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REVIEW

Orphan crops: their importance and the urgency of improvement

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Abstract

Main conclusion **Due to significant contributions of orphan crops in the economy of the developing world, scientific studies need to be promoted on these little researched but vital crops of smallholder farmers and consumers.**

Abstract Food security is the main challenge in the developing world, particularly in the least developed countries. Orphan crops play a vital role in the food security and livelihood of resource-poor farmers and consumers in these countries. Like major crops, there are members of all food types—cereals, legumes, vegetables and root and tuber crops, that are considered to be orphan crops. Despite their huge importance for present and future agriculture, orphan crops have generally received little attention by the global scientific community. Due to this, they produce inferior yields in terms of both quantity and quality. The major bottlenecks affecting the productivity of these crops are little or no selection of improved genetic traits, extreme environmental conditions and unfavorable policy. However, some orphan crops have recently received the attention of the global and national scientific community where advanced research and development initiatives have been launched. These initiatives which implement a variety of genetic and genomic tools targeted major constraints affecting productivity and/or nutritional quality of orphan crops. In this paper, some of these initiatives are briefly described. Here, I provide key suggestions to relevant stakeholders regarding improvement of orphan crops. Concerted efforts are urgently needed to advance the research and development of both the major and orphan crops so that food security will be achieved and ultimately the livelihood of the population will be improved.

Keywords Crops for the future · Disadvantaged crops · Food security · Minor crops · Orphan crops · Understudied crops · Underutilized crops

Abbreviations

AOCC	African Orphan Crops Consortium
AVRDC	World Vegetable Center
BBSRC	Biotechnology and Biological Sciences Research Council
BGI	Beijing Genomics Institute
BMGF	Bill and Melinda Gates Foundation
CCRP	Collaborative Crop Research Program, McKnight Foundation
CEPLAS	Cluster of Excellence in Plant Science
CFF	Crops for Future
CGIAR	Consultative Group for International Agricultural Research
CIAT	International Center for Tropical Agriculture
CIMMYT	International Maize and Improvement Center
CIP	International Potato Center
CRISPR/Cas9	Clustered regularly interspaced short palindromic repeats/CRISPR-associated 9
ECA	Economic Commission for Africa
FAO	Food and Agriculture Organization
GBS	Genotyping by sequencing
GWAS	Genome wide association study
ICARDA	International Center for Agricultural Research in the Dry Areas
ICRAF	World Agroforestry Centre
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFAD	International Fund for Agricultural Development

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IITA	International Institute of Tropical Agriculture
LDC	Least Developed Countries
NEPAD	New Partnership for Africa's Development
NRC	National Research Council of the USA
ODAP	β-*N*-Oxalyl-L-α, β-diaminopropanoic acid
PPP	Public–private partnership
SASSA	Sustainable Agriculture for Sub-Saharan Africa
SFSA	Syngenta Foundation for Sustainable Agriculture
TILLING	Targeting induced local lesions in genomes

Introduction

Food security is the main challenge to the developing world, especially in the Least Developed Countries (LDCs). Sixty-nine percent of the 45 total LDCs are in Africa. Among 52 countries with food deficits, 35 are in Africa (67%) while 11 are in Asia (FAOSTAT 2018). Due to the inability of these nations to grow enough food for their people, nations with large food deficits are obliged to import large quantities of agricultural products. For instance, in 2016, African nations imported agricultural products worth 71 billion USD out of which 29% were spent on importing cereal crops. This indicates the severity of food insecurity in Africa compared to other parts of the world.

Food security is based on four pillars: (1) food availability which refers to the availability of sufficient quantities; (2) food access which refers to having sufficient resources for acquiring appropriate food for a nutritious diet; (3) stability which refers to availability and accessibility of quality food at all times; and (4) utilization which refers to the appropriate use of food based knowledge of basic nutrition and care, as well as adequate water and sanitation (FAO 2006). Under all the four pillars which focus on the availability, access, stability and utilization of food, Africa is in the worst situation followed by Asia. While food availability is defined by the adequacy of dietary energy supply, food access is a measure of the prevalence of undernourishment. A parameter which represents food stability is the variability in per capita food production. Similarly, a single parameter used to represent food utilization is the proportion of children under 5 years of age who are stunted. As expected, there were large variabilities within a continent for these food security parameters. Although the average undernourishment for Africa in 2016 was 20.4%, the values ranged from a high of 31.4% in East Africa to a low of 8.4% in Northern and Southern Africa (FAOSTAT 2018).

Food security could be improved by focusing on both the major and minor (also known as orphan) crops of the world (Fahey 1998). Orphan crops play an important role in the economy of the developing world since they provide nutrition to a large number of people and provide income for small-scale farmers. The need to focus on orphan crops to meetthe demand for food has been emphasized (Raheem 2011; Ejeta 2010).

The objective of this review is to provide highlights on the importance and constraints related to orphan crops as well as highlights on initiatives associated with the improvement of these disadvantaged crops. Suggestions are made for future research and development of orphan crops.

Types and significance of orphan crops

Orphan crops are also known as underutilized crops (Dawson and Jaenicke 2006), lost crops (NRC 1996, 2006, 2008), neglected crops (Bermejo and León 1994) or crops for the future (CFF 2019) (Table 1). According to Crops for the Future (CFF 2019), the diverse names given to these crops reflect the following characteristics: 'neglected' (by science and development), 'orphan' (without champions or crop experts), 'minor' (relative to global crops), 'promising' (for emerging markets, or because of previously unrecognized value traits), 'niche' (of marginal importance in production systems and economies), and 'traditional' (used for centuries or even millennia).

Orphan crops belong to the major groups of crops, which include cereals, legumes, and fruit as well as root crops (Table 2). Selected orphan crops are briefly described below.

