Peru and Kenya. However, data on world production of grain amaranth is sparse and FAOSTAT publishes no records of production (Rosentrater and Evers 2018).

Amaranth grown for seed production requires a different type of management than amaranth grown for grain. Amaranth being a self-pollinating crop, has a high cross-pollination tendency leading to production of hybrid seeds that may not be desired. Strips of corn are sometimes planted between amaranth lines to prevent cross pollination and keep the seeds pure (Manikandan and Srimathi 2014). A seed production filed should be free of weedy varieties of amaranth which can produce weed-crop hybrid seeds with lower yields. This is a major challenge in amaranth seed systems.

Smallholder farmers who are in the informal seed sector save seed from their crop production or collect and buy from neighbors, village markets, or market-day traders. Training of farmers in seed production strategies, linking farmers to seed companies and research institutions for routine renewal of seed stock can help to improve the quality of seeds in the informal sector. Furthermore, the formal sector is less interested in multiplication of seeds of self-pollinating crops. They can be encouraged to produce foundation seeds and sell to trained community growers who produce and sell to farmers in their communities (Oyekale 2014).

The viability of seeds is crucial in the production of amaranths. If amaranth must play an alternative role to food grains such rice, millet wheat and sorghum in sub-Sahara African, a good seed management system must be the focus for stakeholders. A good seed management system involves development of high yielding seeds and an efficient system for making them available to farmers. In order to achieve this, there must be linkages between researchers, extensionists, government agencies, farmer groups and the private sector. There is, therefore, a need to develop a seed platform for targeted crops, like amaranth, that will integrate both commercial and community-based seed supply systems. The system will ensure that production and marketing of quality seed is not compromised.

Post-harvest management operations of amaranth

The practice of efficient post-harvest management is very important for sustenance of the entire value chain of any crop. Post-harvest losses in Sub-Saharan Africa for cereal grain have been estimated at between 5% and 13% (FAO 2011; Tibagonzeka et al. 2018). The amaranth grain just like any other cereal needs post-harvest management practices for the grain to remain viable, retain nutritional contents and command high market value. While the pre-harvest operations differ in amaranth seed production from grain production, the post-harvest management for both seed and grain is similar. The post-harvest management of grains generally encompasses harvesting, field drying, threshing and cleaning, additional drying, storage and processing. These few operations must be practiced with detailed attention it deserves if losses of grains must be minimized (Manikandan and Srimathi 2014).

In developing countries, crop harvesting is performed mainly manually using hand cutting tools such as sickle, knife, and cutter. But in developed countries, using combined harvesters is preferred (Parfitt, Barthel, and Macnaughton 2010; Hodges, Buzby, and Bennett 2011). Harvesting timing and method are important factors dictating the losses during the harvesting operations. Early harvesting at high moisture content increases the drying cost, making the crop susceptible to mold growth if not properly dried, and resulting in high amount of broken grains and low milling yields (Khan 2010). Most amaranth cultivars grow rapidly and may be harvested from 6 to 8 weeks from sowing.

Drying is a critical step after harvesting to maintain the crop quality, minimize storage losses and reduce transportation cost (Abass et al. 2014). Drying can be performed naturally (sun or shade drying) or using mechanical dryers. Natural drying or sun drying is the traditional and economical practice for drying the harvested crop. The safe moisture content for long-term storage of most of the crops is considered below 12% (Kitinoja 2013). Drying of grain in the open for sun drying is prone to eating by birds and insects, and they get contaminated by stones, dust, animal excretal and other foreign materials. Farmers do use mats, plastic sheets for spreading the grains, which reduces the contamination and makes the collection of grains simple. Mechanical drying however addresses some of the challenges of open drying in sun. To avoid the disadvantages of open sun drying, convection solar tent dryers can be used. In an experimental (Ronoh et al. 2010) where solar tent dryer was used to dry *Amaranthus cruentus* grains, freshly harvested grains with an average moisture content of 64% was dried to a stable moisture content of 7% on dry basis after seven days. In that experiment, the ambient temperature and relative humidity ranged from 22.6 to 30.4 °C and 25 to 52%, respectively, while the inside temperature and relative humidity in the solar dryer ranged from 31.2 to 54.7 °C and 22 to 34%, respectively. Threshing and cleaning can be done manually or mechanically after drying. The threshing process is to detach the grain from the panicles while cleaning is to separate whole grains from broken grains and other foreign materials, such as stones, sand and chaff.

