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THE ROLE OF SCIENCE, TECHNOLOGY, AND INNOVATION FOR TRANSFORMING FOOD SYSTEMS IN AFRICA

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ABSTRACT

As recognised by the Science, Technology and Innovation Strategy for Africa – 2024 (STISA-2024), science, technology and innovation (STI) offer many opportunities for addressing the main constraints to embracing transformation in Africa. Preparation for the Summit provides an important moment for shaping the region's future and ensuring that the much-needed agriculture-led growth and development agenda can simultaneously deliver on improving nutrition and health, saving lives and curbing public health expenditure on nutrition-related diseases. Yet, the Comprehensive Africa Agricultural Development Programme (CAADP) and its associated national plans still need to adopt a food systems lens. As food systems need cross-sectoral coordination beyond what CAADP coordination is needed, institutional innovation is essential for Africa to rise to the vision of the AUC Agenda 2063 and the Food Systems Summit's aspirations. This brief seeks to identify the opportunities for African countries to take proactive steps to harness the potential of agriculture and food systems to ensure future food and nutrition security by applying STI solutions. The potential applications cover essential STI solutions to a) improving production systems and restoring degraded systems (including soil quality); b) innovation in the processing and packaging of foods; c) improving human nutrition, health and productivity; d) addressing fragility and instability and e) greater access to information and transparent monitoring

and accountability systems. Change will need to be supported by institutional coordination; clear, food safety and health-conscious regulatory environments; greater access to information and transparent monitoring and accountability systems. Mechanisation and digitisation will speed up such transformation and enable more inclusive advancement of food systems. ICT solutions and advances could play a significant role in advancing food systems and addressing inequalities in access to inputs, knowledge and markets. Adaptation through sustainable intensification and agricultural diversification may have to be combined with the creation of off-farm opportunities, both locally and through strengthened rural-urban linkages. Financial support (microfinance, credit, subsidies, loans, insurance, etc.) plays an important role in risk reduction for producers.

1. Introduction

The vision of the UN Food Systems Summit is to "launch bold new actions, solutions and strategies to deliver progress on all 17 Sustainable Development Goals (SDGs), each of which relies on healthier, more sustainable and more equitable food systems[1]" (UN, 2020). The Summit seeks to transform the way the world produces, consumes and thinks about food and build a just and resilient world where no one is left behind (UN, 2020, von Braun et al., 2021).

In response to growing interest in the role that agriculture and food systems can play in reducing malnutrition, addressing inequalities and reducing poverty, the Inter-Academy Partnership (IAP) embarked on a project to mobilise global Academy expertise to produce a global synthesis and four regional reports on the role of science, technology and innovation to transform the food and agriculture sector in Africa to be more resilient and sustainable systems and simultaneously improve nutrition and food security.

As recognised by the Science, Technology and Innovation Strategy for Africa – 2024 (STISA-2024) (AU, 2014a), science, technology and innovation (STI) offer many opportunities for addressing the main constraints to embracing transformation in Africa. This brief summarises and updates the IAP report entitled *Opportunities and challenges for research on food and nutrition security and agriculture in Africa* (NASAC, 2018) as a contribution to the Summit. The IAP/NASAC report (NASAC, 2018) updated an earlier perspective set out by the InterAcademy Council's (IAC) 2004 report on *Realizing the Promise and Potential of African Agriculture.* This earlier report set out recommendations and proposed approaches and actions to deploy STI to more effectively improve agricultural productivity and food security in Africa (InterAcademy Council, 2004) as commissioned by the United Nations Secretary-General, the late Kofi Annan.

The 2018 IAP/NASAC report and this brief seek to support the preparation of African governments and stakeholders to simultaneously achieve the vision of the

[1] Food systems encompass all the elements and activities that relate to the production, processing, distribution, preparation and consumption of food, as well as the output of these activities, including socio-economic and environmental outcomes (HLPE, 2020). "Sustainable food systems are: productive and prosperous (to ensure the availability of sufficient food); equitable and inclusive (to ensure access for all people to food and to livelihoods within that system); empowering and respectful (to ensure agency for all people and groups, including those who are most vulnerable and marginalized to make choices and exercise voice in shaping that system); resilient (to ensure stability in the face of shocks and crises); regenerative (to ensure sustainability in all its dimensions); and healthy and nutritious (to ensure nutrient uptake and utilization)" (HLPE, 2020).