Cereals

Cereals are rich sources of nutrients for both humans and animals. Among these, millets are a rich source of vitamin, calcium, iron, potassium, magnesium and zinc (Léder 2004). Millets represent different types of millets which include Barnyard millet (*Echinochloa crus-galli*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), kodo millet (*Paspalum scrobiculatum*), little millet (*Panicum sumatrense*), pearl millet (*Pennisetum glaucum*) and proso-millet (*Panicum miliaceum*) as well as tef (*Eragrostis tef*) and fonio (*Digitaria sp.*). They are annually cultivated on a total of 32.2 million hectares of land mainly in India, Niger, Sudan, Nigeria and Chad (FAOSTAT 2018). Among major types of millets, pearl millet is dominantly cultivated as a food crop due to its extreme tolerance to moisture deficit (Kholová et al. 2010). Similarly, finger millet is extensively cultivated in the semi-arid regions of Asia and Africa due to its adaptation to unfavorable climatic and soil conditions especially drought (Williams and Haq 2000; Dawson and

Table 1 Different names given to the orphan crops, which refer to the current status or future potential of these crops

Name	Name refer to	Reference
Abandoned crops	Neglect from research and development	Padulosi (2017)
Alternative crops	Options under extreme environment	Padulosi (2017)
Crops for the future	High potential in future agriculture	CFF (2019)
Disadvantaged crops	Unfavored by research and development	Massawe et al. (2015)
Forgotten crops	Little focus on their research	FAO (2017); Pearce (2013)
Future smart food	High contribution to future food security	Li and Siddique (2018)
Indigenous crops	Native crops	Kamadi (2014)
Life-style crops	Health-related benefits	Cannarozzi et al. (2018a)
Local crops	With domestic importance	Padulosi (2017)
Lost crops	Genetic erosion of the germplasm	NRC (2006, 2008, 1996)
Minor crops	Relative to global (major crops) crops	Padulosi (2017)
Neglected crops	Little focus to science and development	Bermejo and León (1994)
Niche crops	Marginal importance in production systems	Padulosi (2017)
Orphan crops	Without champions or crop experts	AOCC (2018); Tadele (2009a, b)
Promising crops	For emerging markets	FAO (2017)
Superfood	Due to nutritional- and health-related benefits	Provost and Jobson (2014)
Traditional crops	Used for centuries or even millennia	Padulosi (2017)
Underdeveloped crops	With limited investment	Padulosi (2017)
Understudied crops	Due to little scientific research	Tadele and Assefa (2012)
Underused crops	Due to little scientific advancement	EcoBusiness (2015)
Underutilized crops	Due to little research	Dawson and Jaenicke (2006); Massawe et al. (2015)
Wonder plants	Superiority in nutrition- and health-related benefits	EcoBusiness (2015)

Jaenicke 2006). Finger millet is also a popular food among diabetic patients because of its low glycemic index and slow release of glucose to blood due to slow digestion associated with high fiber content (Chandrashekar 2010). Another small cereal, which is extensively cultivated in the Horn of Africa due to its tolerance to abiotic stresses especially to poorly drained soil, is tef. Tef has recently received attention and is considered as a life-style crop due to the lack of gluten, the cause for celiac disease (Spaenij-Dekking et al. 2005). The panicles of selected orphan cereal crops are shown in Fig. 1.

Pseudocereals

Pseudocereals refer to the group of crops, which do not belong to the Grass Family due to their two cotyledons unlike grasses with a single cotyledon. However, pseudocereals show their close relationship to the 'true cereals' by their nutritional content especially with regard to the carbohydrate composition. Amaranths (*Amaranthus spp*.), buckwheat (*Fagopyrum esculentum*) and quinoa (*Chenopodium quinoa*) are the major representatives of this category. While buckwheat is mainly cultivated in several Asian and European countries, quinoa is extensively cultivated in three South American countries, namely Bolivia, Peru and Ecuador. In addition to being free of gluten, pseudocereals have a number of health-related benefits, which include reduction in oxidative stress, anti-cancer, anti-diabetic, anti-inflammatory, anti-hypertensive and prevention of cardiovascular diseases (Mir et al. 2018).

Legumes or pulses

Legumes are the major protein source for consumers. Due to their ability to fix atmospheric nitrogen and convert it to ammonium, legumes contribute towards soil improvement. While Bambara groundnut (*Vigna subterranean*) and cowpea (*Vigna unguiculata*) are extensively cultivated in Africa, horse gram (*Macrotyloma uniflorum*) is mainly cultivated in Asia (FAOSTAT 2018). The seeds of Bambara groundnut are known as a complete food since they contain adequate quantities of protein (19%), carbohydrate (63%), and fat (6.5%) (NRC 2006). Cowpea is annually grown on 12.3 million hectares mainly in three western African countries, namely Niger, Nigeria and Burkina Faso. The crop is tolerant to drought and heat, and it also performs better than many other crops on poor soil conditions (Sanginga et al. 2000). Similarly, grass pea (*Lathyrus sativus*) which is cultivated in Asia, Africa and Europe is extremely tolerant to drought. Due to this property, the crop is considered to

Table 2 Selected orphan food crops with their geographical importance and desirable traits

Common Name	Scientific name	Global area (million ha)	Major cultivating countries	Beneficial traits	Reference
Cereals					
African rice	*Oryza glaberrima*		Nigeria, Burkina Faso, Liberia, Sierra Leone	Resistance to biotic and abiotic stresses	Linares (2002); NRC (1996)
Fonio/acha	*Digitaria exilis*	0.91	Guinea, Nigeria, Mali	Fast maturing	Williams and Haq (2000); FAOSTAT (2018); NRC (1996)
Millets[a]	Diverse types	32.2	India, Niger, Sudan, Mali, Nigeria, Chad, Burkina Faso, Senegal, China, Pakistan, Ethiopia	Abiotic stress tolerance; nutritious and healthy food	FAOSTAT (2018); Dawson and Jaenicke (2006); Williams and Haq (2000); Gupta et al. (2017)
Tef	*Eragrostis tef*	3.10	Ethiopia, Eritrea	Abiotic stress tolerance, free of gluten	Ketema (1997); Spaenij-Dekking et al. (2005)
Pseudocereals					
Amaranth	*Amaranthus spp.*			Fast growing and nutritious	NRC (2006)
Buckwheat	*Fagopyrum esculentum*	4.18	China, Russia, Ukraine, Kazakhstan, Poland	Nutritious	FAOSTAT (2018)
Quinoa	*Chenopodium quinoa*	0.19	Bolivia, Peru, Ecuador	Nutritious and healthy	FAOSTAT (2018)
Legumes					
Bambara groundnut	*Vigna subterranean*	0.26	Niger, Cameroon, Burkina Faso, Mali, Togo, DR Congo	Nutritious and drought tolerance	FAOSTAT (2018); NRC (2006)
Chickpea	*Cicer arietinum*	12.65	India, Pakistan, Australia, Iran, Myanmar, Russia, Turkey, Ethiopia	Nutritious	FAOSTAT (2018)
Cowpea	*Vigna unguiculata*	12.25	Niger, Nigeria, Burkina Faso, Mozambique, Sudan	Drought tolerance and nutritious	FAOSTAT (2018); NRC (2006)
Grass pea	*Lathyrus sativus*	1.50	India, Bangladesh, Nepal, Pakistan, Ethiopia	Extreme drought tolerance and nutritious	Campell (1997); Kumar et al. (2013)
Horsegram	*Macrotyloma uniflorum*		India, Bangladesh, Myanmar, Sri Lanka, Bhutan	Nutritious and healthy food	Chahota et al. (2013)
Lentil	*Lens culinaris*	5.46	Canada, India, USA, Turkey, Australia, Nepal, Bangladesh, Iran, Syria, Ethiopia	Nutritious	FAOSTAT (2018)
Pigeon pea	*Cajanus cajan*	5.49	India, Myanmar, Tanzania, Malawi, Haiti, Kenya		FAOSTAT (2018); Pal et al. (2011)
Vegetables					
Baobab	*Adansonia digitate*		Madagascar, India	Nutritious	NRC (2006)
Moringa	*Moringa oleifera*		India,	Nutritious	NRC (2006)
Okra	*Abelmoschus esculentus*	2.41	Nigeria, India, Niger, Côte d'Ivoire, Cameroon, Sudan, Mali	Tolerance to biotic stresses, fast growing and nutritious	FAOSTAT (2018)
Oil seeds					
Castor bean	*Ricinus communis*	1.44	India, Mozambique, Brazil, China	Healthy	FAOSTAT (2018)

