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Sub-Saharan African maize-based foods: Technological perspectives to increase the food and nutrition security impacts of maize breeding programmes

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ABSTRACT

The demand for maize in Sub-Saharan Africa will triple by 2050 due to rapid population growth, while challenges from climate change will threaten agricultural productivity. Most maize breeding programmes have focused on improving agronomic properties and have paid relatively little attention to postharvest qualities, thus missing important opportunities to increase the contribution to food and nutrition security. This paper considers current and potential food uses of maize in Africa and proposes six objectives to enhance the contribution of maize breeding programmes to food and nutrition security: (1) enhance nutrient density; (2) enhance suitability for use in bread and snacks; (3) improve characteristics for consumption as green maize; (4) improve characteristics that enhance the efficiency of local processing; (5) reduce waste by maximising useful product yield and minimising nutrient losses; (6) reduce the anti-nutrient content of grain.

1. Introduction

The growing availability of staple foods in Sub-Saharan Africa (SSA) since the 1990s has substantially reduced the prevalence of undernutrition (Andersson et al., 2017). Staple foods in SSA are characterized by high carbohydrate content, but are low in other food nutrient components like protein, vitamins and minerals (Ranum et al., 2014). One of the major staple crops in SSA is maize, which is consumed in many forms including infant foods, snacks and main dishes. Populations in regions with heavy maize consumption may suffer malnutrition due to natural deficiencies or low quantities of some nutrients in maize, limitations of the maize food matrix, presence of anti-nutrients, physical loss or chemical damage to the nutritional composition during post-harvest handling and limited alignment of maize breeding programmes with preferences of end users, i.e., maize processors and consumers (Ranum et al., 2014). Preferences for maize and maize-based foods differ across Africa, thus implying that general solutions are not feasible for the diverse and dynamic continent (Smale et al., 2013). Research and development (R&D) policies in Africa generally emphasise improving agronomic properties such as yield and tolerance to abiotic and biotic stresses. In contrast, understanding characteristics such as taste, colour, nutritional value and suitability for use in preparing local or novel dishes seldom receives the attention it deserves (Hebinck et al., 2015).

The ultimate measure of the success of maize breeding efforts is the demand and adoption of their new varieties by end users. Breeders develop new varieties based on product profiles, which are a list of traits and characteristics that must be achieved in the new variety for it to succeed. More than one product profile is needed to define the needs of all clients, including processors and consumers. An adequate understanding of the needs of maize users, and integrating this understanding into product profiles targeted by breeding programmes across SSA will help to properly harness research resources, increase adoption of novel maize varieties, improve nutrition and meet the needs of traditional and modern food processes. Between 2010 and 2050 the population of Africa is expected to double, with urbanization levels changing from one third to more than half. Once food security is assured, consumers will increasingly demand quality traits. Maize food uses can be expanded to support the rural/urban transition by offering more nutritious food products and enhancing processing efficiency.

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This is critical because to date various maize varieties with improved agronomic traits are facing challenges along the value chain, such as differences in organoleptic preferences and processing requirements of users, limiting the utilisation of the crop for food (Muzhingi et al., 2008a; Nkhabutlane et al., 2014). Strategies based on maize breeding and improved processing methods that hinge on a critical understanding of users' preferences and nutritional needs could help people meet their daily dietary requirements, and position breeding programmes in developing countries for greater impact.

This paper examines the preferences and needs of maize users in SSA and suggests traits that maize breeding programmes might include in their portfolio to further increase the impact of new varieties on food and nutrition security. The research did not consider the specific needs of each country in SSA; instead, it focused on what is characteristic for two major maize production and consumption regions, i.e. Western and Eastern/Southern Africa, where maize is a staple food. Likewise, the research did not take into account the ease or difficulty of incorporating these traits into new varieties but identified some possible quality trait targets and the current methods for measurement. The review serves as a foundation for further work to meet users' needs and improve maize value chains.

1.1. Categories of maize-based foods

In general, we can distinguish six categories of maize-based foods in Africa, namely: whole-maize foods, wet-ground maize foods, snacks and bread, maize sourdough and dumplings, porridges and beverages. Examples of maize-based foods are summarised in Table 1; a comprehensive list of maize-based foods, their descriptions and frequency of consumption can be found in Ekpa et al. (2018).

1.2. Maize preferences for food in Africa

Flint, dent, pop-maize (popcorn), waxy, sweet and floury maize types of diverse colours, sizes and shapes are commercially grown for human consumption around the world. Grain colour is an important selection criterion for users in Africa, where white is generally preferred over yellow. Although 90% of globally produced maize is yellow, white maize predominates in Africa with over 90% of the total maize crop; it also accounts for more than 30% of global white maize production (Khumalo et al., 2011; Mccann, 2005).

Yellow maize is in increasing demand for animal feed because it gives a deep yellow colouration to egg yolks, poultry skin and animal fat, which consumers attribute to healthiness and freshness (Anthony, 2014; Iken and Amusa, 2004). Human consumption of yellow maize in Africa may continuously decline as animal feed use rises. For instance, in South Africa, the commercial yellow maize area (mostly for feed) is expected to increase by 1.4% per annum while the white maize area decreases by 1.5% per annum (Bfap, 2016; Rosegrant et al., 2001). In a survey conducted by Pillay et al. (2011), some respondents indicated that they only see yellow maize in shops that sell animal feed, not human food; for that reason, it is only for animals. This issue is outside the scope of the current study, which focuses on maize for human food from a food technological and consumer point of view. Information about trends in maize for animal feed in Africa can be found in (Rosegrant et al., 2001; Smale et al., 2013)

The predominance of white maize for food production may be traced to many cultural valuations or social status (prestige) considerations: "white is superior" or "the whiter the better": the influence of indigenous competitive staple crops; government policies; organoleptic differences; a desire for the brightly coloured finished products; and familiarity (i.e. people are used to eating white maize) (Khumalo et al., 2011; Mccann, 2005; Muzhingi et al., 2008b; Pillay et al., 2011; Ranum et al., 2014; White and Johnson, 2003). The association of yellow maize with food aid that was poorly handled or stored during transport and importation, resulting in an unacceptable taste, has been reported to have negatively influenced its acceptance as food (Pillay et al., 2011). The choice of colour could be customarily driven by indigenous competitive or substitute staple crops. For instance, in the eastern region of Nigeria where *gari* (fermented cassava flakes) is commonly prepared with palm oil, which appears yellowish, people prefer yellow maize, e.g. for making *akamu* porridge. In the western part of the country, where finished products made from cassava are white, people prefers white maize, e.g. for making *ogi* porridge.