Summit along with achieving the 2014 Malabo Declaration on the Comprehensive Africa Agricultural Development Plan (CAADP) (AU, 2014b), Africa's Agenda 2063 (AU, 2009) and their SDG commitments. In July 2020, a Joint Ministerial Declaration and Action Agenda (AU, 2020), called "upon [African] governments and partners to commit adequate resources to build greater productive capacity in agriculture, strengthening resilience in Africa's agri-food systems through the allocation of new resources or repurposing existing public resources".

Preparation for the Summit provides an important moment for shaping the region's future and ensuring that the much-needed agriculture-led growth and development agenda can simultaneously deliver on improving nutrition and health, saving lives and curbing public health expenditure on nutrition-related diseases. This includes addressing the usual elements of undernutrition and widespread micronutrient deficiencies (termed "hidden hunger") and the growing problem of overweight and obesity that is increasing across the African continent. This brief seeks to identify the opportunities for African countries to take proactive steps to harness the potential of agriculture and food systems to ensure future food and nutrition security by applying STI solutions. It should be noted that the biotechnology revolution arose from the convergence of advancements in the biological, physical, engineering, and social sciences. In terms of food systems, what converges is the technical reinforcement of these advancements in terms of product optimization and formulation and the n mutual benefit of different disciplines. Food systems approaches will bring about new innovations from transdisciplinary perspectives to solve unique problems.

2. THE CONTEXT OF AFRICAN FOOD SYSTEMS

Agriculture is at the core of almost all African economies (Baumüller et al., 2021). However, most AU Member States were not on track towards achieving the 2014 Malabo Declaration and CAADP goals and targets by 2025 (AU, 2020). As the Malabo Declaration targets overlap with the Sustainable Development Goals (SDGs), particularly SGD2, Africa is lagging on achieving the goals. The recent COVID-19 pandemic has been a setback in terms of progress towards reducing hunger and malnutrition.

African food systems are diverse and draw on several traditional and modern technologies. Agriculture (including crop production, animal husbandry, fisheries and forestry, and the manufacturing and their processing) can stimulate economic growth and enhance economic transformation in Africa through rising rural incomes, creating jobs, increasing government revenue, and ensure accelerated economic growth and development (Baumüller et al., 2021). Increasing producers' and processors' incomes can positively affect poverty reduction and food security and nutrition (Baumüller et al., 2021). Furthermore, the recently introduced African Continental Free Trade Area (AfCFTA) agreement offers many opportunities for the development of food systems, including diverse livelihoods across the food system and the provision of safe and nutritious food to all on the continent using Africa's own resources and reducing the reliance on imports and development assistance.

Africa will require radical actions to reduce undernutrition, correct micronutrient deficiencies and simultaneously stem the tide of increasing overweight and obesity. Africa had the highest regional undernourishment rate in

2019 (19.1% or more than 250 million undernourished people), more than twice the world average and growing faster than any other region (FAO et al., 2020). The proportion of people undernourished has risen by 1.5% since 2014 and is projected to rise to 25.7% by 2030 (FAO et al., 2020). More than 675 million people in Africa were food insecurity (as measured by the Food Insecurity Experience Scale of FIES) in 2019 (FAO et al., 2020). Recent economic slowdowns and downturns partly explain the increase in hunger in several parts of sub-Saharan Africa (FAO et al., 2020). The COVID-19 pandemic and other emerging diseases have worsened the situation, increasing the poverty of resource-poor food producers, particularly in already fragile regions.

While African agriculture growth has accelerated, growth through innovations (i.e. total factor productivity growth) lags behind other regions of the world (Baumüller et al., 2021). Africa imports large amounts of food - US$ 60 billion per annum (UNCTAD, 2020) - to fill supply gaps. Bouët et al. (2020) report that in net terms, this amounts to about US$ 25 billion per year in cereals, US$ 8 billion in meat and dairy, US$ 4 billion in sugar and US$ 9 billion in the vegetable oil sector. Many African countries' over-reliance on imports to meet the local demand for staple foods renders these economies vulnerable to many risks, insecurities, and uncertainties. While importing staple food is not negative *per se*, disproportional reliance on external sources for food is a risk that threatens long-term resilience.

It is estimated that by 2050 Africa's population will increase 2.5-fold (Suzuki, 2019) and the demand for cereals is likely to triple (van Ittersuma et al., 2016). The region's rapid population growth is attributed to rising life expectancy and declines in death rates, particularly of children (Jayne and Ameyaw, 2016). This will have consequences for agriculture and food systems, including pressure on land, water and other natural resources. Land prices may rise as a result (Jayne and Ameyaw, 2016). The population below the age of 24 years accounts for the largest share of the population in almost all countries in Sub-Saharan Africa (World Bank and IFAD, 2017). The World Bank and IFAD (2017) report that an estimated 440 million young people will enter Africa's rural labour market by 2030. Future demographic trends will influence labour and land productivity and youth needs will need to be factored into future development planning and STI applications (World Bank and IFAD, 2017).