Table 2 (continued)

Common Name	Scientific name	Global area (million ha)	Major cultivating countries	Beneficial traits	Reference
Linseed	*Linum usitatissimum*	3.02	Russia, Kazakhstan, Canada, India, China, USA, Ethiopia, Ukraine	Nutritious and healthy	FAOSTAT (2018)
Noug	*Guizotia abyssinica*		Ethiopia, India	Quality oil, abiotic stress tolerance	Getinet and Sharma (1996)
Sesame	*Sesamum indicum*	10.60	Sudan, India, Myanmar, Tanzania, South Sudan, Nigeria, Ethiopia	Oxidatively stable oil	Dawson and Jaenicke (2006); FAOSTAT (2018)
Root crops					
Cassava	*Manihot esculentum*	26.1	Nigeria, DR Congo, Brazil, Thailand, Mozambique, Tanzania, Uganda, Ghana, Angola, Indonesia, Côte d'Ivoire	Drought tolerance	Ceballos et al. (2004); FAOSTAT (2018)
Enset	*Ensete ventricosum*	0.3	Ethiopia	Drought tolerance	Brandt (1997); Olango et al. (2014)
Sweet potato	*Ipomoea batatas*	12.25	China, Nigeria, Tanzania, Uganda, Ethiopia, Angola, Madagascar	Rich in riboflavin and calcium	Dawson and Jaenicke (2006); FAOSTAT (2018)
Taro cocoyam	*Colocasia esculenta*	1.83	Nigeria, Cameroon, Ghana, China, Côte d'Ivoire, Rwanda, Madagascar	Nutritious and healthy	FAOSTAT (2018); Okpala (2015)
Yam	*Dioscorea spp*	8.38	Nigeria, Côte d'Ivoire, Ghana, Benin, Togo, Sudan	Drought tolerance	Williams and Haq (2000); FAOSTAT (2018)
Fruits					
Banana	*Musa spp.*	5.81	India, Brazil, Tanzania, China, Philippines, Rwanda, Burundi, Ecuador, Uganda	Healthy and nutritious	Heslop-Harrison and Schwarzacher (2007); FAOSTAT (2018)
Plantain	*Musa spp.*	5.43	DR Congo, Uganda, Nigeria, Côte d'Ivoire, Colombia, Ghana Cameroon, Tanzania, Philippines	Healthy and nutritious	Heslop-Harrison and Schwarzacher (2007); FAOSTAT (2018)

The list of countries is presented according to the descending order of the area the crop is cultivated in 2016

[a]Millets refer to all types of millets which include Barnyard millet (*Echinochloa crus-galli*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), kodo millet (*Paspalum scrobiculatum*), little millet (*Panicum sumatrense*), pearl millet (*Pennisetum glaucum*) and proso-millet (*Panicum miliaceum*)

Fig. 1 Panicles of selected orphan cereal crops. Left to right: proso-millet (*Panicum miliaceum*), foxtail millet (*Setaria italica*), finger millet (*Eleusine coracana*) and two tef (*Eragrostis tef*) panicles with red and green color. Scale bar: 10 cm. Photo: Annett Weichert, University of Bern

be an insurance crop as it produces reliable yields when all other crops fail due to extreme moisture scarcity.

Vegetables

There are many indigenous or locally important vegetables in the developing world. Several of them have benefits in some agronomic and/or nutritional traits: for example, okra (*Abelmoschus esculentus*) is fast growing and nutritious (Gemede et al. 2014) or baobab (*Adansonia digitate*), which is a multi-purpose tree with leaves rich in iron and fruits rich in vitamin C (Sanchez 2018).

Oilseeds

Among oilseeds, sesame (*Sesamum indicum* L) is annually cultivated on over 10 million hecatres of land mainly in Sudan, India, Myanmar and Tanzania (FAOSTAT 2018). Other oilseeds with some importance in developing countries are linseed (*Linum usitatissimum*), castor bean (*Ricinus communis*) and noug (*Guizotia abyssinica*).

Root and tuber crops

Among root crops, cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*) and yam (*Dioscorea sp.*) are the source of food for a large number of people in the developing world. Cassava or manioc is annually cultivated on 26.1 million ha of land globally where the major producing countries are Nigeria, DR Congo, Brazil, Thailand and Mozambique (FAOSTAT 2018). Cassava is tolerant to drought, and performs better than other crops on soils with poor nutrients. Other extensively cultivated orphan root and tuber crops include sweet potato on 12.3 million ha and yam on 8.4 million ha (FAOSTAT 2018). While sweet potato is cultivated in different parts of the world, yam is exclusively cultivated in Africa. It is worthwhile to mention the plant called enset (*Ensete ventricosum*), which is also known as 'false banana' because it resembles the domesticated banana plant. Enset is a staple food for over 20 million people in the densely populated regions of Ethiopia. Unlike banana where the fruit is consumed, in enset the pseudo-stem and the underground corm are the edible parts. Enset is an extremely drought-tolerant crop that adapts to different soil types (Brandt 1997).