In developing countries, most of the grains are stored in the traditional structures such as earthen pots, metal bin, bag at the household level for self-consumption and next planting season (Abedin et al. 2012). The optimum way to store the grain after cleaning and drying is in wooden storage bins or in heavy duty paper bags until ready to use. It is important to keep properly dried seeds in a closed container to avoid contamination. For amaranth seed to be successfully stored, the moisture content after drying must not exceed 12%; any value above this will possibly promote growth of mold and reduce quality (Uganda National Bureau of Standards 2011). It is also important to store the grain in container on raised pallets to allow for heat exchange (Tibagonzeka et al. 2018).

Local and global market opportunity for grain amaranth

Pseudo cereals are a niche in Europe where the demand is on the increase annually. However, there is no data on the volume of production and market linkage between the producing and importing countries. The Confederation of British Industry (CBI Product Factsheet 2014) reported that about 6,000 tonnes of niche grains, most of which were amaranth seeds, were imported from developing countries. According to that report, the main consumption market for amaranth seeds is Germany. However, this commodity is becoming increasingly well known in other developed countries such as the UK, the Netherlands, Sweden, Belgium and France. Amaranth is mainly consumed as a health food, and may be sold in small packages (raw, popped or milled) containing up to 500 g of the product, or as an ingredient in breakfast cereals, bakery products or healthy snacks (CBI Product Factsheet 2014).

In Africa, markets for amaranth crops are limited and poorly developed due to limited supply of commodities, low demands and set standards. Smallholder farmers cultivate grain amaranth with no strong linkages to large buyers which decrease sales potential. African leaders and other major stakeholders in industry sector can develop strong market linkage with European countries and provide easily accessible information on areas where the demands are high. This will reduce poverty and promote income generation. Among the notable countries that grow grain amaranth and have market share are Mexico, Russia, China, Indian, Peru and Kenya. (Ainebyona et al. 2012). The grain amaranth market is likely going to be driven by rise in food processing industries and use of organic ingredients in medicinal cosmetics.

Food product development from amaranth

The grain amaranth has been described as "super" grain producing plant that has a great prospect and high commercial potential for product development most particularly in the baking sector of food industries. It is gluten free unlike wheat; thus, a suitable substitute raw material for development of gluten-free products. There are processing techniques that can be adopted to add value to amaranth grain to serve as food and provide the needed nutrition for consumers.

The amaranth grain at household level can be cooked and eaten as porridge (Mugalavai 2013), it can also be malted for beer production, It has been demonstrated that grain amaranth can be popped or roasted for flour production which can be used singly or mixed with other food ingredients to make products like bread, biscuits, pasta, crackers, pancakes, muffins, paste and breakfast cereal (Emire and Arega 2012). Un-popped grain can be ground and mixed with ground fish or flour of other cereals such as maize, sorghum and millet to make thin porridge (O'Brien and Price 2008; Janet 2015). Amaranth grain, if given the needed attention from production to storage, can contribute immensely to food security and nutrition, provide raw and intermediate material for industries to boost the scope of production and employment generation.

Development of amaranth-wheat based bread

Amaranth grain can be used singly or as composite flour in making breakfast foods, bakery products, gluten-free foods and extruded products. To make a leavened bread, it needs to be blended with wheat (Elizabeth 2010). The amaranth flour is used in Latin America and in the Himalayas to produce a variety of flat breads (Teutonico and Knorr 1985). Emire and Arega (2012) developed amaranth-wheat based breads using different blend formulations and adopted the commercial bread making technology used at the Kality Food Share Company in Addis Ababa, Ethiopia. The composite flour was prepared by substituting wheat with amaranth at 5, 10, 15, 20 and 30%. The baked bread with amaranth substitution showed significant nutrient improvement as the amount of amaranth in the blend increased. The amaranth substitution up to 10% improved some rheological properties and sensory characteristics of the breads baked at 220 °C for 18 min.