In Eastern Africa, yellow maize is rarely found in Kenyan markets; only 26% of people would consider buying yellow maize at the same price as white maize (De Groote and Kimenju, 2012). Consumers need an average price discount of 37% in Kenya, 30 − 40% in Mozambique and 10% in Zimbabwe to accept yellow maize instead of white (De Groote and Kimenju, 2012). The perception differs among age groups; preschool children in rural South Africa showed a preference for yellow maize-based over white maize-based food products, while older groups preferred the white maize-based foods (Pillay et al., 2011). The rejection of yellow maize has been attributed to a dislike for the colour and

Table 1
Examples of maize-based foods in Africa.

Food category	Major processing steps	Examples
Whole-grain foods	Cooking, steaming, roasting	Adalu, egbo (Nigeria); githeri, muthokoi (Kenya); aboda (Benin); ayibli, nkyekyerewa, adibabli (Ghana); kandy, makande (Tanzania); mangai, mutakura (Zimbabwe); lusontfwana, tinhlumaya- nemphuphu (Swaziland); setampo (Lesotho); umngqusho, samp (South Africa); corn tchap (Cameroon); roasted & boiled maize (across Africa)
Wet-ground maize foods	Wet grinding, steaming	Amiwo, abla (Benin); sapala, abari (Nigeria); akakla, ofam (Ghana); koga (Cameroon); mohlefe (Lesotho); shamsi, fallahi (Egypt); Maputi (Zimbabwe)
Bread and snacks	Fermentation, baking, frying and roasted	Masa, donkwa (Nigeria); kpome-klekle, tale tale (Benin); dzowee, mamu kaklo (Ghana); injera, dabo (Ethiopia); muufo (Somalia); Monepola oa Poone feela (Lesotho); chigumu (Malawi); Chimodho (Zimbabwe); Popcorn (all over Africa)
Sourdough and dumplings	Soaking, fermentation, steaming and cooking	Ogi, donkunu (Nigeria); amo, kenkey (Ghana); poto-poto, mawe, akassa (Benin); mutwiwa (Zimbabwe); doklu (Côte d'Ivoire); leqebekoane (Lesotho)
Porridges	**Unfermented:** Milling, cooking	Mgaiwa phala (Malawi), tombrown, tuo zaafi (Ghana); phutu (South Africa); ugali (Kenya); sadza (Zimbabwe); tô (Mali); nsima (Zambia); Asida (Sudan); tuwo (Nigeria); papa (Lesotho); owo, yeke yeke (Benin); soor (Somalia)
	Fermented: Soaking, Fermentation, cooking	Mutwiwa pap, sour sadza (Zimbabwe); afiata, koko, ice kenkey (Ghana); uji, ikii (Kenya); aklui (Benin); ting (Botswana)
Beverages	**Non-alcoholic:** Milling, soaking, Cooking	Akpan (Benin); mahewu (South Africa); munkoyo (Zambia, Zaire); kunnu zaki (Nigeria); kirario (Kenya); borde (Ethiopia); togwa (Tanzania)
	Alcoholic: Germination, Fermentation	Obiolo, pito (Nigeria); busaa, chang'aa (Kenya); pombe, chibuku (Zambia); talla, cheka (Ethiopia); malawa, kidongo (Uganda); doro, chikokivana, kachasu (Zimbabwe); kaffir beer, umqombothi (South Africa).