Price and affordability are key barriers to accessing sufficient, safe, nutritious food (Herforth et al., 2020). Food prices and low incomes constrain access to adequate diets for many people in Africa. The FA0 (2020) reported that 829 million of the three billion people in the world who could not afford a healthy diet in 2019 lived in sub-Saharan Africa. Just more than 12 % of people in Africa could not afford a calorie-sufficient diet in 2019. While 56.4% were not able to afford a nutrient-adequate diet and 80.0% could not afford a healthy diet (Herforth et al., 2020). While local prices vary significantly by location and across seasons, the costs of perishable and nutrient-dense foods contribute significantly to the total cost. Yet, these foods are essential to overcome undernutrition and micronutrient deficiencies.

The COVID-19 pandemic (like others in the past) has disrupted food systems and livelihoods in Africa and threaten the significant gains over the past few decades in African development. The pandemic has led to transport restrictions and quarantine measures that restrict farmers' access to input and output markets and services, including human and animal health services (MaMo, 2020). While data suggests that Africa has largely been spared of the pandemic's scourge (Maeda and Nkengasong, 2021), the long-term impacts are yet to unfold.

Food systems transformation is required to ensure adequate incomes for producers and enable access to affordable, healthy diets[2] while managing increasing food demand from growing and rapidly urbanising populations. Yet, CAADP and its associated national plans still need to adopt a food systems lens. As food systems require cross-sectoral coordination beyond what was needed for CAADP, institutional innovation is also needed for Africa to rise to the vision of the AUC Agenda 2063 and the Food Systems Summit's aspirations.

3. TRANSFORMING FOOD SYSTEMS IN AFRICA THROUGH STI

Science has the potential to find sustainable solutions to challenges facing food systems that relate to health, nutrition, agriculture, climate change, ecology and human behaviour (IAP/NASAC, 2018). As many African economies are still largely agriculturally based and many African value chains under-developed, adopting an integrated approach to developing and advancing food systems could provide multiple opportunities for the development of African economies and societies.

With her rich diversity of production systems, significant biodiversity and strong cultural association with traditional diets that are for the most part nutritious and healthy, the development of Africa's food systems have the potential to build healthier, more sustainable and more equitable food systems when supported by advances in technologies and research. Any change in food systems will lead to a multiplicity of changes (either positive or negative) affecting nutrition, health, welfare and the environment. The health implications, welfare outcomes (such as through livelihood outcomes, wages and incomes) and dietary patterns' environmental footprints are strongly dependent on how foods are produced and processed. STI can help support food system development in ways that protect resources, provide livelihoods opportunities and improve incomes across the system and at the same time, deliver more nutritious and healthy diets. The following subsections provide some examples of how STI can support the Summit vision and progress towards the SGDs and Africa's Agenda 2063.

a) Improving production systems and restoring degraded systems (including soil quality)

Improving the efficiency of production systems is necessary given constraints on land and resource availability and the relatively small land plots in most of Africa (Lowder et al., 2016). Improving production efficiency is necessary to meet the growing demand for food (including animal-sourced foods) but is also an environmental imperative. The Food Systems Summit calls for a shift to nature-positive production systems that seek to build food systems that meet the fundamental human right to healthy food while operating within planetary boundaries that limit the natural resources available for sustainable exploitation.

[2] A healthy diet is health-promoting and disease-preventing. It provides adequate nutrients (without excess) and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances (Neufeld et al., 2021).

Modernisation can positively influence the basket of food at the household level (such as foods for local consumption rather than export and foods with a relatively high nutritional value) that households produce or can access economically. Meeting this changing consumer demand will require substantial private investment to increase productivity in agri-food value chains, add value, enhance labour productivity, and create jobs to produce the food demanded by consumers (FAO, 2015a).

Soil fertility. Declining soil fertility is a major constraint to agricultural transformation in Africa (Jayne et al., 2019). Continuous cropping and unsustainable cultivation practices driven by shrinking farm sizes and increasing food demand threaten future food supply in Africa (Jayne et al., 2014), limiting the potential benefit from yield gains offered by plant genetic improvement (Tittonell and Giller, 2013). Appropriate soil improvement practices and informed production choices are essential to prevent further degradation. A holistic and integrated strategy is needed that focuses on raising organic matter and improving moisture retention (Kihara et al., 2016). The soil microbiome affects how plants react to environmental stresses such as high salinity and low water availability and diseases (Nadeem et al., 2014; Spence et al., 2014; Qin et al., 2016). The isolation of microbial strains and modern high-throughput sequencing technologies are being used to catalogue microbial species associated with plants in different soils, including arid and saline soils (Wild, 2016). The development of next-generation crop varieties should simultaneously select beneficial characteristics in the plant and the microbiome to improve soil fertility and crop yields (Gopal and Gupta, 2016). Research is also needed to develop protective seed coatings to protect plants from soil-borne pests and pathogens while also providing micro bio-fertilisers (Rocha et al., 2019).