Fruits

Banana and plantain (*Musa spp.*) are important fruit crops in the developing world although genetic resources and research are very limited. The global cultivation area of these fruits was 5.8 million ha for banana and 5.4 million for plantain in 2016 (FAOSTAT 2018). Banana is extensively cultivated in Asia, Africa and South America. Plantain is the staple food in Africa especially in DR Congo, Uganda and

Nigeria. It is often considered to be a vegetable rather than a fruit since the plantain is cooked like a vegetable. According to Fungo (2009), banana especially the orange pulped type with high carotenoid and iron content could reduce iron deficiency anemia by over 50% and also vitamin A deficiency in East Africa, where a large part of the population lack iron and vitamin A. Banana and plantain are considered to be healthy foods as they are also rich in essential nutrients for humans.

Need for improving orphan crops

There are many reasons to invest in research on orphan crops. The main reasons are described below.

Exclusion of orphan crops from advanced research

Orphan crops play a vital role in the livelihood of the developing world (Tadele 2014, 2017, 2018; Tadele and Assefa 2012). However, compared to major crops of the world, research and development of orphan crops are lagging behind that of major crops at both the global and at the national levels. These two scenarios are briefly discussed below.

Neglect at the global level: exclusion from the Green Revolution

The famous Green Revolution contributed to a significant boost in total production and productivity of wheat and rice in Asia. However, the Green Revolution did not occur either in Africa or on orphan crops (Ejeta 2010; Godfray et al. 2010). In terms of area of cultivation, the top three crops in Africa are maize (23%), sorghum (16%) and cassava (12%), while those in Asia are rice (35%), wheat (24%) and maize (16%) [Fig. 2, (FAOSTAT 2018)]. Similarly, in terms of total production, the top three crops in Africa are cassava (34%), maize (16%) and yam (14%), while in Asia these are rice (28%), maize (15%) and wheat (13%). In Africa, cereals produce inferior yield while root crops such as cassava and yam, which are associated with a high risk of post-harvest losses due to a short shelf-life, contribute to the bulk of production. On the contrary, the major cereal crops in Asia can be stored for long periods, at least until just the harvest of the next cropping season, which corresponds to the critical time of food shortage. This indicates that the dominant African crops in terms of both the area under cultivation and the total production were not given a policy-related focus which is also referred to as an enabling environment (Tadele 2019).

Neglect at the national level: a tale of two cereals from Ethiopia

Here, comparison is made between wheat and tef, the two extensively cultivated cereals in Ethiopia. While tef is an orphan crop with local importance, wheat is a major crop with both local and global importance. In Ethiopia, tef is annually cultivated by 6.7 million farmers while wheat by 4.8 million farmers (Fig. 3a). Similarly, the area of tef and wheat cultivations is 2.9 and 1.7 million hectares, respectively (Fig. 3b). This 40% more of tef farmers over wheat farmers and about 70% more area allocated to tef compared to wheat shows the importance of tef in the Ethiopian agriculture. However, the total production of 4.5 million tons of tef was only 7% higher than that of wheat (4.2 million tons) (Fig. 3c). This small gap in production between the two crops but large gap in the area under cultivation is mainly due to the more advanced research and development implemented in wheat. This can be witnessed from the number of improved varieties. The total number of improved varieties released to the farming community in Ethiopia until the year 2015 was only 35 for tef but 167 for wheat (Fig. 3d). It is also important to note that the total number of varieties released during the 3-year period between 2012 and 2015 was only 3 for tef while it was 15 for wheat. Due to the release and wide dissemination of improved wheat varieties, the national average yield of wheat is currently 2.5 t ha^{-1} compared to only 1.6 t ha^{-1} for tef. The improvement of wheat substantially exceeded that of tef as witnessed by the number of improved varieties available to farmers. This is mainly due to significant contributions to wheat improvement by international organizations such as CIMMYT (International Maize and Improvement Center) from where most wheat breeding lines for improved varieties originated. On the contrary, the bulk of research on tef has been done with little support by domestic and international organizations. Not only the orphan crops but also researchers of orphan crops have a disadvantage due to very limited access to advanced research and technical know-how as most researchers do not have training opportunities in advanced laboratories.

It is not the intention of this author to either call for the complete replacement of wheat fields by tef or to focus only on the orphan crop tef. Wheat is also equally important for farmers and consumers since it is extensively cultivated in the country. However, the intention is to pay attention to the improvement of tef, which is annually cultivated on about 30% of the total cereal area and a staple food for over 60 million people in Ethiopia alone.