In another study (Jerome 2001), grain amaranth flour was mixed with wheat flour at 0–55% level and used to bake bread. It was reported that loaf volume decreased with increased grain amaranth flour and the bread became unacceptable from 15% (W/W) substitution level. Sanz-Penella et al. (2013) found that incorporation of amaranth flour significantly increased protein, lipid, ash, dietary fiber and mineral contents, this accompanied by higher amounts of phytates which may lower the bioavailability of the minerals. In addition, an increase in crumb hardness and elasticity was observed when the amaranth concentration was raised, it was therefore recommended that inclusion of amaranth flour could be limited to a maximum proportion of 20%, in order to maintain both product quality and the nutritional benefit (Sanz-Penella et al. (2013).

Formulation of weaning foods

The gruel made from cereals of maize, millet and sorghum are the common complementary foods used by rural and poor urban mothers in sub-Saharan Africa (Akinsola et al. 2017). The gruel prepared from these cereals are low in energy, quality protein and dietary minerals hence inadequate in providing infants' nutrient requirements. The low energy content is as result of the bulkiness of the porridge which causes eating problems; this necessitates dilution before being given to children. With much dilution, children are not able to meet their energy and other nutritional needs. Amaranth has been used to improve the protein and other important nutrients of weaning foods (Anigo et al. 2009; Akinsola et al. 2017).

A nutrient-dense complementary food was developed from amaranth-sorghum blend at different mixing ratios (Okoth 2011). In order to have improved flour, with reduced anti-nutritional factors, a malted flour from amaranth and sorghum grain were used. The formulation with 90% amaranth and 10% sorghum grain had the highest protein content. This value is within the estimated protein needed in complementary foods for a 12–23-month-old infant of low breast milk intake (9.1 g/d) (WHO 2007). In rural community in Ethiopia, complementary food in form of porridge was formulated from blend of maize, amaranth grain and chickpea at different combinations (Zebdewos et al. 2015). The porridge containing 70% amaranth and 30% chickpea had higher amount of iron, zinc, and calcium; with increased protein and a lower phytate level compared with porridge from whole maize and blend of the three raw materials. The inclusion of amaranth flour was found to increase the quality of protein in the food.

In a study conducted by Mburu et al. (2012), amaranth grains were steeped and pre-gelatinized to obtain a flour which was made into gruel by mixing 15 g of the flour in 100 ml of boiled water. The resulting gruel was acceptable to the sensory panelists; the nutrients in the gruel was reported to provide the daily requirements for magnesium, manganese, tocopherols, protein, phosphorous, iron, zinc, riboflavin and niacin if fed to infants 3 times daily. Grain-amaranth-based complementary foods can thus be promoted to both rural and urban households as it provides a good protein-energy balance for growing children.

Development of amaranth based biscuit

The bakery products which include breads, biscuits and other cookies are the most commonly processed food items in the world (Caleja et al. 2017). Biscuits are mainly made from wheat flour and fat; they are high energy and easily digestible foods. This can negatively impact on health if they are overeaten (Caleja et al. 2017). Thus, there is need for improving the overall nutritional contribution of biscuits by other flours that are rich in essential nutrients.