Water. Water is needed for food production, food processing and industrialisation as well as safe drinking water, sanitation and hygiene. The demand for these resources competes for the available water that can be eased through use of appropriate technology and policy. Urbanisation will place increased pressure on the water demand and compete with water for the production of food. Urbanisation and industrialisation also pose threats to water quality.

Many energy-generation systems also depend on water sources for hydroelectric power, cooling power plants and hydraulic fracturing. Many countries with large-scale irrigation programmes source water from aquifers, threatening long-term sustainability, possibly leading to conflict over water in the future. Competition for water needs to be eased using appropriate technology and policies to protect and manage water resources (including river basins and lakes). Water-harvesting and storage are necessary to support crop and livestock production. More innovation is required in recycling wastewater to increase the overall availability of water. The desalination of seawater offers one option to increase the availability of water for human consumption and agricultural production. However, this technology is still expensive and results in waste (high salt concentrations) pose additional environmental problems (Ahmadi et al., 2020).

Investment and innovation will be necessary for low-cost yet efficient irrigation options to mitigate the impact of water scarcity and expand the availability of diverse foods year-round. Hydroponic production with recirculation of water and nutrients in a closed system can reduce water consumption (Al Shrouf, 2017). These systems also allow the containment of plant diseases, particularly viruses, in tropical regions. For example, drip irrigation delivers just the right amount of water, at a specific time, to a precise spot from where the water will be best absorbed by the plant, producing "more crop per drop". Promoting the use of renewable energies in water desalination for agriculture use could offer competitive cost options for the delivery of modern energy and increase the use of non-conventional water resources to guarantee long-term food security and socioeconomic stability.

Livestock. Livestock is an important element of millions of people's livelihoods in Africa's pastoralist, mixed crop-livestock farming and commercial systems, offeringmultiple opportunities for income and employment. Increases in demand for animal products in African countries outpace supply. Meeting this demand will require substantial increases in production while reducing the environmental footprint of livestock production. Livestock (including poultry, swine, sheep, goats, cattle and rabbits) are good sources of high-quality animal protein with rich amino acid profiles (NASAC 2018). They also provide much needed nutrient-dense foods, vital to overcoming the high rates of child malnutrition in Africa.

However, globally livestock accounts for 14.5% of all greenhouse gas emissions (cattle for 60% of these), with emissions linked to food digestion and feed production dominating emissions from ruminants (Gerber et al., 2013), and about a third of the freshwater footprint for agriculture (Mekonnen and Hoekstra, 2012). Although Africa's livestock sector is still primarily extensive (rather than intensive industrialised production), this may change as the demand for animal-sourced foods increases with shifting urbanisation and changes in income in middle-income countries. Climate change could affect future grazing capacities, lead to more migration of animal herds, and increase zoonotic diseases incidence (MaMo Panel, 2020).

Livestock genetic improvement programmes, interventions to increase carbon sequestration in grasslands and improved management of grazing lands could significantly increase productivity and reduce greenhouse gas emissions (Gerber et al., 2013; Henderson et al., 2015). The use of high-quality forage grasses and legumes offers a wide array of benefits, including higher livestock and crop productivity, restoration of degraded land through the accumulation of organic matter in soils, and improvement of soil fertility through the fixation of atmospheric nitrogen and the inhibition of nitrification in the soil and a year-round supply of feedstock (Rao et al., 2015). Indigenous feed resources can be incorporated into feeds to promote self-reliance. The available genetic variability of forage plants is still largely untapped and largely underutilised (Sandhu et al., 2015). Drought-tolerant *Brachiaria* grasses originated primarily in natural grasslands in Africa, yet they have only recently been re-introduced for commercial cultivation in African countries at a significant scale. It has been estimated that cows reared in Brachiaria pastures could increase by up to 40% in Kenya and Rwanda than native grasslands with spillover benefits further down the value chain (Maina et al., 2016).