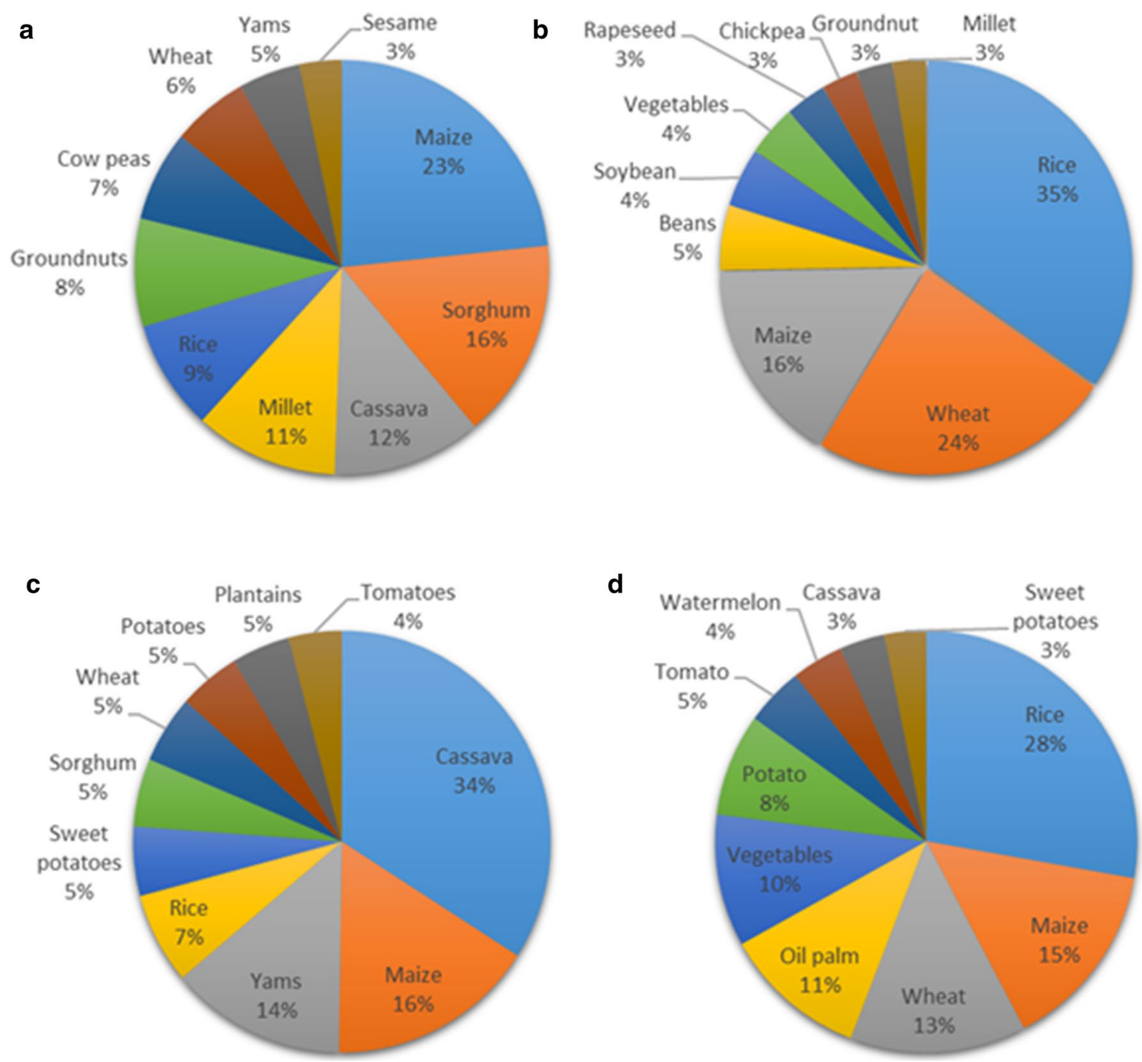

Fig. 2 The proportion of the top ten food crops in 2017 in Africa (**a**, **c**) and Asia (**b**, **d**) in terms of total area (**a**, **b**) and total production (**c**, **d**) Adapted from (FAOSTAT 2018)

Constraints related to inherent properties of orphan crops

Orphan crops fit to the socio-economic and diet of the population in the developing world. However, orphan crops are not without constraints. Some orphan crops are associated with undesirable traits, which need to be altered to improve their productivity and/or nutritional quality. Constraints which are directly related to some orphan crops are the following.

Inferior in productivity

Due to lack of genetic improvement, orphan crops produce inferior yield in terms of both quality and quantity. For instance, the seed yields of African rice (*Oryza glaberrima*), tef and millets are extremely low. The main reasons for poor productivity in these crops are lodging, seed shattering or other crop specific constraints (Assefa et al. 2011; Linares 2002).

Poor or unbalanced nutrition

Root and tuber crops such as cassava and enset produce high yields, but they are largely composed of starches that are deficient in other essential nutrients particularly in protein. Studies showed that large populations in low-income countries who depend on these food products as a sole food source suffer from malnutrition (Stephenson et al. 2010; Gegios et al. 2010). Hence, supplementation with other essential nutrients is necessary. Alternatively, biofortification of staple food crops with essential nutrients can be made to enhance the nutrient content and/or remove undesirable food quality traits.

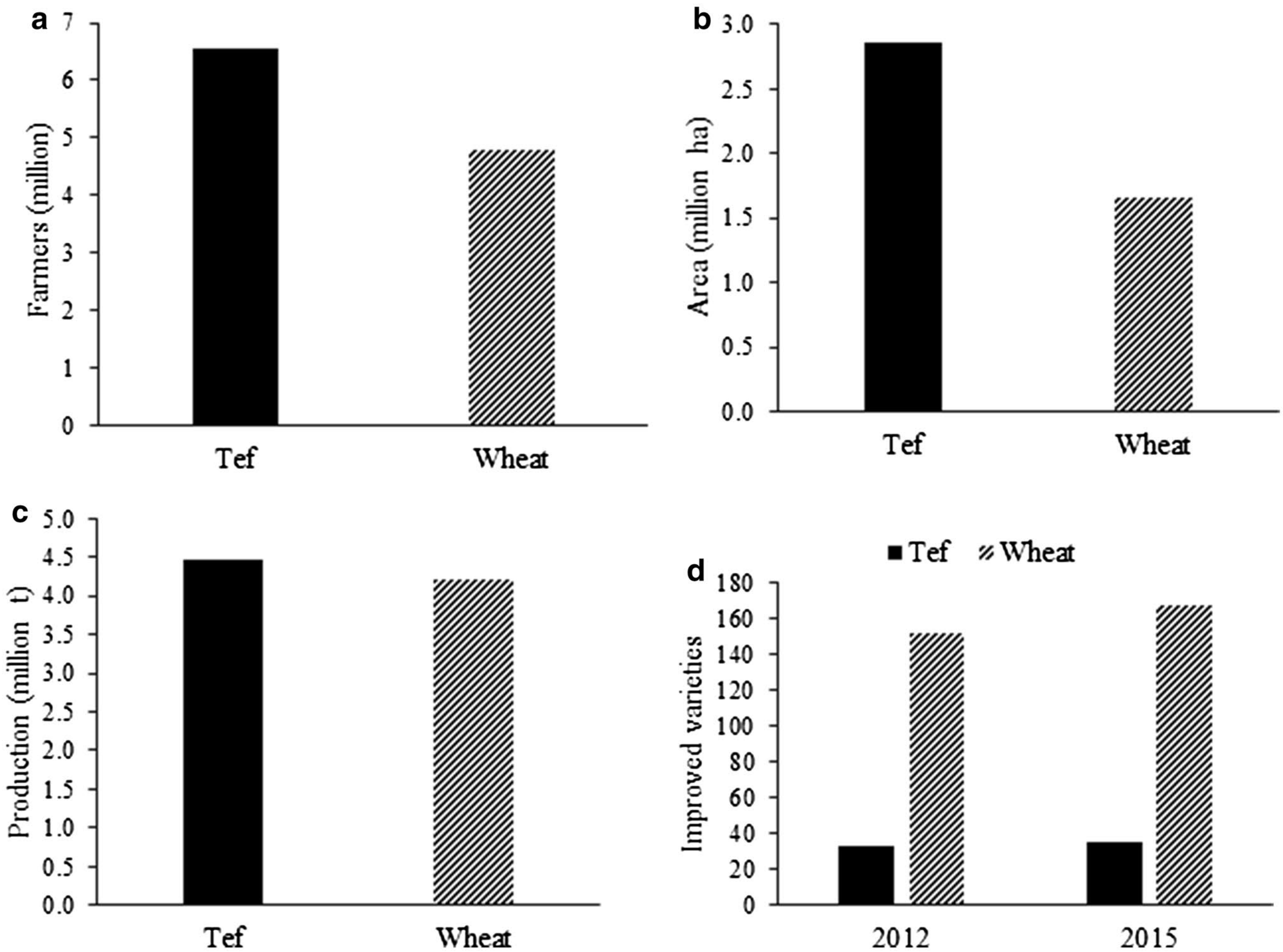

Fig. 3 Comparison between an orphan crop tef and a major crop wheat in Ethiopia. **a** Number of farmers cultivating in 2016; **b** total area under cultivation in 2016; **c** total grain production in 2016; and **d** total number of varieties released by 2012 and by 2015 Adapted from (Mabaya et al. 2017; CSA 2015; WheatAtlas 2019)