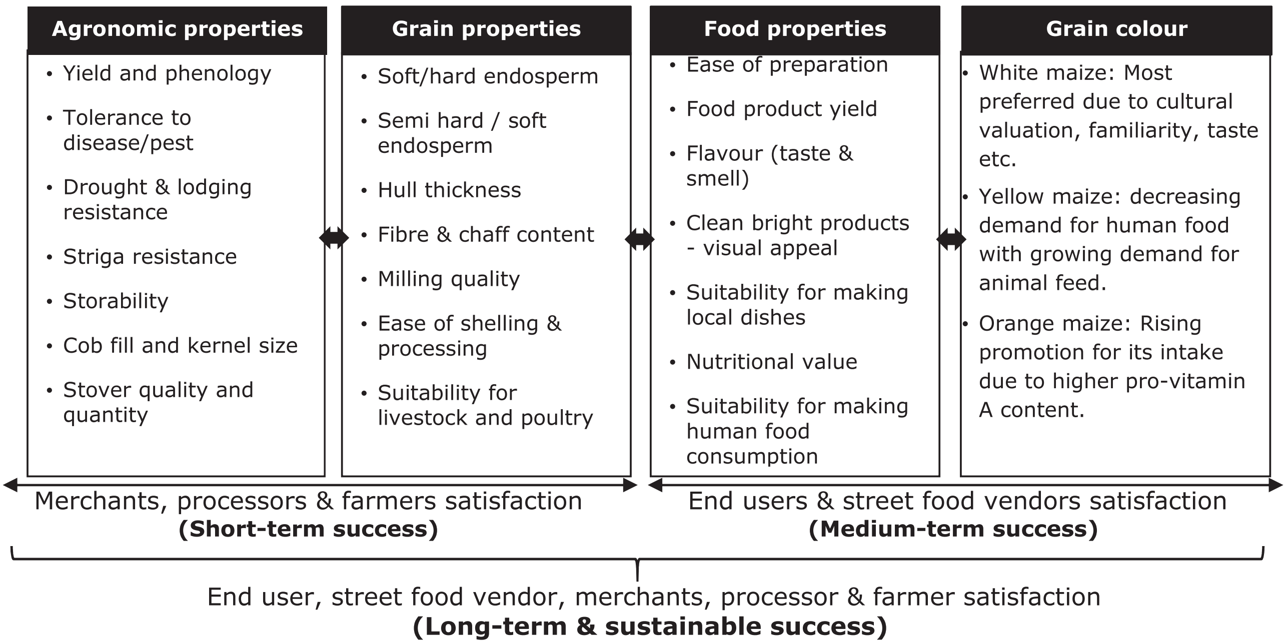

Fig. 1. Factors driving the success of maize breeding program in Africa. The medium-term drivers of maize acceptance for food in Africa are associated with the interest of end users and street food vendors. Success in agronomic properties (farmers satisfaction) which fail to satisfy postharvest qualities, normally result in short-term success, if any. In Africa, end users and food vendors' interest starts with grain colour in which white maize is preferred. This is followed by food properties such as suitability of maize for making traditional dishes and sensory attributes, and the processors are keen about the type of grain texture depending on the available technology. Only a holistic breeding approach which ensures agronomically sound maize varieties matches consumer preferences can lead to a successful maize breeding programme.

to organoleptic or sensory properties, e.g. some respondents have shown a dislike for the smell and taste of yellow maize-based foods (De Groote and Kimenju, 2012; Khumalo et al., 2011; Pillay et al., 2011; Stevens and Winter-Nelson, 2008). However, when nutritional information was provided, while promoting orange provitamin A biofortified maize in Zambia, the consumers preferred and were willing to pay a premium for orange maize varieties (Meenakshi et al., 2012). The differences in maize flavour (aroma and taste) are often elucidated by affective consumer sensory studies, which usually conclude that there are no significant differences. However, farmers in Malawi, Zambia and Zimbabwe have been reported to prefer growing local landraces due to their taste, even when hybrid maize has better yield (Lunduka et al., 2012; Sibiya et al., 2013). Likewise, Hebinck et al. (2015) found that farmers in Luoland (Kenya), preferred the taste of local maize to the taste of available hybrids. Determination of the relationship between the available sensory data and instrumental measurements of the volatile profiles would help to understand the differences in flavour between and among hybrids, open-pollinated varieties (OPVs), local landraces, nutrient-dense varieties and the different colour types. The profile of volatile organic compounds (VOC) in maize varieties can be characterized using Proton Transfer Reaction -Time of Flight - Mass Spectrometry (PTR-ToF-MS), a direct and non-invasive technique for performing high-resolution measurements (Yener et al., 2016). Though the equipment has high sensitivity, resolution and speed, it is costly for national breeding programmes and requires trained personnel. As experienced in the development of biofortified crops, one of the challenges faced by breeders is the availability of high-throughput, reliable and cost-efficient analytical methodologies that can be applied to enable rapid and accurate analysis of traits with high heritability (Guild et al., 2017).

Both dent and flint white maize grains are used for making food products in Africa. The difference between these two types is in the distribution of areas in the endosperm with different starch granules density. In the hard, corneous endosperm starch granules are tightly packed while in the soft, floury endosperm, granules are less dense. Thus in flint kernels, the hard endosperm comprises most of the grain and forms a cap over the germ, while in dent maize, the hard endosperm is on the sides of the kernel, partially surrounding the germ (Serna-Saldivar, 2016). Flint maize is commonly used as "green maize" (roasted or boiled) and, as opposed to most other maize food types, green maize consumption is without colour partiality by users (Iken and Amusa, 2004). In Western Africa, consumers have a preference for soft endosperm varieties because they are easier to steep and mill, and yield finer products (Omueti et al., 2006). This is reasonable because maize foods from the region are largely prepared with whole maize as starting material rather than with maize flour. In a morphological characterization of maize varieties in Nigeria, Anthony (2014) found 48% dent, 14% floury, 14% flint, 13% waxy and 6% sweet maize. In Eastern and Southern Africa, 57% and 85% of maize varieties released (1966 − 98) by public and private breeding programmes, respectively, were dent varieties (Hassan et al., 2001). However, the substantial reliance of these regions on refined maize flour (e.g. for preparing 'ufa woyera', a local refined flour used to make nsima), drives the popularity of flintier maize varieties since the germ and bran can be easily separated by tampering with water (Badu-Apraku et al., 2012; Pircher et al., 2013). For instance, the hard endosperm account for 89% and 79% of maize grains found in Malawi and Tanzania, respectively, due to its suitability for making the preferred food types (Hassan et al., 2001). Despite the consumer preference for flint maize in Malawi, most maize breeding and commercialization have been focused on semi-flint and dent varieties (Pircher et al., 2013). The relatively low post-harvest losses of flint compared to dent varieties during traditional storage are the reason for their preference in parts of Africa. The most widely adopted modern maize variety (H614 - hybrid) in Kenya is semi flint, and about 25% of the modern varieties in Zambia and Zimbabwe also have an intermediate grain texture (Walker et al., 2014). Grain texture and pasting properties (starch content, composition and distribution) are crucial for food preparation. One of the main reasons that farmers in Luoland (Kenya) distance themselves from hybrid maize is that the women, who are generally the cooks at home, believe that it takes twice as much hybrid maize as compared to the local maize to make porridge, i.e. it gives a much 'lighter' ugali (Hebinck et al., 2015; Pircher et al., 2013). In general, as local communities transit from basic processing methods (e.g. pounding with stone or mortar) to mechanised methods (e.g. hammer mills and roller mills) and degerminated maize, their maize kernel characteristics like hardness, proportion of kernel structures (germ, endosperm, pericarp) and kernel size may also change.