Emerging challenges in animal health include improving resistance to disease and combating the misuse of antibiotics in animal production systems (Kimera et al., 2020). An example of such pests is the trypanosome parasites. Trypanosomiasis greatly restricts cattle rearing in 32 countries of Sub-Saharan Africa, leading to losses due to lost animals and animal products of between US$1 billion and US$6 billion annually (Yaro et al., 2016). The development of conventional vaccines against the parasite has been thwarted by trypanosomes' ability to continuously change the antigenic properties of their surface coat and evade attack by the host's immune system (Radwanska et al., 2008). The discovery of innate resistance to trypanosomiasis in some African wild animals is linked to the presence of a protein in their blood that kills trypanosomes, called APOL1, has opened new avenues of research (del Pilar Molina-Portela et al., 2005), offering opportunities to develop effective vaccines.

Fish is an important source of food and nutrients as well as livelihoods in Africa. Fish provides 19% of animal protein in African diets (Chan et al., 2019). Africa is a net importer of fish (Chan et al., 2019). A threefold increase in production is needed to meet expected demands in fish (Chan et al., 2019). Aquaculture, an emerging sector in the continent, holds great potential for rapidly increasing the amount of available protein. Aquaculture production in Africa expanded at an average annual rate of 11.7% between 2000 and 2012 (nearly twice the global average rate of 6.2% (FAO, 2014a). Given the spatial and environmental constraints, this will require improvements in efficiency, husbandry and increased investment in domestication and development of new species for commercial production alongside the genetic improvement of existing commercial stocks. Initiatives to genetically improve fish for aquaculture have so far been quite limited. Of the 400 species cultured, 90 are domesticated, and of these, only 18 (5%) have been the subject of significant genetic improvement programmes (Teletchea and Fontaine, 2014). Genetic improvement can also reduce the environmental footprint of aquaculture. For example, a study that investigated the environmental consequences of genetically improving growth rate and feed conversion in an African catfish established that increases in feed conversion reduced the environmental footprint in all the scenarios tested (Besson et al., 2016). On the other hand, improving growth rates had a beneficial environmental impact only when rearing density limited farm production. Both improvements raised farm productivity (Besson et al., 2016). These results indicate that determining the genetic basis of feed efficiency in fish with potential for commercial production in Africa is an important research objective, but they also show that breeding programmes need to be complemented by studies to improve feed quality and establish the best management practices to maximise productivity sustainably.

Optimising the utilisation of indigenous crops, livestock, fish and underutilised foods. Africa has over 2,000 plant species that include domesticated and semi-domesticated native grains, roots, fruits and vegetables. These are considered to be "lost" species for rediscovery and exploitation in modern food systems owing to their natural health and nutritional benefits and a variety of adaptive and resilient properties (National Research Council, 1996). Many indigenous crops have multiple edible parts such as leaves, fruit, seeds and roots. Many indigenous African livestock, fish and plant breeds are resilient to many risks and adverse growing conditions (Mabhaudhi et al., 2019). but are viewed as famine foods, foraged and turned to by the poor in adverse situations. Yet, many of these foods are described as 'superfoods'. Optimal utilisation of nutritious indigenous and traditional foods holds the potential for diversifying Africa's food systems, especially if more of these can be domesticated and produced in larger quantities. Yet, many highly nutritious African indigenous crops are threatened with extinction. On their own or included in existing monoculture cropping systems, these crops could support more sustainable, nutritious, and diverse food systems in marginalised agricultural environments (Mabhaudhi et al., 2019). There is a need to collect and categorise these underutilised crops and wild populations of important plant species and combine these with modern molecular breeding technologies.

There is an urgent need to create pride and demand for these foods and investment in research and technology development across the food system to integrate these resources into the daily food basket of African communities. The New Nordic Cuisine (Nordic Council, undated) food movement provides an example of how traditional food values can be revived and cuisine modernised and developed to give a renewed appreciation of the wealth of indigenous and traditional foods of high nutritional and health value.

Although not widely adopted in Africa, *biotechnology (techniques to improve plants, animals, and microorganisms) offers many opportunities* to improve productivity, overcome abiotic (such as drought) and biotic stresses (diseases and pests), and save time and effort for farmers in Africa. For example, genetically modified crop varieties are labour-saving and reduce agricultural production's drudgery—especially for women who are often tasked with more labour-intensive tasks such as weeding (Gouse et al., 2016).