Some studies (Sindhuja, Sudha, and Rahim 2005; Renu and Anirban 2015; Virginia and Ajit 2014) have developed biscuits using amaranth-wheat composite flours. Sindhuja, Sudha, and Rahim (2005) substituted wheat flour with amaranth flour up to 35%. The product showed an improvement in organoleptic properties (color, taste, flavor and appearance). The product with 25% amaranth flour substitution was found to be best in terms of organoleptic properties and color, Renu and Anirban (2015) developed cookies with wheat-grain amaranth composite flours and reported a sensory acceptability of the products even when 100% grain amaranth was used. In another study (Virginia and Ajit 2014), grain amaranth and watermelon seeds were incorporated into wheat flour for making biscuit, incorporation of up to 20% of grain amaranth was reported to have the best sensory properties. Schoenlechner, Siebenhandl, and Berghofer (2008) used amaranth, buckwheat, and quinoa to produce gluten-free biscuits. The crispiness of the biscuits was in the order buckwheat, quinoa and amaranth, and biscuits containing buckwheat and amaranth were preferred by a sensory panel. The use of amaranth as a replacement for wheat flour in the production gluten-free biscuits has been demonstrated by these studies.

Development of functional beverage

In recent times, there has been increasing interest in the importance of foods and beverages in disease prevention and treatment. Functional foods and beverages have beneficial physiological functions alongside their nutritional benefits (Corbo et al. 2014). Beverages are the most common functional food category because they are convenient, satisfy consumer demands in terms of packaging and appearance, easy to distribute and shelf stable when refrigerated. Moreover, they serve as an excellent means for delivering nutrients and bioactive compounds to diverse groups. The sale of functional beverages was estimated to $105.5 billion globally (Pandal 2017).

There is a growing interest in the food industry to focus on how functional food can be developed from natural food sources. Extruded amaranth grains were used to produce an instant functional beverage (Milan-Carrillo et al. 2012). The samples produced with amaranth inclusion had better acceptability than the one without amaranth. *Kunu*, a refreshing nonalcoholic beverage consumed in Nigeria was developed by fermenting grain amaranth for different durations and compared to the popular sorghum-based *Kunu* (Isaac-Bamgboye, Edema, and Oshundahunsi 2019). Sensory evaluation results showed that Amaranth-kunu was more acceptable than sorghum Kunu when fermented for 48 hr. Amaranth-Kunu had higher protein, fat and ash contents compared to sorghum-Kunu.

Argüelles-López et al. (2018) developed an amaranth-chai-based beverage using extrusion and germination methods. Germination of amaranth grains and chai seeds were shown to have higher protein content compared to extruded seeds. The beverage was prepared by mixing amaranth and chai flour at ratio a 70:30 respectively. The developed beverage was highly acceptable to the panelists; the corresponding level of satisfaction recorded was between "I like it very much" and "I like it extremely." In a randomized crossover design, some important athletic performance variables were assessed in cyclists who received either an amaranth-based beverage or a commercial beverage (Espino-González et al. 2018). There was no significant difference in all the variables examined except for time-trial performance. Amaranth-based beverage enhanced performance compared to the commercial beverage. The amaranth beverage was prepared by mixing 88.8 g of amaranth grains, 41.3 g of sugar, 0.35 g of sodium chloride and one liter of water, and flavored with grape or orange, this was done in order to achieve a protein concentration of 1.5%, 10% carbohydrates, and 0.35 g/L of electrolytes (sodium chloride). The caloric content of the amaranth beverage (52.48 kcal per 100 mL) was higher than that in commercial beverages (24 kcal per 100 mL), this was thought to be responsible for the time-trial performance differences.

Amaranth grains are excellent raw materials for the beverage industry due to their properties for the prevention and treatment of chronic-degenerative disease. Amaranth thus have the potential to contribute to the nutrient and health benefits offered by functional drinks, it will be a good alternative to energy-dense but low nutrient containing beverages that are dominating the market.

Utilization of amaranth in animal nutrition

There is an increasing demand for ingredients used in animal feed. The pressure on raw materials such as maize is huge as it is a major component of human diets. There is, therefore, a need to look for alternative sources of energy and protein. One crop that could serve this purpose is Amaranthus species. Use of cereals such as sorghum and millet in animal feeds only serve as energy source and will require supplementation with protein sources. Amaranth, due to its energy and protein balance, has the potential to substitute or complement these cereals. The energy provided by grain amaranth is comparable to other cereals while the protein content is twice as high. Both the grain and leaf of amaranth have been used in many countries as a forage or silage crop for many animals, including cattle, chickens, pigs and rabbits (Peiretti 2018).