As shown in Fig. 1, the selection of maize varieties for food in Africa usually starts with grain colour. This is followed by grain texture and food properties, which are the core determinants of the processing and preparation attributes, storability, appearance, palatability, and product yield. These qualities are considered prior to agronomic characteristics during the long-term adoption of new varieties in local communities in Africa (Badu-Apraku et al., 2012; Lunduka et al., 2012; Omueti et al., 2006). An excellent agronomic performance does not guarantee adoption for consumption (Hebinck et al., 2015). Participatory varietal selection and plant breeding play a significant role in the adoption of improved varieties. Farmers and end users tend to adopt varieties they handpicked based on their own set of criteria and preferences. (Tadesse et al., 2014). Modern maize varieties have an adoption rate of about 50% in Sub-Saharan Africa, i.e. 44% and 66% in Eastern/Southern Africa and Western/Central Africa, respectively (Walker et al., 2014). Greater alignment with the product quality demands of various actors, i.e., processors (who are informed by food technologists, among others) and consumers, in the maize value chain can enhance the adoption and value of new maize varieties.

1.3. Maize breeding for end-user's preferences and nutritional enhancement

Identification of maize quality attributes that are important to processors and consumers is crucial for breeders to select the most suitable germplasm from a demand perspective while ensuring grain yield and tolerance to biotic and abiotic stresses. Though closing the gap between actual and potential maize yields, and the improvement of some nutritional components have been the major focus of breeding programmes in Africa, attributes such as sensory preferences, ease of processing, end-product quality, and storability are important for end users when adoptiing new and/or improved maize varieties (Badu-Apraku et al., 2012; Omueti et al., 2006; Pircher, 2010). Incorporating end users' preferences in breeding programmes enables consumers to get their favourite maize foods without having to change their valued traditional ways of food processing, preparation and consumption. It also allows processors to enhance their efficiency and reduce grain losses (Anthony, 2014). Fig. 2 shows breeding objectives that are important from the end usee and nutritional quality point of view in Africa and how the components of the maize value chain are integrated to achieve food security and nutrition. The identified breeding objectives for processing and nutritional enhancement are discussed in the following paragraphs.

1.3.1. Breeding to enhance nutrient density

Vitamin A deficiency remains a major problem in SSA (Simpungwe et al., 2017). Development of biofortified crops could contribute to solving the problem. This has been achieved by conventional, and about 40 provitamin A biofortified maize varieties have been released in 8 African countries since 2012, including varieties such as HPH1317 and MH42A that contain the nutritional target of 15 ppm (Andersson et al., 2017). Due to the chemical nature of carotenoids, any provitamin A enriched maize kernels will be orange. Acceptability studies have shown that consumers do not object to the colour and they like the flavour of provitamin A enriched maize (Muzhingi et al., 2008b) It is not clear if the flavour difference when compared to white maize is due to preconceived notions or to the inherent organoleptic properties of the maize (Muzhingi et al., 2008b). As mentioned earlier, an extensive blind test of consumer preferences across SSA combined with laboratory analyses of volatile profiles could give a more objective result. Oxidation of lipids in maize, including provitamin A biofortified maize, occurs during storage in tropical conditions and during processing (e.g. cooking, frying and baking), affecting the colour of maize products, causing the formation of off-flavours, and reducing the antioxidant status and nutritional value (Gayen et al., 2015; White and Johnson, 2003). This oxidative tendency can be limited by breeding varieties with an increased level of antioxidants. The variability in kernel tocopherols and carotenoids creates an opportunity to improve both at the same time without affecting the synthesis of the other. Muzhingi et al. (2017) observed that an increased level of β-carotene and β-cryptoxanthin had no negative effect on the level and the antioxidant capacity of both tocopherols and tocotrienols in maize. Lipoxygenase (LOX)-facilitated deteriorations (e.g. oxidation, rancidity and off-flavours) have been a problem in yellow maize. Gayen et al. (2015) stabilised the carotenoid content of β-carotene-enriched golden rice by reductiing LOX activity using RNAi-mediated silencing. As the method has no negative effect on agronomic traits, it can be used to preserve the provitamin A content and flavour of maize during storage.

The prevalence of inadequate intake of zinc in Africa was estimated to be 37 − 62% (Caulfield and Black, 2004), contributing significantly to poor child growth and immune system weakness (Chaudhary et al., 2014; Chomba et al., 2015). Introducing maize biofortified zinc (zinc concentration above 37 ppm) would make a significant contribution. A study of human zinc absorption from biofortified zinc maize in Zambia confirmed that eating biofortified maize can meet zinc requirements (Chomba et al., 2015). Although kernel zinc content is strongly affected by genetic and environmental effects, the relatively high genetic diversity for zinc in maize (mean 20 $\pm$ 5, range 15 – 47 µg/g) (Hindu et al., 2018), indicates that further improvements of zinc concentration are achievable (Bänziger and Long, 2000; Ortiz-Monasterio et al., 2007). Similarly, anaemia prevalence rates of 55%, 71% and 46% were reported in Eastern, Central/Western and Southern Africa, respectively, among children aged under 5 years of age (Stevens et al., 2013), with more than half of the cases due to iron deficiency. Anaemia results in poor mental and physical capacities and decreases the immunological capacity to fight prevailing diseases. Unfortunately, the known genetic diversity of iron content in maize is small (mean 25, range 11 – 39 µg/g) and largely due to a location effect (Bänziger and Long, 2000; Ortiz-Monasterio et al., 2007). A further hurdle is that the bioavailability of iron in maize is very low, largely offsetting any gains that might be made through breeding for increased iron concentrations (Pixley et al., 2011). Therefore, breeding to biofortify maize by increasing iron concentration in grain does not seem promising. A more fruitful strategy might be to select varieties with improved iron bioavailability, given that only about 5% of iron in maize is bioavailable (Pixley et al., 2011). However, currently existing screening methodologies for iron bioavailability are not sufficiently time and cost-effective to support a breeding program. Transgenic approaches offer a possible solution for improving the iron content of maize as long as they do not result in negative sensory changes and if accepted by the public. Up to 70% increase in iron content was reported for a transgenic maize bred with a soybean ferritin gene (Drakakaki et al., 2005). New tools like gene editing could open opportunities to develop maize with enhanced iron bioavailability, for example, by modestly reducing the amount of phytate in the grain.(Table 2)