Toxic products

Widely cultivated crops such as cassava and grass pea produce toxic compounds that affect the health of human and/or livestock. The edible parts of cassava produce a poisonous substance called cyanogenic glycosides which release cyanide (Ceballos et al. 2004). Hence, the consumption of unprocessed cassava results in a paralytic disease called *konzo*. Similarly, the grains of grass pea contain a neurotoxic substance called ODAP (β-*N*-oxalyl-L-α, β-diaminopropanoic acid) which causes irreversible paralysis of the lower body when consumed over long periods (Yan et al. 2006).

Extreme environmental conditions

Since most fertile lands are used to grow crops other than indigenous crops, native crops are mostly cultivated on less fertile and moisture-deficit soils. In addition, crop productivity is affected by a variety of abiotic and biotic stresses (Tadele 2019). Abiotic stresses which are prevalent in developing countries are drought, flooding, heat, soil salinity and soil acidity. At the same time, biotic stresses which include a variety of diseases, insects and weeds also tremendously reduce crop productivity. The adverse effects of biotic factors on crop productivity are more obvious in the tropical regions due to their presence in high density and diversity. Hence, the extent and type of environmental challenges are more intense for orphan crops.

Opportunities related to orphan crops

Orphan or indigenous crops are associated with some desirable properties which can be useful in the promotion of these crops to a higher level of production. The compatibility of these crops to the agro-ecology and socio-economic conditions as well as their potential to adapt to changing climate are a few examples of opportunities for using orphan crops.

Compatibility with agro-ecology and socio-economic conditions

Most orphan or indigenous crops perform better under adverse climatic and soil conditions than the exotic or introduced crops. In addition, orphan crops are compatible with the agro-ecology and socio-economic conditions. However, when other crops that are new to the locality replace indigenous crops, some problems might occur. For example, the incidence of malaria has been increased when the indigenous crop tef was replaced by maize in the northwestern part of Ethiopia since mosquitos prefer to feed on maize pollen rather than on indigenous cereals (Ye-Ebiyo et al. 2000).

Orphan crops play a vital role in changing climate conditions

Climate change poses a significant threat to the present crop production systems, infrastructures, and markets (Muller et al. 2011). It is expected that the total amount and distribution of rainfall will be substantially affected in the near future. Based on in situ station data and satellite observations, up to 15% decrease in rainfall is expected in the Eastern and Southern Africa (Funk et al. 2008). However, according to other studies, a wetter climate with more intense wet seasons and less severe droughts is predicted in East Africa (Shongwe et al. 2011) while a substantial decrease in rainfall and an increase in temperature in West Africa (Sarr 2012). According to other investigators, the long-term variability and changes of rainfall in the southern Africa will lead to more intense and widespread drought (Fauchereau et al. 2003). Orphan crops are expected to perform better than major crops under the changing climate due to their resilience to diverse environmental constraints (Chivenge et al. 2015).

In general, the positive traits of orphan crops should initiate research approaches to abolish the undesirable traits associated with orphan crops towards developing high yielding, nutritionally superior and resilient crops.

Initiatives on the awareness and improvement of orphan crops

Recently, some institutions in both, the developed and developing counties, are actively participating in the promotion of orphan crops. A number of promotions have been made to introduce the potential role of orphan crops in agriculture. Selected examples to increase the awareness of orphan crops are described. *Media*: famous newspapers heralded the nutrition- and health-related benefits of orphan crops. For instance, the story of the benefits of tef as a life-style crop has been recently presented in the New York Times (O'Connor 2016), the Washington Post (Gordon 2014), the Guardian (Provost and Jobson 2014), BBC (Jeffrey 2015) and many others.

The Lugar Center (http://www.thelugarcenter.org/ourwork-Orphan-Crops.html), under the leadership of the former United States Senator Richard G. Lugar, provides a platform for debates on global issues and also includes key information on orphan crops which are useful for researchers and other stakeholders including policymakers (Lugar 2019).

International Year of Quinoa

The United Nations General Assembly has declared 2013 as the International Year of Quinoa, in recognition of ancestral practices of the Andean people, who have managed to preserve quinoa in its natural state as food for present and future generations (FAO 2013). This was followed by publishing a comprehensive book on the global importance of this particular crop (Bazile et al. 2015).

Conferences and podium discussions

The first African Orphan Crops Conference was held in September 2007 at the University of Bern in Switzerland with the participation of researchers from all over the world (Tadele 2009a). This was followed by a conference held in September 2018 by the Cluster of Excellence in Plant Science (CEPLAS) in Cologne Germany (CEPLAS 2018).

Publications

In addition to original research articles in scientific journals and research reports, some journals dedicated a special issue to promote the research and knowledge of orphan crops; among them, a recently published report which describes orphan crops as 'Future Smart Food', in eight countries in South and Southeast Asia. The countries included in the report are Bangladesh, Bhutan, Cambodia, Lao PDR, Myanmar, Nepal, Viet Nam and West Bengal in India. The potential crops were selected based on four criteria such as nutrition, production, ecology and socio-economy. The crops include ten cereals, six root and tuber crops, nine pulses, nine fruit and vegetable crops, and five nuts and spices. The special issue in the African Technology Development Forum Journal (Tadele 2009b) and this issue of *Planta* should also be mentioned.

Conservation and maintenance of germplasm

National institutions

Worldwide, more than 1700 gene banks hold collections of food crops for safekeeping (CropTrust 2019). However, many of these are not only vulnerable to natural catastrophes and war, but also suffer from poor funding. Hence, the conditions are not optimal for the conservation of valuable genetic resources.