However, amaranth has been shown to have some growth inhibiting factors that can be reduced by exposure to heat. In an experiment where rats were placed on amaranth grains with different pretreatment (raw, dry-heating, moist-heating, soaking in water), only the group fed on moist heat grains gained weight over the 14-day of the experiment, other rats gained weight in the first 6 days and lost it afterward (Pond et al. 1991). Pre-heated Amaranth grains can be used as a feed ingredient for broilers. The heat treatment is capable of reducing or destroying the anti-nutritive factors in the grains. Research has shown that extruded grain amaranth can be fed to broiler chicks without adversely affecting body weight. Fasuyi and Nonyerem (2007) used sun-dried leaves of *Amaranthus cruentus* to formulate potentially rich feed meal that could be added to broiler finisher diets. The anti-nutritional factors in amaranth leaf that can interfere with the bioavailability of important nutrients were reduced through steeping in water followed by sun-drying. The study showed that 10% inclusion of *Amaranthus cruentus* leaf in bird meal was suitable to obtain a better performance in broiler birds without any adverse effects. Fasuyi and Akindahuns (2009) the steam pelleting diets containing amaranth grain led to increased feed intake and growth performances, with a higher fat deposition in broilers. Tillman and Waldroup (1986) suggested a maximum inclusion level of 40% of Amaranthus *cruentus* grain in broiler diets, but only when the amaranth is properly processed either by extrusion or autoclaving (Peiretti 2018).

Seguin et al. (2013) showed that ensiling *Amaranthus hypochondriacus* produced silage that are suitable and degradable by ruminants. Ensiling was shown to reduce oxalate content of amaranth. Olorunnisomo and Ayodele (2009) showed that *Amaranthus cruentus* had the potential to produce good-quality silage, it was well digested by the West African dwarf sheep used in the study. Alegbejo (2014) reported that *Amaranthus retroflexus* and *Amaranthus hybridus* have been successfully included in feeds for sheep and calves as forage

Amaranth oil (squalene) and its industrial application

Squalene is a very valuable compound commonly found in vegetables and animal cells; it is highly appreciated because of its biological importance. The amaranth plant has been reported as the richest source of squalene in the plant world (Alvarez et al. 2010; Venskutonis and Kraujalis 2013). Plant-based squalene oil may be used in cosmetics and personal care products (Ofitserov 2001). Amaranth squalene shows a high antioxidant content and prevents free-radical induced oxidative injuries particularly in the skin (Huang et al., 2009). Amaranth oil supports skin regeneration and helps the skin's protective layer to be renewed. It activates cellular