The protein efficiency ratios of quality protein maize (QPM) are more than 50% higher than for conventional maize and almost comparable to protein in milk (Prasanna et al., 2001). In addition, studies have shown a faster starch digestibility in QPM than in conventional maize, which enhances energy use (Hasjim et al., 2009). About 90 QPM varieties have been released in Africa, which represent 53% of total worldwide releases (Twumasi-Afriye et al., 2016). Presently, there are QPM varieties that are as productive as non-QPM varieties, with some having superior yields, e.g. Obatanpa QPM (Twumasi-Afriye et al., 2016). Considering the limited access of many Africans to assorted protein sources, continuous development of QPM to improve its

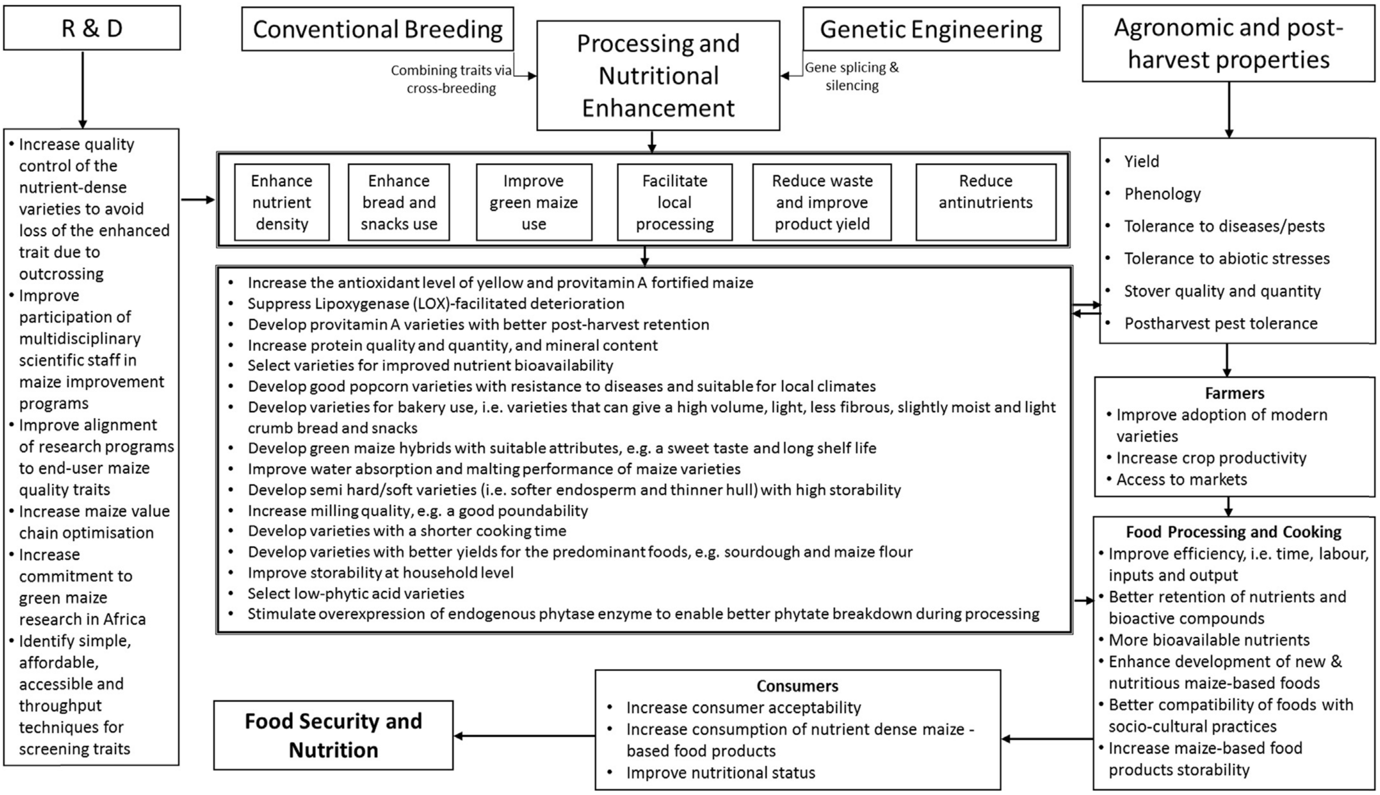

Fig. 2. An analytical framework highlighting maize breeding objectives and the interrelationship with relevant segments of the value chain.

nutritional value, organoleptic quality, yield, disease resistance and tolerance to abiotic stresses is crucial. This development must be accompanied by affordable, fast and high-throughput seed and grain quality control methods to monitor the levels of lysine and tryptophan since outcrossing due to pollination with non-QPM varieties is possible. In addition, prioritizing selection to maintain maize protein content concentrations in maize within the current range of 8–14% is important because increased grain yield is generally associated with increased starch and reduced total protein concentration in the grain, (Table 3).

In general, the continuous introduction of nutrient-dense crops with high post-harvest retention and bioavailability in combination with other approaches like diet diversification and nutritional education can contribute to alleviating qualitative malnutrition. Breeding programmes should continuously encourage the release of nutrient-dense maize varieties that are acceptable to maize processors and consumers.