Biotechnology can support food security in the face of major challenges such as declining per capita availability of arable land; lower productivity of crops, livestock and fisheries, heavy production losses due to biotic (insects pests, weeds) and abiotic (salinity, drought, alkalinity) stresses; significant postharvest crop damage and a declining availability of water. Biotechnology techniques that could be applied include tissue culture; marker-assisted selection, which entails the development of genetic markers to fast track selection of natural traits in plant breeding the "omics" (sciences such as genomics, and proteomics and transcriptomics); the development of diagnostics; genetic modification; and a newer set of tools collectively referred to as the new plant breeding technologies (NASAC, 2018). Some examples of the application of biotechnology in Africa include the development of disease-resistant bananas and cassava; vitamin enriched bananas and nitrogen-efficient rice in Uganda (Ainembabazi et al., 2015; Wagaba et al., 2016); insect tolerant cowpea in Nigeria, Niger and Ghana; and drought-tolerant maize in Kenya (Mohammed et al., 2014; Muli et al., 2016). Tissue culture can play an important role in producing disease-free planting material for vegetatively propagated crops such as banana and cassava (Akin-Idowu et al, 2009; Kikulwe et al., 2016) and is an essential tool for the conservation, improvement and mass production of African indigenous crops (Opabode, 2017). Marker-assisted selection has been used successfully to improve a variety of traits in crops in crops such as drought-tolerant maize varieties (Beyene et al., 2016), *Striga* resistant cowpeas in Nigeria and sorghum in Sudan (Omoigui et al., 2017; Ali et al., 2016). Marker-assisted selection has also been applied to developing crop varieties with higher nutritional contents (Andersson et al., 2017).

New advances in science offer opportunities for the development and mass production of microbes and microbial enzymes to enhance the quality and efficiency of feed processing and utilisation in the gut microbiome of livestock, which plays a crucial role in animal digestion and the resulting level of emission of greenhouse gases (O'Callaghan et al., 2016).

b) Innovation in the processing and packaging of foods

Transformation of the food system in Africa demands that we harness STI to promote product diversification with nutritious foods; processing to extend shelf life and make healthy foods easier to prepare, and improved storage and preservation to retain nutritional value; ensure food safety; extend seasonal availability and reduce postharvest losses (including aflatoxin) and food waste (Hendriks and Covic, 2016). These solutions should consider current changes in demand, predict future demand changes, and shape the African food system's future in ways that will provide nutritious food for all.

Preserving food and reducing food loss is an imperative part of an efficient and sustainable food system. The growth of the middle-class and increased urbanisation are likely to increase demand for processed foods. However, limited and unreliable electricity supply may constrain the wide adoption of such technologies. Access to energy is crucial for the transformation of Africa's food systems and has a transformative impact on the livelihoods of the rural poor, reducing the drudgery of their work and generating higher incomes (MaMo Panel, 2019a). Many options are emerging that Africa could benefit from in terms of off-grid and mini-grid technologies for hydro, wind, and solar power.

Postharvest handling and technologies offer opportunities to reduce food losses and waste, particularly in the African context where cold chains and refrigeration are largely missing (MaMo, 2019b) and seasonality leads to gluts and shortages of perishable goods. Many of these losses can be prevented through proper training and handling of goods, adopting appropriate tools or technologies, sound policies and marketing-related improvements (Statherset al., 2020). More investment is also needed in developing and making available solar driers and agro-processing equipment such as shellers and de-pulpers.

Food processing has the potential to contribute to the reduction of postharvest losses, enhancement of food safety and quality, creation of diversity, and stabilisation of food supply, reducing the prevalence of seasonal hunger and improving market access. Food processing can generate jobs and increase the retention of organic waste in farming areas. Even simple processing methods can transform perishable crops into a range of convenient, storable, value-added products, which meet the needs of expanding markets (Muyonga, 2014). Processing foods may smooth supplies but can create deleterious health consequences (overweight, obesity and non-communicable diseases) depending on their ingredients (trans fats, high sugar and sugar alternatives and excessive preservatives and other additives) (Pot et al., 2017). On the other hand, processing can also be used to create products that address specific nutrition needs. By blending staples and foods with complementary nutritional value and applying suitable processing procedures, it is possible to develop nutrient- and energy-enhanced foods to supplement prevailing nutritionally inadequate diets, which are particularly important for infants and young children.

Food safety is critical to the advancement of foods systems. Poverty exacerbates the problem since it leads to overdependence on one foodstuff and may lead to the consumption of contaminated foods because of the lack of alternatives

(Shephard and Gelderblom, 2014). Evidence on foodborne disease (FBD) in low and middle-income countries (LMICs) is still limited, but important studies in recent years have broadened our understanding. Grace (2015) reports that most of the known burden of FBD disease in low and middle-income countries comes from biological hazards, primarily from fresh, perishable foods sold in informal markets (Grace, 2015). Testing is often expensive and constrains the approval, distribution and export of foods. The lack of suitable regulations to prevent food contamination, or their poor enforcement when regulations exist (often applied to export goods, but not the domestic market) combined with the low levels of capacity for detecting food toxins, are serious concerns (Matumba et al., 2017). Rapid and cheap out-of-laboratory analytical techniques designed for field conditions can offer solutions to these problems (Shephard and Gelderblom, 2014). An example is fluorescence spectrophotometry for quantifying mycotoxin levels in grains and raw groundnuts (Shephard, 2016) and the Lab-on-Mobile-Device (LMD) platform that can accurately detect mycotoxins using strip tests (Dobrovolny, 2013).