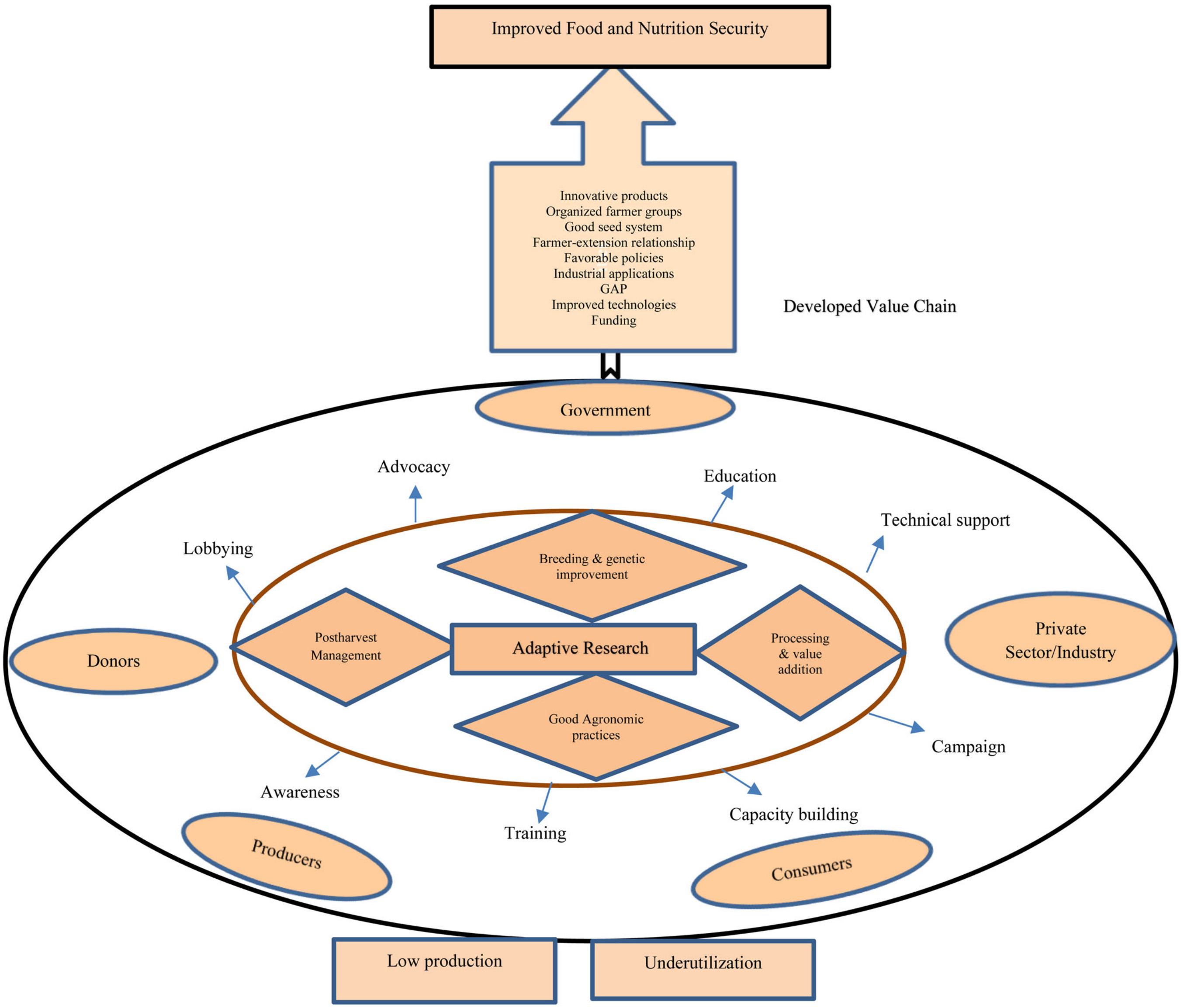

Figure 1. Framework for actions and actors needed to develop grain amaranth value chain for improved food and nutrition security.

protection, increases the skin's ability to retain moisture and minimizes water loss (Huang et al. 2009).

He and Cai (2002) extracted the squalene from the oil of 104 genotypes and 30 species of amaranth and found more squalene in the grains (4.2% on average) than the leaves (0.26% on average). Squalene is present in other plant sources; these include olive oil – 564 mg/100 g, soybean oil – 9.9 mg/100 g, grape seed oil – 14.1 mg/100 g, peanut – 27.4 mg/100 g, corn – 24.7 mg/100 g, sunflower seed oil – 13.8 mg/100 g and amaranth – 5942 mg/100 g (Nergiz and Çelikkale 2011; Lozano-Grande et al. 2018). In spite of the high content of squalene in amaranth, it is not well exploited for commercial purposes. Most commercial extraction is from olive oil. It is believed that squalene will gain wide applications in the next decade, therefore it important to study other plant sources like amaranth and develop innovative extraction techniques that guarantee quality and yield at commercial scale.