1.3.2. Breeding to enhance the suitability of maize for making bread and snacks

The use of maize in the production of bread and snacks is limited mainly by the absence of functional gluten, high lipid content that leads to low product storability, and limited use of alternative processing techniques such as nixtamalization. Cooking maize in an alkaline solution, or nixtamalization is used for making more than 300 products in Mexico alone. Wheat is used extensively for making bread and snacks, but because the prevailing agro-ecologies in SSA are unsuitable for wheat production, most wheat is imported. This makes bread unaffordable for many Africans. Breeding of maize varieties useful for making bread and other bakery products is therefore relevant i.e., varieties that give floury, less fibrous, slightly moist and light crumb products). An increase in native lipid complexes with a matrix of starch granules has been shown to slow the staling of bread by decreasing starch retrogradation and gluiness while increasing freeze-thaw stability (Thakur et al., 2017). Rapid viscosity analysis could help monitor the starch properties, and these anti-staling attributes could be achieved by selecting maize varieties with high polarity lipids in the starch granules. Differential scanning calorimetry (DSC), X-ray diffraction and iodine-binding capacity are important techniques commonly used for monitoring starch-lipid interactions (Thakur et al., 2017). Development

Table 2
Biofortified provitamin A maize varieties released under HarvestPlus by IITA and CIMMYT.

Country	Varieties	Provitamin A content (ppm)	Minimal increase required to meet the target 15 ppm (%)
DR Congo	Sam Vita 4-A, Sam Vita 4-B, Muibaki 3, Muibaki 2, Muibaki 1, GV662	5 – 10	33
Ghana	Ahoɔdzin, Dzifoo, Ahoɔfɛ, CSIR-CRI Honampa, CSIR-CRI Odomfo, CSIR-CRI Owanwa	6 – 11	27
Malawi	MH39A, MH40A, MH42A, MH43A	9 – 15	0
Mali	Nafama, Abebe, Duba, Kodialan, Dakan	7 – 10	53
Nigeria	Ife Hyb 3, Ife Hyb 4, Sammaz 38, Sammaz 39, Sammaz 43, Sammaz 44,	7 – 8	47
Tanzania	HPH1317, HP1005	8 – 15	0
Zambia	GV671A (HPH1301), GV673A (HPH1303), GV665A (HP1005), GV662A (HP1002), GV664A (HP1004)	5 – 11	27
Zimbabwe	ZS242 (HP1005), ZS244 (HPH1301), ZS246 (HPH1302), ZS248 (HPH1303)	7 – 11	27

Adapted from Andersson et al. (2017).

Table 3
Genetic, environmental and post-harvest handling effects on main nutrient and nutraceutical compounds in maize kernels.

Compound	Genetic effect (Diversity reported)	Environmental effect	Post-harvest handling effect	References
Protein	8 − 14%	Decrease at lower nitrogen levels. Higher plant density leads to decrease grain protein concentration	Digestibility of protein decrease during 6 months storage at high temperature	(White and Johnson, 2003; Rehman, 2006)
Starch	65 − 75%	Increase at lower nitrogen levels.	Starch and amylose content are negatively influenced by high temperatures	(White and Johnson, 2003)
Fat	2 − 4.5%	Pollen effect on oil concentration	Increase acidity and high peroxide index by increase of free fatty acids during storage at high temperature	(White and Johnson, 2003; Rehman, 2006)
Carotenoids	Total carotenoids: 0.15 − 8 9 μg/g DW ProVA: 0.5 − 22 μg/g DW	None reported	ProVA carotenoid decay during storage at high temperature. Milling leads to higher proVA decay.	(Ortiz-Monasterio et al., 2007; Pixley et al., 2011)
Tocopherols	α-tocoferol: 0.4 − 75 μg/g DW γ-tocoferol: 3.3–141 μg/g DW	High heritability and no genotype by environment effect	None reported	(Muzhingi et al., 2017)
Anthocyanins	2.5 − 1989 μg/g DW Pel	High heritability and no genotype by environment effect	None reported	(Hernández-Quintero et al., 2017; Paulsmeyer et al., 2017)
Phenolic compounds	Ferulic acid: 0.2 − 6.9 μg/g DW *p*-Coumaric acid: 0 − 6.07 μg/g DW	None reported	None reported	(Muzhingi et al., 2017; Cuevas Montilla et al., 2011)
Resistant starch	9.4%	None reported	None reported	(Vázquez-Carrillo et al., 2016; Pollak et al., 2011)
Iron	11 − 39 ppm	Large environmental effect (soil and foliar fertilization;)	Contamination from soil, threshing and storing conditions	(Bänziger and Long, 2000; Ortiz-Monasterio et al., 2007)
Zinc	15 − 47 ppm	Large environmental effect (soil and foliar fertilization; high nitrogen reduces Zn content in kernels)	Contamination from soil, threshing and storing conditions	(Bänziger and Long, 2000; Ortiz-Monasterio et al., 2007)

of varieties with *wxsu2* (waxy and sugary-2 mutant alleles) may be another useful strategy, given that bread made with flour from maize varieties containing this double mutant gene combination has softer, moister crumbs after baking and maintains freshness during storage (Zallie et al. (1986). A combination of molecular (molecular markers for the alleles) and analytical methods will be required. Varieties with soft endosperm, smaller starch granules and thinner pericarp are more suitable for snacks and bread-like products (Narváez-González et al., 2006). However, soft endosperm kernels are more prone to post-harvest losses due to insect damage; thus appropriate storage conditions need to be in place.