More research and development is needed in packaging solutions to extend the shelf life of food, thereby reducing enzymatic activity and the growth of microorganisms and preventing moisture loss and decay. Thermal processing has been widely employed in the food industry for food safety assurance and extending product shelf-life by inhibiting or inactivating microorganisms (Caminiti et al., 2011; Stoica et al., 2013). Other technologies that could have significant benefits for food safety in Africa include non-thermal inactivation technologies such as electromagnetic fields, pulsed electric fields, high-voltage discharge, pulsed light, ionising radiation, microwaves and cold plasma (NASAC, 2019). Hybrid technologies and combinations of these methods have not yet been applied to the indigenous food industry but could hold promise for transforming African food systems.

National agro-processing strategies and interventions are needed to meet the anticipated rise in demand for these foods. Some possible interventions include establishing agro-processing incubators, promoting local production of food packaging materials, provision of fiscal incentives, and promoting research aimed at developing appropriate processing technologies.

c) Improving human nutrition, health and productivity

Making more nutritious food options available to a wide range of consumers is another pathway to influencing nutritional outcomes. This can include public and private sector investment in research and innovation of technologies and processes that improve foods' nutritional value. Recent advances in gene sequencing technologies enable investigation of the complex gut biome at both the genetic and functional (transcriptomic, proteomic and metabolic) levels and can map microbiome variability between species, individuals and populations, providing new insights into the importance of the gut microbiome in human health. Together with studies of traditional diets that include a wide range of herbal, medicinal and fermented products from Africa's wealth of indigenous foods, these offer opportunities for understanding how foods and the gut biome interact to protect human health and immunity.

Food fortification initiatives such as salt iodisation, adding vitamin A to cooking oil and multivitamin mixes to maize flour, as well as the bio-fortification of crops such as the varieties of vitamin-A-enriched orange-flesh sweet potato, offer options for reaching a high proportion of the population. More research is needed into which African crops could benefit from breeding programmes for biofortification to diversify the food basket and preserve the genetic diversity of nutritious traditional crops. Breeding, processing and additives such as prebiotics and probiotics offer the potential for enhancing the bioavailability of nutrients for absorption and metabolism (Markowiak and Śliżewska, 2017) or decreasing the concentration of antinutrient compounds that may inhibit the absorption of nutrients (for example, phytates and oxalates) (Popova and Mihaylova, 2019).

Advances in gene sequencing technologies enable investigation of the complex gut biome at both the genetic and functional (transcriptomic, proteomic and metabolic) levels. They can map microbiome variability between species, individuals and populations, providing new insights into the importance of the gut microbiome in human health (Brunkwall and Orho-Melander, 2017). Together with studies of traditional diets that include a wide range of herbal, medicinal and fermented products from Africa's wealth of indigenous foods, these offer opportunities for understanding how foods and the gut biome interact to protect human health and immunity.

d) Addressing fragility and instability

Climate change and increasing competition for key resources such as land and water provoke violence and armed conflicts, exacerbating the vicious circle of hunger and poverty (FAO et al., 2020). Conflict disrupts food production, blocks the flow of food and humanitarian aid, and drives food prices beyond the level of affordability (NASAC, 2018). COVID-19, climate change, conflict (including that between farmers and herdsmen) and protracted crises could increase hunger and child malnutrition and reverse the gains achieved over the past two decades. As part of the broader considerations for local-global interconnectedness in food systems, future food production must be achieved with a lower impact on the environment (German et al., 2016) and more efficient use of inputs and land.

Addressing these critical challenges will require an integrated approach that deals with issues about the sustainable use of natural resources (including water, energy, soils); increasing the productivity of crops and livestock; expanding the number of species used for food production to include neglected indigenous crops, and promoting diversification in livelihood activities. Environmental protection is essential for preserving the production potential of agriculture in Africa.

e) A data revolution for greater access to information and transparent monitoring and accountability systems

The complex nature of food systems demands transdisciplinary collaboration and inter-sectoral governance. ICT can enhance learning between stakeholders in the system as well as between disciplines to support innovation and the emergence of practical technologies that arise from transdisciplinary collaboration.