Proposed framework for development of grain amaranth value chain for food and nutrition security

No doubt, amaranth has been identified as a priority crop for value chain development among hundreds of underutilized species cultivated across Africa (Njoroge et al. 2014). In spite of the positive attributes, it is daunted with many constraints along its valve chain. These constraints are related to cultivation, processing and marketing of grain amaranth and its products (Emokaro, Ekunwe, and Osifo 2007). Cultivation of grain amaranth is challenged by availability of quality seeds, poor knowledge of good agronomic practices, weak farmer organization leading to poor networks with extensionists and research organizations. This is coupled with existing agricultural challenges in developing countries such as; limited access to land, high cost of labor, lack of irrigation facilities, scarcity of fertilizers, poor transportation system, poor market channels and lack of financial support (Chemining'wa et al. 2016).

At the postharvest end, grain amaranth is constrained by tremendous losses and lack of technological know-how and facilities for processing and storage. The marketing of grain amaranth has not fully evolved due to lack of awareness of its nutritional and medicinal properties. Consumers who are supposed to create the demand have limited knowledge of the benefits thereby having little or no preference for grain amaranth and its products. Even if the demand were to be there, this will be hampered by irregular supplies and low quality of products. The same applies to policy makers who have limited information about the potential of this important crop and therefore do not give due consideration to the development of its value chain (Chemining'wa et al. 2016).

However, if grain amaranth is to achieve and fulfill its potential for food and nutrition security, there must be the right framework and guidelines to eliminate the constraints. The national innovation platform workshop held in three countries, i.e. Zimbabwe, Kenya and Benin made six recommendations for the development of amaranth value chain. Creation of market access and consumer demand, strengthening the input (seeds, fertilizers and agrochemicals) system, improving technology for planting and value addition, proper organization of farmers and linkages with extensionists and other researchers, engaging the policy makers through lobbying and advocacy, and generating funds through both private and public sector were the standpoints proposed at the end of the workshop (Hall et al. 2014).

A value chain development approach is needed to promote production, processing and demand for grain amaranth and its product in Africa. This type of approach is focused on improving linkages between small and big actors. Figure 1 displays a proposed framework for the development of grain amaranth value chain. The proposed framework identifies the present state of amaranth value chain which is largely limited to small scale production and very low utilization. It identifies the central role of research along the value chain and links it to actors and actions needed to promote grain amaranth. There is room for alliances and partnerships between researchers, farmers, private and public sector.

Although, the scientific community has always researched and promoted underutilized crops, there is an urgent need for a concerted and coordinated effort in amaranth value chain. The diverse germplasm available in Africa needs to be collected followed by selection and breeding of adaptable and quality varieties. This should be accompanied by technological developments to ease the constraints of production and processing. Research programs have to develop strategic planning in which production, processing and marketing are integrally linked. Research outputs have to feed industrial applications evident by incorporation of grain amaranth into food products acceptable to consumers. Most of the advanced research and development on industrial uses of underutilized crops is undertaken in developed countries and supported by their policies. This should be encouraged in developing countries; however, the scale of development must be adaptable to the realities on ground. A value chain development approach will facilitate and encourage collaborations with private sector which will benefit smallholders by providing more secure market for produce and products (Devaux et al. 2018).

A network for grain amaranth stakeholders is becoming imperative. The goal of the network should be for knowledge and resource sharing and coordination of actions. This could be done in an innovation platform. These are multi-stakeholder platforms that foster technical and business relationships. Researchers should focus not only on generating new knowledge and technologies but more importantly on using the new knowledge and technology to change processes and strengthen actors. Farmers are to be involved in the whole process, private sector need to be engaged to influence their willingness to process and market grain amaranth products, policy dialogues should be aimed at creating awareness and generating support, donors are to be partnered with for financial support while looking inwards for further funding sources.

Conclusions

The amaranth species are crops with great potentials to reduce malnutrition and its attendant diseases. They are high yielding and tolerant to stressful conditions. Amaranth is rich in nutritional contents and bioactive compounds; it has huge relevance for domestic and industrial applications. It is a crop with a great prospect to redeem Africa from shackle of poverty and food and nutrition insecurity. But its full potentials are yet to be exploited. There is need for concentrated and continuous efforts in research, and coordination of all stakeholders for effective implementation of relevant actions.

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