International institutions

The consultative group for international agricultural research (CGIAR) plays a vital role among international institutions involved in germplasm collection and conservation. From the 15 CGIAR centers, those with the mandate on orphan crops are: Africa Rice on rice; International Center for Agricultural Research in the dry areas (ICARDA) on lentil and chickpea; International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) on chickpea, pigeon pea, and pearl millet; International Institute of Tropical Agriculture (IITA) on banana, plantain, cassava, cowpea and yam; International Center for Tropical Agriculture (CIAT) on beans and cassava; International Potato Center (CIP) on sweet potato and Bioversity International on banana (CGIAR 2019b). The total number of crop accessions including major and orphan crops deposited at CGIAR centers are estimated to be around 760,000 (CGIAR 2019a). These centers have been providing substantial technical and financial support to the national institutions in the developing world. However, highly nutritious and healthy crops such as tef are not included in the mandate of any CGIAR center.

Crop diversity trust

The trust supports crop conservation through developing global strategies for the ex situ conservation of 21 crops which include orphan crops such as cassava, chickpea, cowpea, finger millet, grass pea and sweet potato (CropTrust 2019).

Svalbard Global Seed Vault

This seed vault with the capacity to store 4.5 million varieties of crops is located at Svalbard in Norway which is only 1000 km from the North Pole. The vault is an ideal location for long-term seed storage due to the following reasons: (1) Svalbard is a remote location, so there are few human-related activities around it, (2) the area is geologically stable and humidity levels are low, (3) the vault is well above sea level, protected from ocean flooding according to worst case scenario sea level rises, and (4) the permafrost offers the vault room with a natural freezing, providing a cost-effective and safe method to conserve seeds (CropTrust 2019). Hence, the Svalbard Global Seed Vault provides insurance against catastrophic loss of crop diversity. Currently, 983,524 varieties from all over the world have been conserved at the storage facility of the vault. It is interesting to note that some researchers have already started requesting the seeds they earlier deposited at the vault. The typical example is ICARDA, an International Agricultural Research Center, which sent thousands of its germplasm samples of different crops to the vault before the conflict in Syria destroyed its gene bank in Aleppo. Later, the center received over 38,000 seed samples from the seed vault to grow the plants at the newly relocated centers in Lebanon and Morocco, enabling continuation of the research (ICARDA 2015).

Advanced research on orphan crops

Improvement of orphan crops mostly uses conventional techniques particularly selection of lines from landraces. Some breeding programs of orphan crops also implement introgressions involving interspecific or intraspecific crosses. Recently also advanced breeding tools have been implemented for selected orphan crops through partnerships between institutions in developed and developing countries. Examples of advanced research on selected orphan crops are shown in Table 3. These advanced techniques include marker-based studies including GBS (genotyping by sequencing) and GWAS (genome-wide association study). High-throughput techniques which identify alleles such as TILLING (Targeting Induced Local Lesions in Genomes) from induced mutagenized populations and EcoTILLING from natural populations have been applied to selected orphan crops. Similarly, omic tools have been implemented on a few orphan crops. The African Orphan Crops Consortium (AOCC) was formed with primary goal of sequencing the genomes of 101 African food plants and improving nutrition in the continent through genome-assisted breeding resources and training (AOCC 2018). The consortium is formed by the New Partnership for Africa's Development (NEPAD), World Agroforestry Centre (ICRAF), Beijing Genomics Institute (BGI), University of California at Davis and Mars Incorporated. Other omic tools which include transcriptomics and proteomics have been used to describe gene expression profiles of some orphan crops. Genome editing techniques especially the CRISPR/Cas9 (clustered regularly interspaced short palindromic repeats/CRISPR-associated protein9) approach has been implemented on cassava and recently on ground cherry (*Physalis pruinosa*) (Lemmon et al. 2018; Bull et al. 2018; Gomez et al. 2018; Odipio et al. 2017; Hummel et al. 2018). The CRISPR/Cas9 technology has a high potential to modify undesired traits in orphan crops in a short time and should be implemented to orphan crops such as cassava, millet or tef (Mollins 2017).

Table 3 Examples of advanced breeding and genomic techniques implemented on selected orphan crops

Technique	Crop targeted	Reference
Speed breeding	Cassava, chick pea, finger millet	Chiurugwi et al. (2018)
Marker assisted		
GBS	Cassava, chickpea, cowpea, finger millet, pearl millet, tef	Kumar et al. (2016); Girma et al. (2018); Rabbi et al. (2014, 2015); Moumouni et al. (2015); Deokar et al. (2014); Xiong et al. (2016); Fatokun et al. (2018)
GWAS	Cassava, chickpea, finger millet, foxtail millet	Zhang et al. (2018); Jia et al. (2013); Li et al. (2018); Sharma et al. (2018)
Genome editing		
CRISPR/Cas 9	Cassava, ground cherry (*Physalis pruinosa*)	Lemmon et al. (2018); Bull et al. (2018); Gomez et al. (2018); Odipio et al. (2017); Hummel et al. (2018)
High throughput		
TILLING	Tef	Esfeld et al. (2013a)
EcoTILLING	Chickpea	Bajaj et al. (2016)
Omics		
Genome sequence	Chickpea, cowpea, enset, pearl millet, pigeon pea, tef, 101 African crops	Cannarozzi et al. (2014); Hittalmani et al. (2017); Hatakeyama et al. (2017); AOCC (2018); Varshney et al. (2017b); Mahato et al. (2018); Varshney et al. (2017a); Yematawa et al. (2018); Parween et al. (2015); Munoz-Amatriain et al. (2017)
Transcriptome sequence	Chickpea, tef	Cannarozzi et al. (2014); Verma et al. (2015)
RNASeq	Chickpea, finger millet, tef	Cannarozzi et al. (2018b); Hittalmani et al. (2017); Kudapa et al. (2018)
Proteome sequence	Chickpea, pearl millet, tef	Ghatak et al. (2016); Kamies et al. 2017; Bhushan et al. (2007)

GBS genotype by sequencing, *GWAS* genome-wide association study, *CRISPR/Cas 9* clustered regularly interspaced short palindromic repeats/CRISPR-associated protein9, *TILLING* Targeting Induced Local Lesions in Genomes

Institutions dedicated to research and improvement of orphan crops

National research institutions

Research and higher learning institutions in developing countries are involved in the improvement of significant crops of their respective countries. However, the expected level of advancement has not been made on many locally important crops due to limited investment and lack of skilled personnel.

International institutions

In addition to CGIAR centers indicated above, some higher learning institutions in developed countries are also interested in improving a single or multiple orphan crops. These institutions have been providing substantial technical and financial support. Few of these institutions are briefly presented below.