Popcorn is an important snack, liked and consumed across Africa with no discrimination between white and yellow coloured kernels (Iken and Amusa, 2004). This presents an opportunity in the maize value chain to breed popcorn varieties. Though no separate data on popcorn production in Africa are available, consumption relies on imports, especially from the USA. The cultivation of popcorn varieties has been very limited in Africa due to foliar diseases like rust, blight and streak (Iken and Amusa, 2004), and the lack of varieties suited to tropical conditions (Jele et al., 2014). The most important quality attributes of popcorn are large expansion or popping volume (to obtain a fluffy and tender texture), minimal hull and flavour (Jele et al., 2014). Anthony (2014) and Iken and Amusa (2004) identified popcorn varieties with a taste profile comparable to that of imported varieties, but susceptible to diseases and with lesser popping volume. Popping volume is affected by non-genetic factors, such as moisture content (optimum: 13.5–14.5%) and added ingredients, and by genetic factors including kernel pericarp thickness, shape, size and density (White and Johnson, 2003). Currently, there are high-throughput methodologies based on scanning that could eventually be adapted to support breeding efforts. As a result of the quest to stimulate local production, government policies on food importation in Africa have progressively toughened, thereby strengthening the need for breeding efforts to develop local popcorn varieties (Iken and Amusa, 2010; Jele et al., 2014).

1.3.3. Breeding to improve maize for use as green maize

In SSA, the first crop to reach the marketplace after the dry season is usually green maize, thus helping to break the hunger gap. Green maize has greater local economic value and increases food security (Qwabe, 2011). Green maize is consumed as whole kernels, thus giving more nutritional benefits than most maize-based products, which are prepared using flour from degerminated and decorticated kernels. However, to our knowledge, there are currently no specific research or breeding efforts to improve green maize in Africa. Limited green maize genetic materials are available, but most varieties are intended for grain production and do not meet all the attributes desired by green maize end users. A sweet taste (high sugar content), soft endosperm, large ears/cob, a long shelf life and good roasting qualities (non-popping) are the most desirable attributes for green maize (Alamu et al., 2015; Badu-Apraku et al., 2012; De Groote and Kimenju, 2012; Iken and Amusa, 2004; Qwabe, 2011). Roasted or boiled green maize is often yellow grained; consumers have no grain colour bias for green maize consumption. Qwabe (2011) identified maize hybrids (e.g. GMH129, GMH126, GMH146 and GMH171) with potential for green maize in Africa, while a variety like WH301 in Kenya has been acknowledged to be particularly suitable for green maize production (Walker et al., 2014). In spite of the increasing demand for green maize foods, their consumption is limited to the rainy season because maize farming in SSA is mainly rain fed. If suitable green maize varieties are made available, sustainable agricultural intensification via irrigation could make green maize available all year round, thus alleviating the normal long period of hunger during the dry season. Another advantage of green maize research in Africa could be the opportunity to incorporate dual purpose traits i.e., to generate a variety that can produce green maize for food and good quality stover for animal feed (Erenstein et al., 2013). Maize stover quality and quantity are attributes considered important by farmers (De Groote et al., 2013). Maize stover is very palatable and a good source of nutrients with high digestibility; it is one of the best non-legume fodders (Chaudhary et al., 2014). Since 2010, more than 12 maize varieties that maintain green leaves and stems after maturity or after the cobs are harvest have been released in Kenya for use as cattle fodder (Walker et al., 2014). Research in Ethiopia has also led to the identification of suitable for dual-purpose germplasm. Near-infrared methodologies are used to monitor stover quality parameters and promising genomic regions associated with stover quality have been identified recently (Erenstein et al., 2013). Current research efforts to develop molecular markers for this aspect, if successful, will be very beneficial for a more efficient breeding program. The acceptance of green maize across Africa is good motivation to give attention to developing varieties that meet the desires of both growers and end users.

1.3.4. Breeding to improve characteristics that enhance the efficiency of local processing

Soaking is the first critical step in traditional maize processing in many parts of West Africa (Nago et al., 1998); it softens the kernel for easy separation of the hull and milling. Steeping also reduces phytic acid (a significant anti-nutrient in maize) by solubilising it before draining it out. Horny/hard endosperm takes a longer time to steep due to slow water absorption, which means that soft and intermediate kernel texture is most suitable (Kikuchi et al., 1982). Grain water absorption is also affected by the thickness of the pericarp, kernel size and protein content and distribution (Oladeji et al., 2016). Soft endosperm has high viscosity and swelling value, and better gelatinization and digestibility, making it suitable for traditional sourdough (Kikuchi et al., 1982). Good water absorption correlates with good cooking quality (i.e., cooking takes less time and less energy) and better organoleptic properties (Oladeji et al., 2016). Furthermore, soft maize is preferred for traditional dry milling and wet milling due to ease of processing (Omueti et al., 2006). Local maize varieties (usually soft endosperm varieties like Gnonli, Gbogboue, Gbaeve, Gougba and Djakpe from Benin) give finer flour and less damage to starch content than improved varieties (Nago et al., 1997); this may partly explain the small adoption rates of improved varieties. However, for traditional food processing that requires home-based pounding or refining processes such as de-hulling and de-germination (common in southern/eastern Africa), usually hard grain is preferred for easy separation (Badu-Apraku et al., 2012). Many traditional maize-based foods in Africa are made using de-hulling and sieving processes. Despite the extensive nutrient loss during these processes, the aim is to achieve a smoother texture, shorter cooking time, bland taste and white colour. Such processing steps could be minimised by using varieties with a consistent clean colour, thin or soft hulls, less fibre/chaff and soft/floury endosperm. The aroma, colour, feel, consistency and taste of a finely textured maize meal are usually acceptable in local communities (Khumalo et al., 2011). In the preparation of ogi (porridge), the variety affects the ease of cooking (Adeyemi et al., 1987). Appropriate metrics to fulfil the specific quality are needed. However, colorimeter and kernel scanning methodologies are often robust enough to support breeding programmes.