Evidence-based policies and planning require extensive and up-to-date data. There is an urgent need to strengthen national and regional institutional capacities for knowledge, data generation, and management that support evidence-based planning, implementation, and monitoring and evaluation (Bahiigwa et al., 2016). ICT innovations also offer multiple opportunities for improving and optimising food systems that could support the establishment of "big data" systems, analysis and reporting of cross-sectoral data, and monitoring and evaluation of implementation. Therefore, more significant investment is needed in more and better data, and inclusive annual national and subnational reporting mechanisms need to be developed and implemented to assess progress on commitments for food security and nutrition outcomes and actions in a timely way (Hendriks and Covic, 2016).

Collecting, managing and reporting data requires extensive information systems. "Big data" systems offer opportunities to analyse vast datasets to reveal patterns, trends and associations, especially in multi-sectoral applications such as those seen in the SGDs and national performance and monitoring situations related to food systems through innovative approaches and algorithms. Some applications include fraud and risk detection, logistic planning in programmes and price comparisons, as well as predictive and proactive health disease and health management systems (NASAC, 2018).

Public awareness of the problems, hazards and solutions is essential. Cloud computing allows for crowdsourcing and the active participation of citizens in mutual accountability systems and the provision of highly disaggregated geo-referenced data that can play an important role in monitoring contexts such as climate change, disease patterns and early warning systems. Communication science offers opportunities for exploring how to deploy digital media and improve communication systems to share knowledge at all levels.

The role of ICT in rapid identification of pests and diseases and mapping of their locations and spread are important tools for managing and mitigating risks due to the spread of pests and diseases (Christaki, 2015) and for increasing the awareness and preparedness of farmers, especially as much of the African food chain is informal. Investment in qualified staff within government, extension, and supporting research institutes is crucial, with a particular need for investment in young researchers and entrepreneurs. Comprehensive soil mapping is necessary to address the deficiencies through appropriate soil improvement practices and the cultivation of the most suitable crops for each area. Overlaying these with weather and crop suitability maps can provide hands-on information to farmers through mobile technology. Mobile technology could be used to improve early warning systems and dissemination of knowledge. One example is the Participatory Integrated Climate Services for Agriculture, which can help farmers make informed decisions based on accurate, location-specific, climate and weather information combined with the locally relevant crop, livestock and livelihood options, and participatory tools (Dayamba et al., 2018).

Satellite Earth Observations as a novel opportunities of the ICT revolution, combined with in-situ data, provide a source of consistent and reliable information to benefit the water, energy, and food Sustainable Development. Such observations are necessary to begin understanding the complex feedback processes between the natural environment and human activities (FAO, 2014)b.

ICT can solve many of the current constraints about access to information, data analysis, predictions and early warning. Innovations in mobile technology can overcome many trade and market-related information challenges, link farmers to markets and provide two-way communication between producers, consumers and researchers. ICT applications and advances in digital banking offer opportunities for solving some of these constraints.

However, African countries need to invest in capacity building, including STI research and development; training and education; communication; monitoring and evaluation; and governance and building international collaborations. Clear long-term commitment and funding (for both infrastructure and human capacity) are crucial to attaining targets such as improving production and food systems. Additional capacity for biotechnology is necessary in Africa, particularly to build a critical mass of expertise that can select, diffuse, adapt and use technologies from abroad.

4. CONCLUDING MESSAGES

STI offers many promising opportunities for agricultural transformation in Africa. Modern science can unlock the potential and protect the heritage of Africa's nutritious food sources and ensure sustainable and diverse diets. Changing the path of future food systems in Africa will demand a structural transformation (transitioning from low productivity and labour-intensive economic activities to higher productivity and skill-intensive activities) of food systems and considerable value chains development. The mandate and operations of S&T institutions are necessary to enhance their contribution to the exploitation of S&T for sector transformation.

The context-specific essential STI solutions relevant to transforming food systems in Africa relate to:

a) improving production systems and restoring degraded systems (including soil quality);

b) innovation in the processing and packaging of foods;

c) improving human nutrition, health and productivity;

d) addressing fragility and instability and

e) greater access to information and transparent monitoring and accountability systems.

The Food Systems Summit offers opportunities for stakeholders in African food systems to reflect on the role STI can play in transforming food system outcomes to improve the supply of safe and nutritious food for all while restoring and protecting the degradation of natural resources to ensure the sustainability for future generations.

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This report presents an update and summarised version of the report *Opportunities and challenges for research on food and nutrition security and agriculture in Africa*.

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