Crops for the Future (CFF)

The center, based at Semenyih in Malaysia, is dedicated to the development of underutilized crops, increasing income for producers and enhancing nutrition (CFF 2019). The center is affiliated with Nottingham University (UK) where advanced research on Bambara groundnut is performed.

African Orphan Crops Consortium (AOCC)

The main partners of consortium are new partnership for Africa's Development (NEPAD), Mars incorporated, World Agroforestry Centre (ICRAF), BGI, University of California, and Biosciences Eastern and Central Africa (BecA). The consortium is committed to sequence the genome of 101 traditional African food crops with high nutritional value which include cereals, vegetables, root and tubers and fruit trees (AOCC 2018).

World Vegetable Center

The center is based at Shanua in Taiwan and has six regional centers in Asia and Africa. The mandate of the World Vegetable Center is to conduct research and promote vegetables including orphan vegetables. To date, over 60,000 accessions of 440 species from 151 countries are conserved at the center out of which 10,000 accessions are traditional vegetables (AVRDC 2019).

Tef Improvement Project

The project aims at improving the orphan cereal crop tef and it is hosted at the Institute of Plant Sciences at the University of Bern in Switzerland. The project employs key genetic and genomic tools (Esfeld et al. 2013b; Girma et al. 2018) and collaborates with the National Tef Improvement Program in Ethiopia to develop tef varieties with desirable traits (Cannarozzi et al. 2018a; Kebede et al. 2018). The group led an international group of scientists which resulted in the genome sequence of the draft genome of tef (Cannarozzi et al. 2014).

Funding institutions

A list of institutions involved in orphan crop research, development and funding was earlier presented (Tadele 2009c). Here, only few institutions which are currently providing financial support to orphan crops research are presented.

Biotechnology and Biological Sciences Research Council (BBSRC): through Sustainable Agriculture for Sub-Saharan Africa (SASSA) program, it provides financial grant to address research challenges relating to the sustainable intensification of agricultural systems in Africa (BBSRC 2019).

Bill and Melinda Gates Foundation (BMGF): In addition to supporting the germplam conservation at Svalbard Seed Vault and sequencing the 101 African crops, the foundation supports the genetic improvement of cassava (BMGF 2019).

McKnight Foundation: throughits Collaborative Crop Research Program (CCRP), the foundation provides financial support for research and development of vital crops in Andes and Africa. Among orphan crops, Bambara groundnut, cowpea and finger millet are currently receiving grants from the foundation (CCRP 2019).

Syngenta Foundation for Sustainable Agriculture (SFSA). It provides both financial and technical support to projects in Africa, Asia and South America. Among these, the foundation supports the scientific work on an orphan crop tef (SFSA 2019).

International organizations: this includes organizations such as the World Bank, Food and Agriculture Organization (FAO) and International Fund for Agricultural Development (IFAD) who provide support to the work on orphan crop through their projects in developing countries.

Suggestions for improving orphan crops

Diverse types of orphan crops are cultivated at diverse agro-ecological and socio-economic conditions of developing world. Due to these extensive variabilities, the same types of suggestions cannot be forwarded for the research and development of these neglected crops. However, the following general suggestions can be provided to promote orphan crops.

Policy-related suggestions

A favorable policy or enabling environment is required to promote the research and development of orphan crops (Tadele 2017). These include the following:

Implementation of the right type of strategy

Locally appropriate technologies need to be developed in addition to human and institutional capacity building as well as forming conducive policy. Governments also need to implement land, marketing, and credit policies conducive to support agricultural development.

Investment on innovative agriculture

Stakeholders involved in agricultural research and development need to invest in agricultural innovation as it contributes towards improving the production, marketing or distribution system. An innovative Push–Pull Technology earlier developed in Kenya to control insect pests and a parasitic weed from maize fields has received a high acceptance in East Africa (Murage et al. 2015).

Provision of inputs and credit

In addition to policy-related and environmental constraints, poor crop productivity of orphan crops is due to the use of inefficient agricultural practices which begin from land preparation, weeding, harvesting and finally to threshing and storage. In addition, sub-optimal use of input such as fertilizers, herbicides and pesticides contributes to the low productivity of crops (Denning et al. 2009). The fertility of the land and the land tenure system has a huge impact on crop productivity. The access of farmers to the inputs and credit is important as they affect the productivity of crops.

Creation of robust extension system

Success in agricultural development is not achieved without the adoption of improved technologies by a large number of farmers. This calls for the establishment of strong extension system, which links the research community to the farming community. The transfer of new technologies to end users and their acceptance by farmers are facilitated when farmers are involved in decision-making starting at an early stage of technology development.

Germplasm collection and utilization

The germplasm of many under-studied crops have not been properly collected and utilized by researchers. To avoid loss of genetic materials due to human and natural disasters, it is advisable to save the duplicate of all germplasm of orphan crops at Svalbard Seed Vault. To harness the genetic diversity among the landraces, the Germplasm needs to be available to researchers from both developed and developing countries.

Developing crops that adapt to changing climate

Since abiotic stresses such as drought, salinity and heat as well as climate change substantially affect the productivity of crops and food security, future research should also focus on developing resistance or tolerance against these environmental calamities. The ability of indigenous crops to resist one or more stresses increases the chance to be selected as a potential crop to be used as an alternative crop in the changing climate. However, some undesirable traits associated with these crops (e.g., low productivity) need to be improved.

Partnership with relevant stakeholders

Establishing efficient partnerships with the national, regional and international institutions are important for improving orphan crops. Nowadays, public–private partnership (PPP) is considered as an effective mechanism to bring together the public and the private sectors towards enhancing agricultural sustainability in the developing world.

Conclusions

Orphan crops are very important for food security especially in the developing world and for the diversity of genetic resources. Despite their huge importance, these crops have generally received little attention by the global scientific community. It is important to promote research on both the major and orphan crops. Hence, major changes in agriculture are required to increase food production for under-researched crops to feed the ever-increasing population of the developing world. The next Green Revolution needs to include these locally adapted crops that are mostly known as orphan or under-studied crops. Crop improvement by itself does not lead us to the final goal unless supported by policies that include extension, land tenure and credits. Strategies and policies conducive for boosting productivity need to be devised in addition to establishing partnerships with relevant stakeholders. These partnerships among relevant stakeholders are necessary to tackle the challenges especially in the face of climate change.

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Compliance with ethical standards

Conflict of interest I declare that there is no financial interest or conflict of interest.

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