1.3.5. Breeding to reduce waste by maximizing useful product yield and minimizing nutrient losses

Ogi (porridge) has been identified as the most consumed maize food in Western Africa (Olayiwola et al., 2016). Breeding programmes in the region must prioritise the suitability of maize for *ogi* production. *Ogi* yield is usually between 40% and 86% of the starting material (maize) (Adeyemi et al., 1987; Nago et al., 1998; Omueti et al., 2006), implying high wastage due to maize characteristics (hull, fibre and the nature of starch). The highest yield reported in the literature is 86% from Gnonli and Gbogboué local maize varieties in Benin. The authors attributed the high yield to a better softening (water absorption) nature of the varieties (Nago et al., 1998). Indeed, the floury endosperm is most suitable for wet milling and results in a higher *ogi* yield (Omueti et al., 2006). Though kernel weight was found not to influence *ogi* yield, varietal differences significantly influenced *ogi* yield (Adeyemi et al., 1987). Since *ogi* preparation is similar to how most maize foods are prepared in Western Africa, the development or selection of varieties with high yield of the fermented and unfermented dough is crucial. In contrast, Eastern/Southern African foods rely mostly on refined maize flour, so in those regions, breeding for varieties with high flour yield during dry milling is important.

1.3.6. Breeding to reduce anti-nutrient concentrations in grain

It was estimated that 68% of total dietary phytate intake in Africa comes from cereals (Joy et al., 2014), and about 37% from maize. The high phytate intake in cereal-dependent populations contributes significantly to deficiencies of minerals, i.e., iron and zinc. According to Joy et al. (2014), it is possible to achieve sufficient zinc bioavailability in 46 African countries if phytate intake is reduced at least to half of the current intake. Phytate reduction during traditional maize processing is not sufficient to achieve maximum micronutrient bioavailability. The occurrence of adverse agronomic performance such as poor germination, susceptibility to diseases, reduced grain weight and low abiotic stress tolerance in low phytic acid mutant crops has frustrated breeding programmes aimed at improving nutrient bioavailability. However, maize mutants (*Ipa1, Ipa2* and *Ipa3*) with low phytic acid and high phosphate contents have been reported to have normal seed germination and unaffected dry matter content, which has substantially improved iron and zinc bioavailability in maize-based diets (Shi et al., 2007). A transgenic approach to reduce the expression of the gene encoding for the biosynthesis of inositol-pentakisphosphate 2-kinase (Shi et al., 2003) and silencing the expression of the multidrug resistance-associated protein ATP-binding cassette (MRP-ABC) transporter (Shi et al., 2007) are reported to be options for reducing phytate without diminishing agronomic performance. The overexpression of the phytase enzyme in maize is an alternative that is perhaps a more feasible breeding approach since it prevents possible problems associated with reduced seed phytate. Drakakaki et al. (2005) and Chen et al. (2008) found an increase of up to 50% in phytase activity in maize through the transgenic expression of *Aspergillus phyA* (encoding phytase), thereby doubling the chance of phytate reduction during processing, preparation and consumption. In the same research, Drakakaki et al. (2005) observed a 95% phytate reduction when transgenic maize flour was mixed with water and fermented, implying that it may be possible to achieve maximum phytate reduction and micronutrient bioavailability through the use of low phytate and/or increased phytase enzyme varieties for making some traditional foods in Africa. However, in most African countries there are severe regulatory constraints and very long delays in getting transgenic varieties into production are highly probable. Gene editing may offer a viable approach by reducing phytate production sufficiently to meaningfully increase iron and zinc bioavailability but not enough to cause negative agronomic effects.

2. Conclusion

The current rapid population growth rate in Sub-Saharan Africa, coupled with persistently high malnutrition rates, calls for strategies that stretch across the entire food value chain – a *Crop-to-Health Strategy,* i.e. from agriculture to nutrition and health. Strategies that enhance nutrition-focused food uses of maize can contribute to providing daily dietary requirements of micronutrients as well as macronutrients. Combining improved grain yield (tolerance to abiotic and biotic challenges) with user preferences and nutritional benefits is essential to meet the growing demand for maize that is suitable for processing into traditional and novel food types. An adequate understanding of needs of the producers, processors and consumers, and incorporating these into breeding programmes will increase the adoption of new varieties, reduce losses, improve nutrition and preserve the socio-cultural and culinary traditions of local communities. Breeding new varieties takes many years, especially if it concerns traits that are not yet commonly available in elite lines with adequate agroecological adaptation. Timely incorporation of probable future preferences of maize consumers and processors is therefore especially relevant.

Although we have focused on opportunities to enhance breeding strategies to achieve greater grain processing and nutritional qualities, it must be emphasised that these are not isolated or “magic bullet” solutions. Sustainable and profitable diversified crop production strategies, together with post-harvest management strategies that reduce food waste and loss of nutritional goodness, will contribute to improve the nutrition, health and lives of African and global consumers.

3. Recommendations

To achieve higher impact of maize breeding for Africa, we recommend the following:

1. Clearly define maize quality parameters, norms and screening analytical methods from the viewpoints of all actors in the maize value chains, i.e., processors and users as well as to primary producers.
2. High-throughput methods for efficient measurement must be available to support breeding efforts.
3. Ensure that agronomically excellent varieties also fulfil the preferences and needs of processors and consumers.
4. Incorporate the essential quality traits of all value chain actors from the start of any breeding programme. This will require that effective, high-throughput and low cost screening methods are available for each trait.
5. Ensure close interdisciplinary work by including pertinent specialists in the breeding team: socio-economists, food technologists, nutritionists, quality specialists and agronomists. Others may be required depending on the product profile of the varieties that must be developed.
6. Link with processors demanding naturally nutrient enriched food in order to prioritise the nutritional traits
7. Strengthen efforts to introduce nutrient dense crops with superior post-harvest performance and enhanced nutrient bioavailability.

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Declarations of interest

None.

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